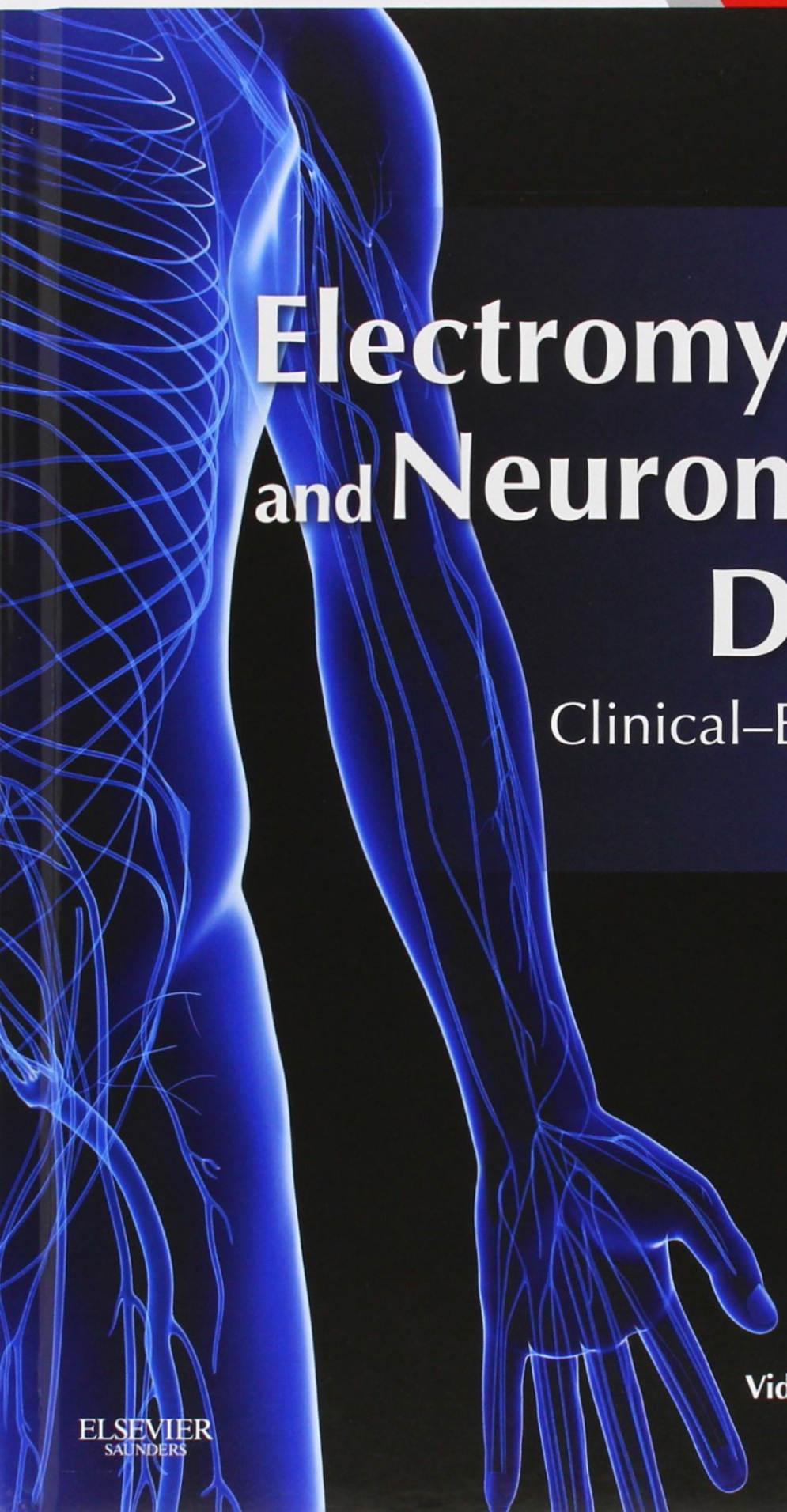

Third Edition

Electromyography and Neuromuscular Disorders

Clinical–Electrophysiologic Correlations

David C. Preston
Barbara E. Shapiro

Videos available online

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Electromyography and Neuromuscular Disorders

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Electromyography and Neuromuscular Disorders:

Clinical–Electrophysiologic Correlations

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Foreword

Electromyography (EMG) is a relatively new test. When I started my residency training at the Mayo Clinic in 1973 with Drs. Ed Lambert and Jasper Daube, it was not widely available, and the equipment was rudimentary. The machines were based on vacuum tube technology, were large and cumbersome, took up most of the room, and had to be tweaked and calibrated. Filters had to be set manually for each patient as well as each test. Heating lamps were not necessary, because the heat alone from these machines in a small room was enough to keep patients warm and make the neophyte trainee perspire, especially when the instructor entered the room.

Since then, much has changed. New technology has produced compact, microchip-based, and highly accurate and reliable machines. Gains and filters are available at the touch of a button. Moreover, fostered by the efforts of pioneers such as Lambert, Daube, and many others, there has been an explosion of knowledge in the field of EMG and clinical neurophysiology. As a result, we now know a great deal about the neurophysiologic findings in many diseases of the peripheral nervous system. Indeed, for those of us in the day-to-day practice of clinical neuromuscular diseases and clinical neurophysiology, EMG and related electrophysiologic studies can be an enormous help in diagnosis and management. Most of us regard EMG as the single most useful test in clarifying the differential diagnosis of an obscure neuromuscular problem, second only to the clinical examination.

We all pay lip service to the concept that the EMG is an extension of the clinical examination and best used in conjunction with a careful clinical examination. In practice, however, there are many occasions when this rule is violated, and there has been a trend lately to develop "clinical neurophysiologists" who practice in the laboratory and have little clinical experience. This is a dangerous approach, because although EMG and related tests are powerful and sensitive technology, they are also subject to interpretive error. As such, they must always be evaluated in light of careful consideration of the clinical findings by an experienced clinician. Improperly interpreted or performed EMG tests can lead to useless diagnostic tests and dangerous treatments. On virtually a weekly basis, patients are referred to my clinic because of tests done improperly or misinterpreted in the light of the clinical findings. Thus, there is a need for publications that continue to teach the clinical approach to neurophysiology.

Although several excellent texts cover the technical and, to some extent, clinical aspects of EMG, this book by Preston and Shapiro is unique in its emphasis on clinical and EMG correlation. The book amply and clearly covers the technical aspects, but its strength lies in its emphasis on clinical/neurophysiologic correlation, a hands-on, interactive approach for the reader, and a style that most closely approximates how a clinical neurophysiologist thinks when approaching a complicated patient. The authors' discussion of potential pitfalls in testing is also most helpful. The authors' admonition that, when in doubt, the examiner should stop stimulating and needling, retake the history, and repeat the clinical examination bears repeating to every trainee in every program.

This text will be a positive and important addition to the EMG literature. It will be helpful to trainees in EMG and should also be useful as a refresher to experienced electromyographers. I congratulate Drs. Preston and Shapiro on an excellent book. I'm jealous: I wish I had written it.

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Preface to the Third Edition

Since the publication of this book in 1997, followed by the second edition in 2005, we have been profoundly gratified by the continued overwhelmingly positive reception it has received from physicians, both in training and in practice. It has become one of the key resources for residents and fellows who are learning electrodiagnostic testing and clinical neuromuscular disorders. The goal of the first edition was to create a textbook that integrated electrodiagnostic studies and neuromuscular disorders in a practical and concise manner, always remembering the important principle that nerve conduction studies and electromyography (EMG) are an extension of the clinical examination. In the second edition, the companion CD of EMG waveforms was added so that the reader could have the benefit of being able to see and hear examples of classic EMG waveforms. The second edition was also expanded in the number of chapters and the breadth of information, adding chapters on Pediatric EMG, Electricity and Electronics, EMG in the ICU, Iatrogenic Electrodiagnosis, and Statistics for EMG studies.

As the intention of this text was, and remains, to convey basic and essential information, and the vast majority of the basic and essential information has not changed, the question again arises, "why do a third edition?" The reasons are multifactorial.

First, the authors now read many of our neurology journals and an increasing number of books on our iPads and other similar devices. We also now use these devices to connect to our electronic medical record, and look up drug information and a host of medical information. It therefore makes sense for a third edition to be both in print and completely electronic. Although it is difficult for many of us to think about replacing books with electronic media, this is clearly where the world is moving, led by our students, residents, and fellows in training.

Second, writing a third edition gave us the opportunity to review the medical literature since 2005 on all the topics in the text, especially the chapters that deal with clinical disorders. Since the publication of the second edition there have been significant advances in understanding the genetics, pathophysiology, and treatment of many neuromuscular conditions, and these are included in the third edition. In addition, some electrodiagnostic techniques have been improved and other new ones described that are included in this third edition of the book.

Third, with advances in publishing, we have now greatly improved the figures and color has been added to many of them. Most of the photographs are now in color. Being strong believers in "a picture is worth a thousand words," we have added over 100 new figures and photos, and others have been updated. In addition, one of the major improvements in the third edition has been the inclusion of cross-sectional anatomy of the muscles used for needle EMG. To really master the needle EMG, one needs to be able to think three dimensionally – not only where the muscle is, but what other muscles are nearby and, even more important, what other important vascular structures and nerves are nearby that one needs to avoid. To this end, we adapted cross-sectional line drawings from the outstanding work of Eycleshymer and Schoemaker published in 1911. Each individual drawing was scanned and then oriented to the position used for EMG. The muscle of interest was shaded red and, likewise, all major nerves, veins, arteries and tendons were color coded. Finally, a life size image of a conventional needle EMG was placed in the correct orientation used for EMG. Thus, each muscle used for needle EMG now has a photo showing its correct insertion point along with its relevant cross-sectional anatomy at that location.

Like the first and second editions, this text is meant to provide a single resource for those physicians training in or practicing electrodiagnostic studies. From our perspective of teaching for over 20 years, on a post-graduate, residency, and fellowship level, we feel that if one can master the fundamentals in this book, one should have all the basic concepts and information one needs to competently understand and interpret electrodiagnostic studies. Although a great deal of information is presented regarding the performance of studies, there remains no substitute for hands-on experience under supervision. However, for the recognition and interpretation of EMG waveforms, the videos now published on the web should make this much easier to master.

The continued goal of this text is to present material in an easily understandable and logical manner. The authors have often commented to their students that with knowledge of anatomy, physiology, and neurologic localization, the practice of electrodiagnostic studies makes sense. We hope that with the information contained in this text, one can sit down with a patient, take a history, perform a physical examination, and use the appropriate electrodiagnostic studies to reach a diagnosis.

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Preface to the Second Edition

Since the publication of the first edition of this book in 1997, we have been gratified by the overwhelmingly positive reception it has received from physicians, both in training and in practice. The goal of the first edition was to create a textbook that integrated electrodiagnostic studies and neuromuscular disorders in a practical and concise manner, always remembering the important principle that nerve conduction studies and electromyography (EMG) are an extension of the clinical examination. As this text is intended to convey basic and essential information, the question arises, "why do a second edition?" The authors acknowledge that no new muscles have been discovered in the human body over the past six years. Likewise, PCR and genetic tests have failed to identify any new nerves. Although much of the basic information in the fields of electrodiagnostic studies and neuromuscular disorders has not changed, we have written this second edition to improve and expand on many topics.

First and most important, needle electromyography relies upon the proper interpretation of waveforms in real-time. While one can read about waveforms until they are blue in the face, it is very difficult to appreciate the audio and visual qualities of a waveform unless one can see and hear it. For the last fifteen years, we have collected video examples of classic EMG waveforms from a variety of patients. Two years after the publication of the first edition of this book, we introduced a companion videotape of common EMG waveforms. With new digital technology, we have now been able to digitize these video waveforms and put them on a companion CD which accompanies this book. Thus, in this second edition, the reader can view the CD on any computer, and watch and hear every common and classic EMG waveform. Because all the waveforms are digital, the reader can freeze or replay any waveform at any time. The textbook description and discussion of each waveform are now greatly enhanced by the companion CD.

Since the publication of the first edition there have been significant advances in some neuromuscular conditions, and these are included in the second edition. Some new disorders have been described, among them paralytic poliomyelitis caused by the West Nile virus. In addition, several new techniques that have been described and validated in the electrodiagnosis of neuromuscular conditions are included in this second edition of the book. For instance, the electrodiagnosis of ulnar neuropathy at Guyon's canal has significantly improved over the past few years, and several new techniques that are useful in making this diagnosis are included in this second edition.

We spent a considerable amount of time thinking of better ways to present complex material in a logical and concise manner for this second edition of the book. Being strong believers in "a picture is worth a thousand words," we have added many new figures, and others have been updated. Indeed, we have added or updated more than 175 figures to the first edition of the book.

We have improved the book in several other ways. First, we have expanded many of the clinical chapters, and in some cases separated them into new chapters, including median neuropathy at the wrist, proximal median neuropathy, ulnar neuropathy at the wrist, ulnar neuropathy at the elbow, amyotrophic lateral sclerosis, and atypical motor neuron disorders. All of the clinical chapters follow the same format that was used in the first edition, first presenting the important anatomic and clinical aspects of the disorder, followed by a discussion of the relevant electrodiagnostic studies. Each chapter ends with example cases based on actual patients, illustrating many important clinical and electrodiagnostic teaching points. In addition, in section three we have added a new chapter on basic statistics for electrodiagnostic studies, discussing several basic statistical concepts that every electromyographer needs to know in order to properly interpret a study.

The first edition was divided into six separate sections. This new edition has been expanded to eight. The first new section deals with EMG in Special Clinical Settings, including the approach to electrodiagnostic studies in the intensive care unit, and the approach to electrodiagnostic studies in the pediatric patient. In the last several years, electromyographers are called upon more frequently to perform EMG studies in the intensive care unit to evaluate patients with profound weakness. New clinical disorders and electrodiagnostic techniques to evaluate these disorders have been extensively reported over the last several years and are reflected in this new edition. We have included a discussion of pediatric EMG because of its own unique set of challenges and techniques that differ from adult studies.

The other new section deals with the basics of electricity and electronics, in addition to the potential risks and complications of electrodiagnostic studies. Some knowledge of electricity and electronics is extremely helpful in understanding electrodiagnostic studies. From a practical point of view, this knowledge is also very helpful in understanding and correcting many of the technical problems that arise in the everyday practice of electrodiagnostic medicine. The latter chapter arose from a continuing medical education course which we were asked to give at an annual meeting of the American Association of Electrodiagnostic Medicine, which was followed up as a review article in the journal Muscle and Nerve. Although nerve conduction studies and EMG are usually well tolerated and in most patients have minimal side effects, there are potential risks and complications, especially in certain patient populations. It is essential that all physicians performing these studies are aware

of these potential risks and complications, albeit rare, and follow simple protocols to minimize them.

Like the first edition, this text is meant to provide a single resource for those physicians training in or practicing electrodiagnostic studies. From our perspective of teaching for many years, both on a post-graduate and residency level, we feel that if one can master the fundamentals in this book, one should have all the basic concepts and information one needs to competently understand and interpret electrodiagnostic studies. Although a great deal of information is presented regarding the performance of studies, there is no substitute for hands-on experience under supervision. However, it is our hope that with the companion CD as part of the textbook, the recognition and interpretation of EMG waveforms will be easier to master.

Finally, the goal of this text is to present material in an easily understandable and logical manner. The authors have often commented to their students that with knowledge of anatomy, physiology, and neurologic localization, the practice of electrodiagnostic studies makes sense. We hope that with the information contained in this text, one can sit down with a patient, take a history, perform a physical examination, and use the appropriate electrodiagnostic studies to reach a diagnosis.

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Preface to the First Edition

This text is written primarily for clinicians who perform and interpret nerve conduction studies and electromyography (EMG), as well as for physicians who use the results of these electrodiagnostic studies to evaluate patients with peripheral nervous system disorders. Nerve conduction studies and EMG are best considered an extension of the clinical examination. Indeed, these studies cannot be properly planned, performed, or interpreted without knowing the patient's symptoms and findings on the clinical examination. Numerous nerves and literally hundreds of muscles can be studied. To study them all would be neither practical for the electromyographer, nor desirable for the patient. In every case, the study must be individually planned, based on the clinical differential diagnosis, and then modified as the study progresses and further information is gained. The electromyographer needs to perform the studies necessary to both confirm and exclude certain diagnoses while minimizing the amount of patient discomfort. Most often, nerve conduction studies and EMG can successfully localize the lesion, provide further information about the underlying pathophysiology, and assist in assessing the disorder's severity and temporal course.

Although there are many excellent textbooks on electrodiagnosis and several superb references on clinical neuromuscular disorders, few integrate the two in a practical and concise manner. The approach we take in this text parallels our teaching program developed for the EMG fellowships and neurology residencies at the Brigham and Women's Hospital and the Massachusetts General Hospital in Boston.

The book is divided into six fundamental sections. Section One covers the overall practical approach to a patient in the EMG laboratory, followed by a review of the basic anatomy and neurophysiology that every electromyographer needs to understand. Section Two discusses the fundamentals of nerve conductions, including motor, sensory, and mixed nerve studies, as well as late responses, blink reflexes, and repetitive nerve stimulation studies. In Section Three, important technical factors and artifacts are discussed, including the anomalous innervations. Section Four discusses the practical details of performing the most commonly used nerve conduction studies. In Section Five, the focus changes to needle EMG. After discussing the overall approach to the needle EMG, the anatomy of the bulbar, upper extremity, and lower extremity muscles is reviewed in detail. The last two chapters in this section cover the approach to the needle EMG examination, including the assessment of spontaneous activity and the analysis of motor unit action potentials.

Section Six, Clinical–Electrophysiologic Correlations, forms the core of the text. After an overview of the important patterns, all of the major peripheral nervous system conditions are discussed, from both the clinical and the electrophysiologic points of view. Included are the mononeuropathies, polyneuropathies, motor neuron diseases, radiculopathies, plexopathies, disorders of the neuromuscular junction and muscle, and the myotonic and periodic paralysis disorders. At all times, the text integrates the important basic clinical and electrophysiologic points. In Chapters 16–32, clinical cases and their respective nerve conduction and EMG data are presented. Each case example is that of an actual patient taken from our EMG teaching file during the past 10 years.

The authors appreciate that some specific techniques and normal values may vary from laboratory to laboratory. Nevertheless, the goal of this book is to present a logical approach in the EMG laboratory that combines the clinical and electrophysiologic evaluations of a patient with a disorder of the peripheral nervous system.

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Dedication

To our daughters, Hannah and Abigail

Acknowledgments

The authors are indebted to their mentors in clinical neurophysiology: Drs. John J. Kelly, Jr., Eric L. Logigian, and Bhagwan T. Shahani. In addition, the authors wish to thank their colleagues, technologists, and present and former EMG fellows at the University Hospitals Case Medical Center, the Brigham and Women's Hospital and the Massachusetts General Hospital. Dale Preston's and Richard (Zack) Zydek's contributions to the photography were all greatly appreciated. At Elsevier, Charlotta Kryhl, Louise Cook, Rachael Harrison, and Julie Taylor were instrumental in bringing this third edition to written and electronic print.

1 Approach to Nerve Conduction Studies and Electromyography

Electrodiagnostic (EDX) studies play a key role in the evaluation of patients with neuromuscular disorders. Among these studies are included nerve conduction studies (NCSs), repetitive nerve stimulation, late responses, blink reflexes, and needle electromyography (EMG), in addition to a variety of other specialized examinations. *NCSs and needle EMG form the core of the EDX study*. They are performed first, and usually yield the greatest diagnostic information. NCSs and needle EMG are complementary, and therefore are always performed together and during the same setting. Performed and interpreted correctly, EDX studies yield critical information about the underlying neuromuscular disorder and allow use of other laboratory tests in an appropriate and efficient manner. Likewise, the information gained from EDX studies often leads to specific medical or surgical therapy. For example, a patient with a peripheral neuropathy clinically, who is subsequently found to have an acquired demyelinating neuropathy with conduction blocks on EDX studies, most often has a potentially treatable condition.

In practice, EDX studies serve as an extension of the clinical examination and should always be considered as such. Accordingly, a directed neurologic examination should always be performed before EDX studies in order to identify key clinical abnormalities and establish a differential diagnosis. With numerous nerves and literally hundreds of muscles available, it is neither desirable for the patient nor practical for the electromyographer to study them all. *In each case, the study must be individualized, based on the neurologic examination and differential diagnosis, and modified in real time as the study progresses and further information is gained.*

NCSs and EMG are most often used to diagnose disorders of the peripheral nervous system (Figure 1–1, Box 1–1). These include disorders affecting the primary motor neurons (anterior horn cells), primary sensory neurons (dorsal root ganglia), nerve roots, brachial and lumbosacral plexuses, peripheral nerves, neuromuscular junctions, and muscles. In addition, these studies may provide useful diagnostic information when the disorder arises in the central nervous system (e.g., tremor or upper motor neuron weakness). Occasionally, information from the EDX study is so specific that it suggests a precise etiology. In most cases, however, the exact etiology cannot be defined based on EDX studies alone.

LOCALIZATION OF THE DISORDER IS THE MAJOR AIM OF THE ELECTRODIAGNOSTIC STUDY

The principal goal of every EDX study is to localize the disorder. The differential diagnosis is often dramatically narrowed once the disorder has been localized. Broadly speaking, the first order of localization is whether the disorder is neuropathic, myopathic, a disorder of neuromuscular transmission, or a disorder of the central nervous system (CNS). For example, in patients with pure weakness, EDX studies can be used to localize whether the disorder is caused by dysfunction of the motor neurons/

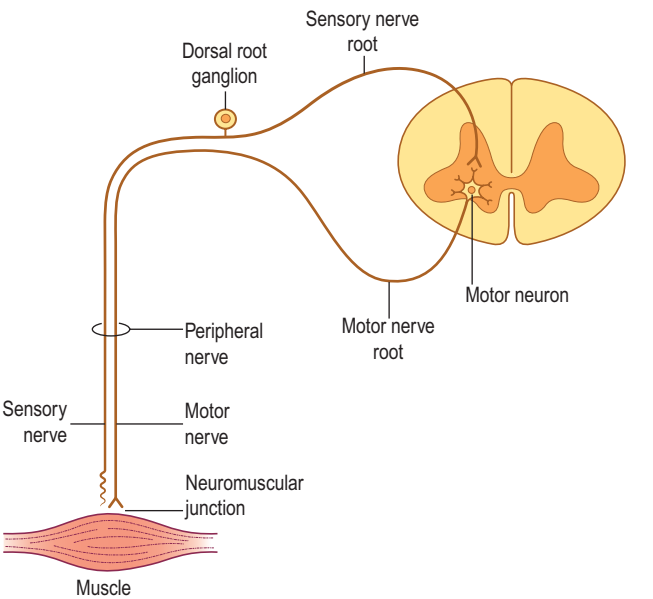

FIGURE 1–1 Elements of the peripheral nervous system. Note that the primary motor neuron resides within the spinal cord, whereas the primary sensory neuron, the dorsal root ganglion, lies outside the spinal cord. The dorsal root ganglion is a bipolar cell. Its proximal process forms the sensory nerve root; the distal process becomes the peripheral sensory nerve.

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axons, neuromuscular junctions, muscles, or has a central etiology. The pattern of nerve conduction and especially EMG abnormalities usually can differentiate among these possibilities and guide subsequent laboratory investigations. For example, a patient with proximal muscle weakness may have spinal muscular atrophy (i.e., a motor neuron disorder), myasthenic syndrome (i.e., a neuromuscular junction disorder), or polymyositis (i.e., a muscle disorder), among other disorders, including those with central etiologies (e.g., a parasagittal frontal lesion). EDX studies can easily differentiate among these conditions, providing key information to guide subsequent evaluation and treatment, which differ markedly among these diseases.

Box 1–1. Disorders of the Peripheral Nervous System

- Motor neuronopathy
  - Amyotrophic lateral sclerosis
  - Spinal muscular atrophy
  - Infectious (poliomyelitis, West Nile virus)
  - Monomelic amyotrophy
- Sensory neuronopathy
  - Paraneoplastic
  - Autoimmune
  - Toxic
  - Infectious
- Radiculopathy
  - Disk herniation
  - Spondylosis
  - Neoplastic
  - Infarction
  - Infectious
  - Inflammatory
- Plexopathy
  - Radiation induced
  - Neoplastic
  - Entrapment
  - Diabetic
  - Hemorrhagic
  - Inflammatory
- Neuropathy
  - Entrapment
  - Polyneuropathy
    - Demyelinating
    - Axonal
  - Mononeuritis multiplex
- Neuromuscular junction disorders
  - Myasthenia gravis
  - Lambert–Eaton myasthenic syndrome
  - Botulism
  - Toxic
  - Congenital
- Myopathy
  - Inherited
    - Muscular dystrophy
    - Congenital
    - Metabolic
  - Acquired
    - Inflammatory
    - Toxic
    - Endocrine
    - Infectious

Once the localization is determined to be neuropathic, myopathic, a disorder of the NMJ or of the CNS, EDX studies can usually add other important pieces of information to localize the problem further (Figure 1–2). For instance, the differential diagnosis of a patient with weakness of the hand and numbness of the fourth and fifth fingers includes lesions affecting the ulnar nerve, lower brachial plexus, or C8-T1 nerve roots. If EDX studies demonstrate an ulnar neuropathy at the elbow, the differential diagnosis is limited to a few conditions, and further diagnostic studies can be directed in a more intelligent manner. In this situation, for instance, there is no need to obtain a magnetic resonance imaging scan of the cervical spine to assess a possible cervical radiculopathy because the EDX studies demonstrated an ulnar neuropathy at the elbow as the source of the patient's symptoms.

In a patient with a CNS disorder who is mistaken as having a peripheral disorder, the EDX study often correctly suggests that the localization is central. For example, transverse myelitis may mimic Guillain–Barré syndrome, or a small acute cortical stroke may mimic the pattern of a brachial plexopathy. In settings such as these, the EDX study is often the first test to suggest that the correct localization is central rather than peripheral.

Neuropathic Localization

Neuropathic is probably the most common localization made on EDX studies. Neuropathic literally means a disorder of the peripheral nerves. However, in common usage, it includes the primary sensory and motor neurons as well. EDX studies are particularly helpful in neuropathic conditions. First, in conjunction with the history and examination, they can usually further localize the disorder to the neurons, roots, plexus, or peripheral nerve. In the case of peripheral nerve, further localization is usually possible to a single nerve (mononeuropathy), multiple individual

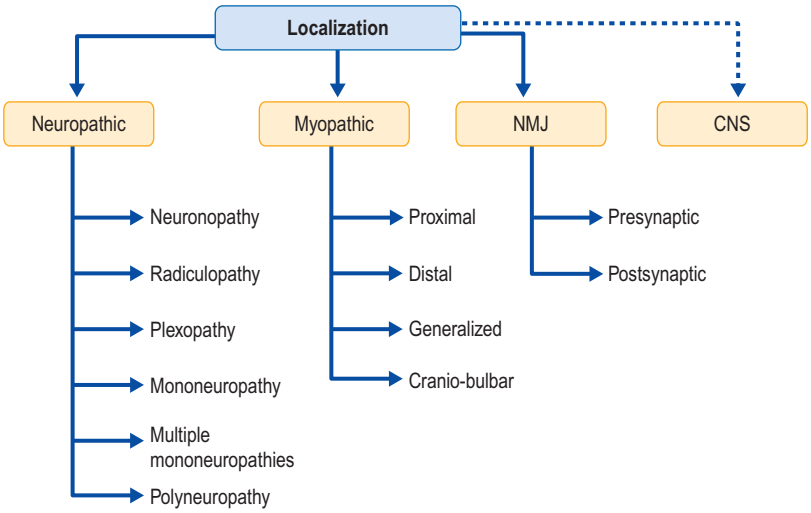

FIGURE 1–2 Possible localizations determined from the electrodiagnostic study.

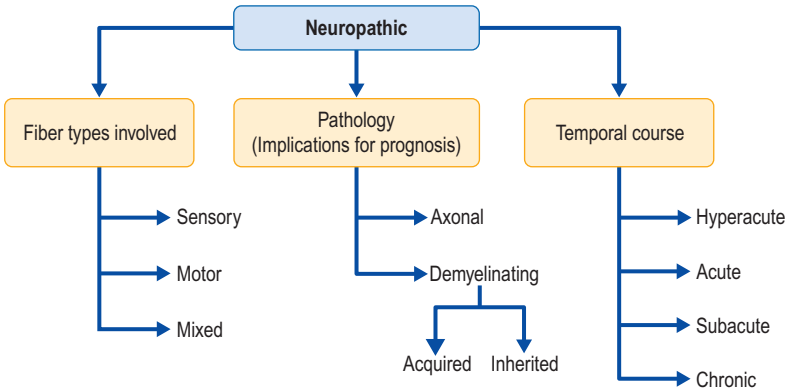

FIGURE 1–3 Key EDX findings in a neuropathic localization.

nerves (mononeuropathy multiplex) or all nerves (polyneuropathy). In the case of a single nerve, the exact segment of nerve responsible for the problem may be localized in some cases.

In the case of neuropathic lesions, EDX studies often yield further key information, including the fiber types involved, the underlying pathophysiology, and the temporal course of the disorder (Figure 1–3).

Information About the Fiber Types Involved and the Underlying Nerve Pathophysiology can be Gained, which then Further Narrows the Differential Diagnosis

In the case of neuropathic disorders, the involved fiber types and the underlying pathology can usually be determined. First, EDX studies are more sensitive than the clinical examination in determining which fiber types are involved: motor, sensory, or a combination of the two. Sensorimotor polyneuropathies are common and suggest a fairly large differential diagnosis. On the other hand, predominantly motor or predominantly sensory neuropathies are rare and suggest a much more limited set of disorders. For instance, a patient with numbness in the hands and feet and diminished reflexes may be diagnosed with a peripheral neuropathy. However, if EDX studies demonstrate abnormal sensory nerve conductions with completely normal motor nerve conductions and needle EMG, then the differential diagnosis changes from a peripheral neuropathy to a pure sensory neuropathy or neuronopathy, which has a much more limited differential diagnosis.

Second, EDX studies often can define whether the underlying pathophysiology is demyelination or axonal loss. Although most demyelinating neuropathies have some secondary axonal loss and many axonal loss neuropathies have some secondary demyelination, EDX studies usually can differentiate between a primary demyelinating and a primary axonal neuropathy. Because EDX studies usually can make this differentiation quickly and non-invasively, nerve biopsy is essentially never required to make this determination. Furthermore, the differentiation between primary axonal and primary demyelinating pathology is of considerable diagnostic and prognostic importance, especially in the case of polyneuropathies. The vast majority of polyneuropathies are associated with primary axonal degeneration, which has an extensive differential diagnosis. In contrast, the number of true electrophysiologic primary demyelinating neuropathies is extremely small. They are generally subdivided into those that are inherited and those that are acquired. EDX studies can typically make that determination as well. The finding of an unequivocal primary demyelinating polyneuropathy on EDX studies often leads quickly to the correct diagnosis and, in the case of an acquired demyelinating polyneuropathy, often suggests a potentially treatable disorder.

Assessing the Degree of Axonal Loss versus Demyelination has Implications for Severity and Prognosis

A nerve that has sustained a demyelinating injury often can remyelinate in a very short time, usually weeks. However, if there has been substantial axonal loss, whether primary or secondary, the prognosis is much more guarded. The rate of axonal regrowth is limited by the rate of slow axonal transport, approximately 1 mm per day. Clinically, axonal loss lesions can rarely be differentiated from demyelinating ones, especially in the acute setting. For example, in a patient who awakens with a complete wrist and finger drop, the etiology usually is compression of the radial nerve against the spiral groove of the humerus. However, the paralysis could result from either conduction block (i.e., demyelination) or axonal loss, depending on the severity and duration of the compression. Clinically, both conditions appear the same. Nevertheless, if the injury is due to axonal loss, it has a much worse prognosis and a longer rehabilitation time to recovery than a similarly placed lesion that is predominantly demyelinating in nature. EDX studies can readily differentiate axonal from demyelinating lesions.

Assessment of the Temporal Course can Often be Made

For neuropathic conditions, there is an orderly, temporal progression of abnormalities that occurs in NCSs and needle EMG. A combination of findings often allows differentiation among hyperacute (less than one week), acute (up to a few weeks), subacute (weeks to a few months), and chronic (more than a few months) lesions. The time course suggested by the EDX findings may alter the

impression and differential diagnosis. For example, it is not uncommon for a patient to report an acute time course to his or her symptoms, whereas the EDX studies clearly indicate that the process has been present for a longer period of time than the patient has been aware of.

Conversely, the temporal course described by the patient may impact the interpretation of the EDX findings. For instance, the finding of a normal ulnar sensory nerve action potential recording the little finger, in a patient with numbness of the little finger, has very different implications depending on the time course of the symptoms. If the symptoms are truly less than one week in duration, the normal ulnar sensory response could indicate an ulnar neuropathy (with incomplete wallerian degeneration), a proximal demyelinating lesion, or a lesion at the level of the nerve root or above. On the other hand, if the symptoms have been present for several weeks or longer, the same finding would indicate either a proximal demyelinating lesion or a lesion at the level of the nerve root or above. *These temporal changes underscore the electromyographer's need to know the clinical time course of symptoms and signs in order to ensure an accurate interpretation of any electrophysiologic abnormalities*.

Myopathic Localization

In the case of myopathic (i.e., muscle) disease, EDX studies can also add key information to further define the condition (Figure 1–4). First, the distribution of the abnormalities may suggest a particular diagnosis: are they proximal, distal or generalized? Most myopathies preferentially affect proximal muscles. Few myopathies, such as myotonic dystrophy type I, affect distal muscles. Some very severe myopathies (e.g., critical illness myopathy) can be generalized. In rare myopathies, there is prominent bulbar weakness; accordingly, EDX abnormalities may be most prominent in the bulbar muscles. Most myopathies are fairly symmetric; the finding of asymmetry either clinically and/or on EDX studies can be very helpful in narrowing the differential diagnosis. For example, inclusion body myositis may present asymmetrically, whereas polymyositis and dermatomyositis do not.

Second, the presence of spontaneous activity on needle EMG is helpful in limiting the differential diagnosis and suggesting certain underlying pathologies. Most myopathies are bland with little or no spontaneous activity. However, myopathies which are inflammatory, necrotic and some which are toxic may be associated with active denervation. In addition, other myopathies may have prominent myotonic discharges at rest. The presence of myotonic discharges in a myopathy markedly narrows the differential diagnosis to only a few possible disorders.

Lastly is the issue of the temporal course. Although this determination is more challenging than with neuropathic lesions, in some myopathies, a determination can be made if the myopathy is acute, subacute, or chronic, a finding which again narrows the differential diagnosis.

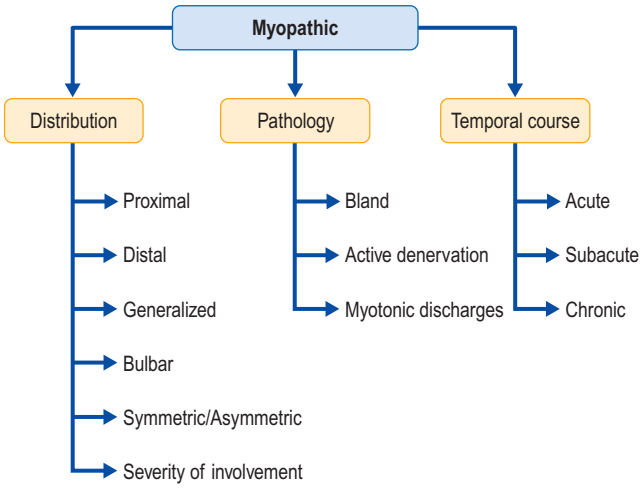

FIGURE 1–4 Key EDX findings in a myopathic localization.

Neuromuscular Junction Localization

Disorders of the neuromuscular junction (NMJ) are distinctly uncommon. However, when they occur, EDX studies not only help in identifying them, but can add other key pieces of information (Figure 1–5). First is the distribution of the abnormalities on EDX testing: are they proximal, bulbar or generalized? For instance, myasthenia gravis preferentially affects oculobulbar muscles and then proximal muscles on EDX studies, whereas myasthenic syndrome is a generalized disorder on EDX studies, although clinically it has a predilection for proximal muscles.

Broadly speaking, the underlying pathology can be divided into pre-synaptic and post-synaptic disorders. EDX studies are usually very good at making this determination. Myasthenia gravis is the prototypic post-synaptic disorder, whereas myasthenic syndrome and botulism target the presynaptic junction.

Lastly is the issue of the etiology of the NMJ disorder, whether it is acquired or inherited. Almost all NMJ disorders are acquired. However, there are rare inherited NMJ disorders. In some of these, there may be unique findings on EDX testing that suggest one of these rare disorders.

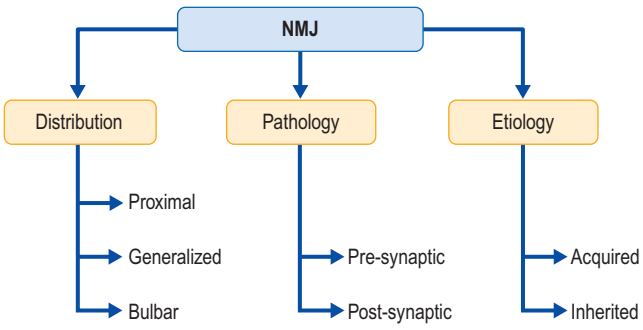

FIGURE 1–5 Key EDX findings in a neuromuscular junction localization.

Box 1–2. Patient Encounter

1. Take a brief history and perform a directed physical examination
2. Formulate a differential diagnosis
3. Formulate a study based on the differential diagnosis
4. Explain the test to the patient
5. Perform the nerve conduction studies and modify which nerve conduction studies to add based on the findings as the test proceeds
6. Perform the needle electromyography study and modify which additional muscles to sample, based on the findings as the test proceeds

PATIENT ENCOUNTER

Every EDX study begins with a *brief* history and *directed* physical examination (Box 1–2). *This point cannot be overemphasized*. Some may (incorrectly) argue that the history and clinical exam are not part of the EDX exam, and that the EDX needs to stand on its own. Nothing could be further from the truth. One is not expected to perform the same detailed history and physical examination that is done in the office consultation setting. *However*, before starting every study, the EDX physician must know some basic facts:

- What are the patient's symptoms?
- How long have they being going on?
- Is there any important past medical history (e.g., diabetes, history of chemotherapy, etc.)?
- Is there muscle atrophy?
- What is the muscle tone (normal, decreased or increased)?
- Is there weakness and, if so, where is it and how severe is it?
- What do the reflexes show (normal, decreased or increased)?
- Is there any loss of sensation and, if so, what is the distribution; what modalities are disturbed (e.g., temperature, pain, vibration, etc.)?

The duration, type, and distribution of symptoms, along with the physical examination, help determine the differential diagnosis, which in turn is used to plan the EDX studies. The EDX study is planned only after the differential diagnosis is determined. For instance, the EDX evaluation of a patient with slowly progressive proximal weakness is very different from that of a patient with numbness and tingling of the fourth and fifth fingers. In the former case, the differential diagnosis includes disorders of the anterior horn cell, motor nerve, neuromuscular junction, or muscle. In the latter case, the differential diagnosis includes an ulnar neuropathy at its various entrapment sites, a lower trunk brachial plexus lesion, or cervical radiculopathy. The EDX plan includes which nerves and muscles to study and whether specialized tests, such as repetitive nerve stimulation, may be helpful. The study can always be amended as the testing proceeds. Before beginning, however, one should first explain to the patient in simple terms what the test involves. Many patients are very anxious about the examination and may have slept poorly or not at all the night before the EDX study. A simple explanation, both before the test begins and while it is ongoing, can greatly reduce a patient's anxiety.

After the test is explained to the patient, the NCSs are performed first, followed by the needle EMG. A proper balance must be maintained among obtaining a thorough study, collecting the necessary information to answer the clinical question, and minimizing patient discomfort. If performed correctly, nearly all NCSs and needle EMG can be completed within 1.0 to 1.5 hours. Rarely, a longer study is needed if specialized tests such as repetitive nerve stimulation are performed in addition to the standard studies. There clearly is a limit to what most patients can tolerate. The electromyographer should always remember the Willy Sutton rule concerning robbing banks: "Go where the money is." If there is any question as to whether a patient will tolerate the entire examination, the study should begin with the area of interest. For instance, in the patient with numbness and tingling of the fourth and fifth fingers, the ulnar motor and sensory studies should be done first. Likewise, needle EMG examination of the ulnar-innervated muscles, as well as the C8-T1 non-ulnar-innervated muscles, are of most interest in such a patient. Plan ahead and consider which nerve conduction studies and needle examination of which muscles should be performed first, in case the patient can tolerate only one or two nerve conductions or examination of only a few muscles by EMG.

CARDINAL RULES OF NERVE CONDUCTION STUDIES AND ELECTROMYOGRAPHY

EDX studies rely on the physician's ability to pay meticulous attention to technical details during the study while keeping in mind the bigger picture of why the study is being performed. As more data are obtained, the study must be analyzed in real time and the test altered as needed. Analysis of online results gives the electromyographer the opportunity to modify the strategy as the testing proceeds, an opportunity that is lost once the patient has left the laboratory. The following cardinal rules of EDX studies should always be kept in mind while an EDX study is being performed (Figure 1–6):

1. *NCSs and EMG are an extension of the clinical examination.* NCSs and EMG cannot be performed without a good clinical examination. Every examination must be individualized based on the patient's symptoms and signs and the resulting differential diagnosis. If marked abnormalities are found on electrophysiologic testing in the same distribution where the clinical examination is normal, either the clinical examination or the electrophysiologic testing must be called into question. One usually finds that

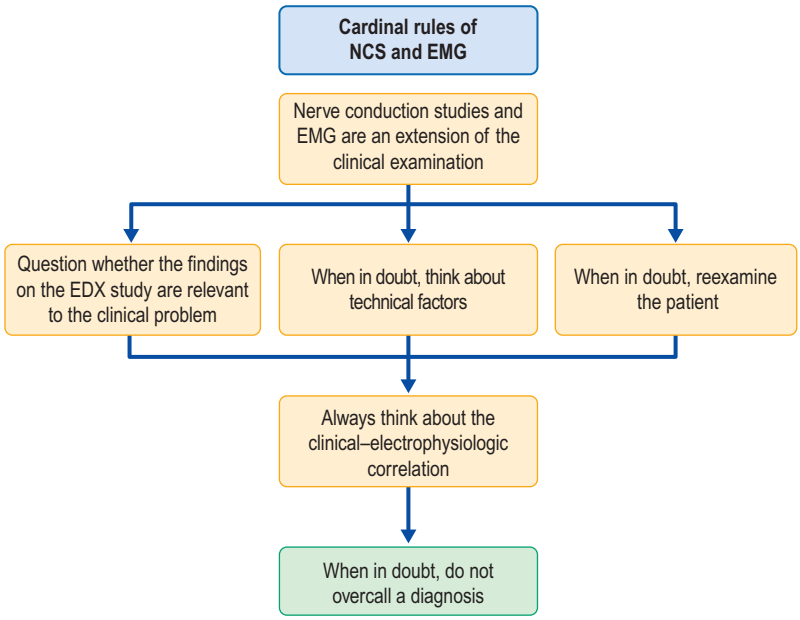

FIGURE 1–6 Cardinal rules of nerve conduction studies and electromyography.

the better the clinical examination, the better the differential diagnosis, and thus the more clearly directed the EDX studies will be.

2. When in doubt, always think about technical factors. EDX studies rely upon collecting and amplifying very small bioelectric signals in the millivolt and microvolt range. Accomplishing this is technically demanding; a large number of physiologic and non-physiologic factors can significantly interfere with the accuracy of the data. Accurate NCSs and EMG depend on intact equipment (e.g., EMG machine, electrodes, and stimulator), as well as correct performance of the study by the electromyographer. Technical problems can easily lead to absent or abnormal findings. Failure to recognize technical factors that influence the EDX study can result in type I errors (i.e., diagnosing an abnormality when none is present), and type II errors (i.e., failing to recognize an abnormality when one is present). Although both are important, type I errors are potentially more serious (e.g., the patient is labeled with an abnormal EDX study result, such as neuropathy, when the "abnormality" on the EDX testing is simply due to unrecognized technical errors). Such faulty diagnoses can lead to further inappropriate testing and treatment. If there is an unexpected abnormal EDX finding that does not fit the clinical examination, the lack of a clinical–electrophysiologic correlation should suggest a technical problem. For instance, if a routine sural nerve sensory conduction study shows an absent potential but the patient has a normal sensory examination of the lateral foot (i.e., sural territory), one should suspect a technical problem (e.g., improper electrode placement or too low stimulus intensity). If the data are not technically accurate, then correct data interpretation can never occur, either at the time of the study or later by the treating physician.
3. *When in doubt, reexamine the patient.* This is essentially an extension of cardinal rule number 1. In the example given with rule number 2, if the sural sensory response is absent after all possible technical factors have been corrected, the clinician should reexamine the patient. If the patient has clear loss of vibration at the ankles, there is less concern about an absent sural sensory response. If the patient's sensory examination is normal on reexamination, the absent sensory response does not fit the clinical findings, and technical factors should be investigated further.
4. *EDX findings should be reported in the context of the clinical symptoms and the referring diagnosis.* In every study, electrophysiologic abnormalities must be correlated with the clinical deficit. Because electrophysiologic studies are quite sensitive, it is not uncommon for the electromyographer to discover mild, subclinical deficits of which the patient may not be aware. For example, a diabetic patient referred to the EMG laboratory for polyneuropathy may show electrophysiologic evidence of a superimposed ulnar neuropathy but have no symptoms of such. Accordingly, the electromyographer should always report any electrophysiologic abnormality in the context of its clinical relevance so that it can be properly interpreted.
5. *When in doubt, do not overcall a diagnosis.* Because electrophysiologic tests are very sensitive, mild, subclinical, and sometimes clinically insignificant findings often appear on EDX testing. This occurs partly because of the wide range of normal values,

which vary with the nerve and muscle being tested. In addition, there are a variety of physiologic and non-physiologic factors that may alter the results of both NCSs and EMG, despite attempts to control for them. These factors, often when combined, may create minor abnormalities. Such minor abnormalities should not be deemed relevant unless they correlate with other electrophysiologic findings and, most importantly, with the clinical history and examination. It is a mistake to overcall an electrophysiologic diagnosis based on minor abnormalities or on findings that do not fit together well. Sometimes, the clinical or electrophysiologic diagnosis is not clear-cut and a definite diagnosis cannot be reached.

Occasionally, NCSs and EMG are clearly and definitely abnormal but a precise diagnosis still cannot be determined. For example, consider the patient whose clinical history and examination suggest an ulnar neuropathy at the elbow. The EDX study often demonstrates abnormalities of the ulnar nerve in the absence of any localizing findings, such as conduction block or slowing across the elbow. Although the referring surgeon usually wants to know whether the ulnar neuropathy is at the elbow, often the only accurate impression the electromyographer can give is one of a non-localizable ulnar neuropathy that is at, or proximal to, the most proximal abnormal ulnar-innervated muscle found on EMG.

6. *Always think about the clinical–electrophysiologic correlation.* This rule combines all of the earlier rules. One usually can be certain of a diagnosis when the clinical findings, NCSs, and EMG abnormalities all correlate well. Consider again the example of the patient with weakness of the hand and tingling and numbness of the fourth and fifth fingers. If NCSs demonstrate abnormal ulnar motor and sensory potentials associated with slowing across the elbow, and the needle EMG shows denervation and reduced numbers of motor unit potentials in all ulnar-innervated muscles and a normal EMG of all non-ulnar-innervated muscles, there is a high degree of certainty that the patient truly has an ulnar neuropathy at the elbow, and the electrophysiologic abnormalities are indeed relevant.

If all three results fit together, the diagnosis is secure. However, if the NCSs and EMG findings do not fit together and, more importantly, they do not correlate with the clinical findings, the significance of any electrical abnormalities should be seriously questioned. Consider a patient with pain in the arm who has an otherwise normal history and examination. If the NCSs are normal except for a low ulnar sensory potential and the EMG demonstrates only mild reinnervation of the biceps, one should be reluctant to interpret the study as showing a combination of an ulnar neuropathy and a C5 radiculopathy. These mild abnormalities, which are not substantiated by other electrophysiologic findings and do not have clear clinical correlates, may have little to do with the patient's pain. In such a case, the patient should be reexamined. If no clinical correlate is found, the studies should be rechecked. If the abnormalities persist, they may be noted as part of the impression but interpreted as being of uncertain clinical significance.

When performed properly, NCSs and EMG can be very helpful to the referring physician. However, the limitations of EDX studies must be appreciated, technical factors well controlled, and a good differential diagnosis established before each study. Otherwise, the study may actually do a disservice to the patient and to the referring physician by leading them astray by way of minor, irrelevant, or technically induced "abnormalities." If the cardinal rules of NCSs and EMG are kept in mind, EDX studies are far more likely to be of help to the referring clinician and the patient with a neuromuscular disorder.

2 Anatomy and Neurophysiology

The electromyographer need not have detailed knowledge of all the electrical and chemical events that occur at a molecular level in order to perform an electrodiagnostic (EDX) study. However, every electromyographer must have a basic understanding of anatomy and physiology in order to plan, perform, and properly interpret an EDX study. In the everyday evaluation of patients with neuromuscular disorders, nerve conduction studies (NCSs) and electromyography (EMG) serve primarily as extensions of the clinical examination. Knowledge of gross nerve and muscle anatomy is required to be able to perform these studies. For NCSs, one needs to know the location of the various peripheral nerves and muscles so that the stimulating and recording electrodes are properly positioned. For the needle EMG study, knowledge of gross muscle anatomy is crucial for inserting the needle electrode correctly into the muscle being sampled. On the microscopic level, knowledge of nerve and muscle anatomy and basic neurophysiology are required to appreciate and interpret the EDX findings both in normal individuals and in patients with various neuromuscular disorders. Lastly, knowledge of anatomy and physiology are crucial to understanding the technical aspects of the EDX study and appreciating its limitations and potential pitfalls.

ANATOMY

The strict definition of the peripheral nervous system includes that part of the nervous system in which the Schwann cell is the major supporting cell, as opposed to the central nervous system in which the glial cells are the major support cells. The peripheral nervous system includes the nerve roots, peripheral nerves, primary sensory neurons, neuromuscular junctions (NMJs), and muscles (Figure 2–1). Although not technically part of the peripheral nervous system, the primary motor neurons (i.e., anterior horn cells), which are located in the spinal cord, are often included as part of the peripheral nervous system as well. In addition, cranial nerves III through XII are also considered to be part of the peripheral nervous system, being essentially the same as peripheral nerves, except that their primary motor neurons are located in the brainstem rather than the spinal cord.

The primary motor neurons, the *anterior horn cells*, are located in the ventral gray matter of the spinal cord. The axons of these cells ultimately become the motor fibers in peripheral nerves. Their projections first run through the white matter of the anterior spinal cord before exiting ventrally as the *motor roots*. In contrast to the anterior horn

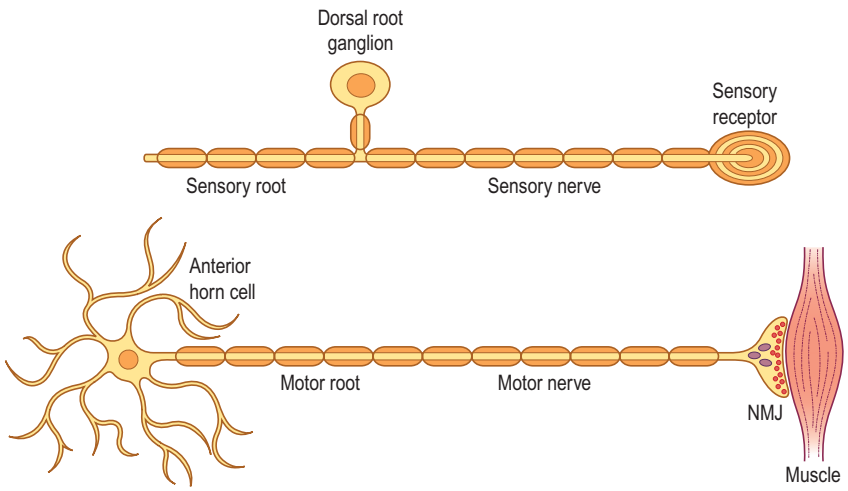

FIGURE 2–1 Elements of the peripheral nervous system. The peripheral nervous system includes the peripheral motor and sensory nerves; their primary neurons, the anterior horn cells, and dorsal root ganglia; the neuromuscular junctions (NMJs); and muscle. The dorsal root ganglion, a bipolar cell located distal to the sensory root, is anatomically different from the anterior horn cell. Consequently, lesions of the nerve roots result in abnormalities of motor nerve conduction studies but do not affect the sensory conduction studies, as the dorsal root ganglion and its peripheral nerve remain intact.

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cell, the primary sensory neuron, also known as the *dorsal root ganglion* (DRG), is not found within the substance of the spinal cord itself but rather lies outside the spinal cord, near the intervertebral foramen. The dorsal root ganglia are bipolar cells with two separate axonal projections. Their central projections form the *sensory nerve roots*. The sensory roots enter the spinal cord on the dorsal side to either ascend in the posterior columns or synapse with sensory neurons in the dorsal horn. The peripheral projections of the DRGs ultimately become the sensory fibers in peripheral nerves. Because the DRGs lie outside the spinal cord, this results in a different pattern of sensory nerve conduction abnormalities, depending on whether the lesion is in the peripheral nerve or proximal to the DRG, at the root level (see Chapter 3).

Motor and sensory roots at each spinal level unite distal to the DRG to become a mixed *spinal nerve*. There are 31 pairs of spinal nerves (8 cervical, 12 thoracic, 5 lumbar, 5 sacral, 1 coccygeal; Figure 2–2). Each spinal nerve divides into a *dorsal* and *ventral ramus* (Figure 2–3). Unlike the dorsal and ventral nerve roots, the dorsal and ventral rami both contain motor and sensory fibers. The dorsal ramus runs posteriorly to supply sensory innervation to the skin over the spine and muscular innervation to the paraspinal muscles at that segment. The ventral ramus differs, depending on the segment within the body. In the thoracic region, each ventral ramus continues as an *intercostal nerve*. In the lower cervical to upper thoracic (C5–T1) region, the ventral rami unite to form the *brachial plexus* (Figure 2–4). In the mid-lumbar to sacral regions, the ventral rami intermix to form the *lumbosacral plexus* (Figure 2–5).

Within each plexus, motor and sensory fibers from different nerve roots intermix to ultimately form individual *peripheral nerves*. Each peripheral nerve generally supplies muscular innervation to several muscles and cutaneous sensation to a specific area of skin, as well as sensory innervation to underlying deep structures. Because of this arrangement, motor fibers from the same nerve root supply muscles innervated by different peripheral nerves, and sensory fibers from the same nerve root supply cutaneous sensation in the distribution of different peripheral nerves. For instance, the C5 motor root supplies the biceps (musculocutaneous nerve), deltoid (axillary nerve), and brachioradialis (radial nerve), among other muscles (Figure 2–6). Similarly, C5 sensory fibers innervate the lateral arm (axillary nerve) and forearm (lateral antebrachial cutaneous sensory nerve), in addition to other nerves.

All muscles supplied by one spinal segment (i.e., one nerve root) are known as a *myotome*, whereas all cutaneous areas supplied by a single spinal segment are known as a *dermatome* (Figure 2–7). For both myotomes and dermatomes, there is considerable overlap between adjacent segments. Because of the high degree of overlap between spinal segments, a single root lesion seldom results in significant sensory loss and never in anesthesia. Likewise, on the motor side, even a severe single nerve root lesion usually results in only mild or moderate weakness and never in paralysis. For instance, a severe lesion of the C6 motor root causes weakness of the biceps; however, paralysis would not occur because C5 motor fibers also innervate the biceps. In contrast, a severe peripheral nerve lesion usually results in marked sensory and motor deficits because contributions from several myotomes and dermatomes are affected.

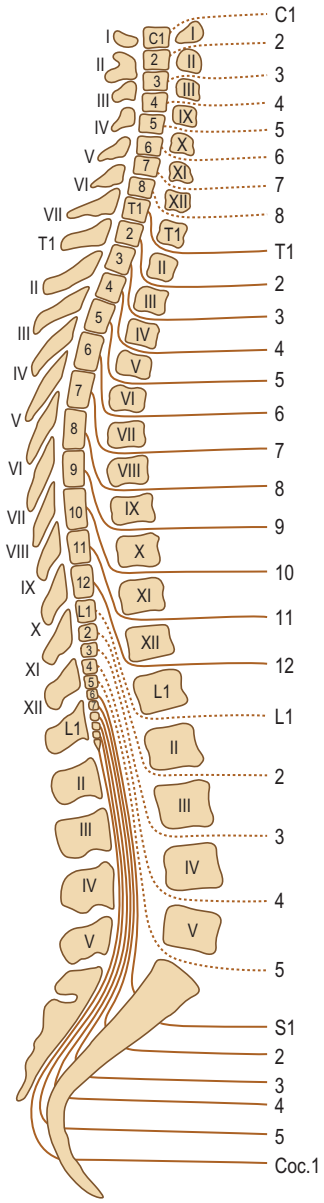


FIGURE 2–2 Spinal cord and nerve roots. The spinal cord is divided into 31 segments (8 cervical, 12 thoracic, 5 lumbar, 5 sacral, and 1 coccygeal). At each segment, motor and sensory fibers leave the spinal cord as nerve roots before exiting the bony spinal column. In the adult, the spinal cord usually ends at the level of the L1 vertebra. Consequently, below this level, only the lumbosacral nerve roots, known as the cauda equina, are present within the spinal column. (From Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia, with permission.)

At the microscopic level, nerve fibers are protected by three different layers of connective tissue: the epineurium,

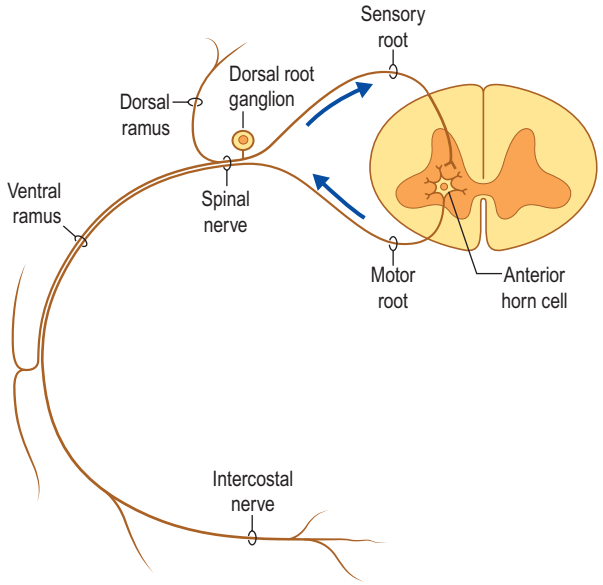


FIGURE 2–3 Nerve roots and rami. The motor root, originating from anterior horn cells, leaves the cord ventrally, whereas the sensory root enters the cord on the dorsal side. Immediately distal to the dorsal root ganglion, the motor and sensory roots come together to form the spinal nerve. Each spinal nerve quickly divides into a dorsal and ventral ramus. Each ramus contains both motor and sensory fibers. The dorsal rami supply sensation to the skin over the spine and muscular innervation to the paraspinal muscles. The ventral rami continue as intercostal nerves in the thoracic region. In the lower cervical region, the ventral rami fuse to form the brachial plexus. In the mid-lumbar through sacral segments, the ventral rami intermix to form the lumbosacral plexus.

perineurium, and endoneurium (Figure 2–8). The thick *epineurium* surrounds the entire nerve and is in continuity with the dura mater at the spinal cord level. Within the epineurium, axons are grouped into fascicles, surrounded by *perineurium*. A final layer of connective tissue, the *endoneurium*, is present between individual axons. Effectively, a *blood–nerve barrier* is formed by the combination of vascular endothelium supplying the nerve and the connective tissue of the perineurium. Together, the three layers of connective tissue give peripheral nerve considerable tensile strength, usually in the range of 20 to 30 kg. However, the weakest point of a nerve occurs where the nerve roots meet the spinal cord, where the nerve can sustain only 2 to 3 kg of force. For this reason, nerve root avulsion may occur after a significant trauma and especially after a stretch injury.

PHYSIOLOGY

The primary role of nerve is to transmit information reliably from the anterior horn cells to muscles for the motor system and from the sensory receptors to the spinal cord for the sensory system. Although functionally nerves may seem similar to electrical wires, there are vast differences between the two. At the molecular level, a complex set of chemical and electrical events allows nerve to propagate an electrical signal.

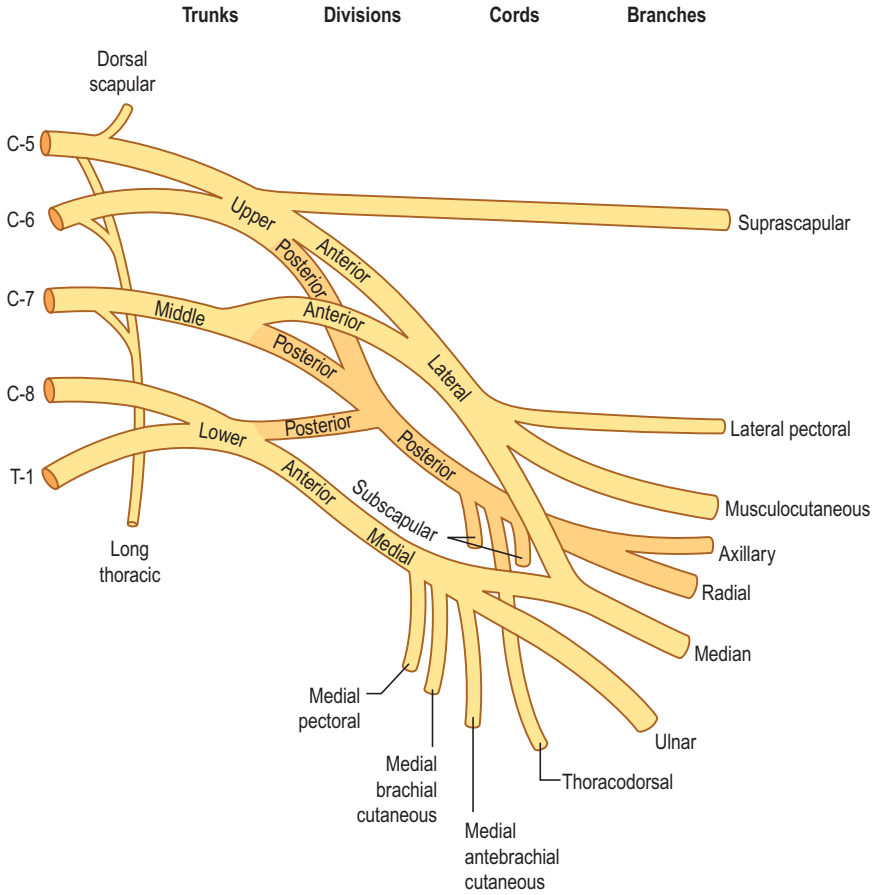


FIGURE 2–4 Brachial plexus. The ventral rami of the C5–T1 nerve roots intermix to form the brachial plexus between the neck and shoulder. From the brachial plexus, the major upper extremity peripheral nerves are derived.
(From Hollinshead, W.H., 1969. Anatomy for surgeons, volume 2: the back and limbs. Harper & Row, New York, with permission.)

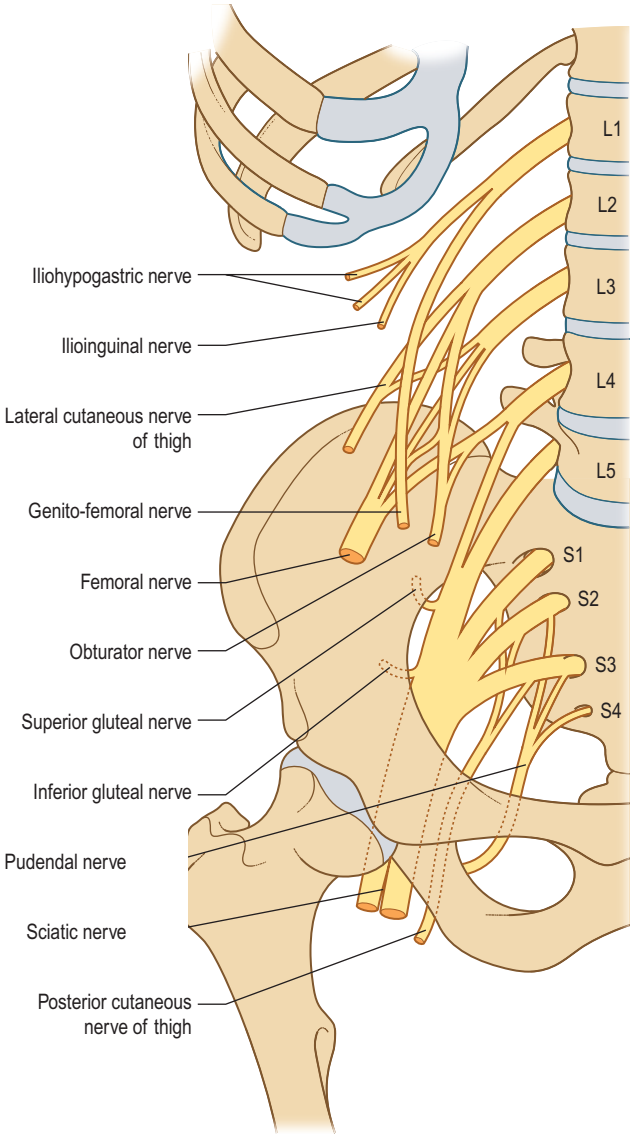


FIGURE 2–5 Lumbosacral plexus. The L1–S4 nerve roots intermix in the pelvis to form the lumbosacral plexus. From this plexus, the individual major peripheral nerves of the lower extremity are derived. (From Mayo Clinic and Mayo Foundation. 1956. Clinical examinations in neurology. WB Saunders, Philadelphia, with permission.)

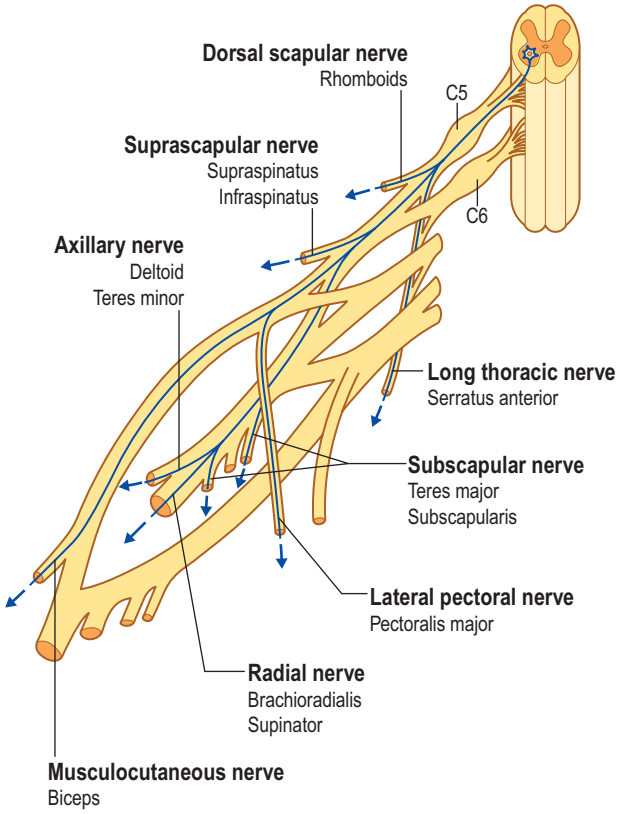


FIGURE 2–6 Myotomal and peripheral nerve innervation. Motor fibers from one nerve root, a myotome, supply muscles innervated by different peripheral nerves. For example, the C5 motor root supplies the biceps (musculocutaneous nerve), deltoid (axillary nerve), and brachioradialis (radial nerve), among other muscles. (Adapted from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia, with permission.)

The axonal membrane of every nerve is electrically active. This property results from a combination of a specialized membrane and the sodium/potassium (Na^+/K^+) pump (Figure 2–9). The specialized axonal membrane is semipermeable to electrically charged molecules (anions and cations). The membrane is always impermeable to large negatively charged anions, and it is relatively impermeable to sodium in the resting state. This semipermeable membrane, in conjunction with an active Na^+/K^+ pump that moves sodium outside in exchange for potassium, leads to concentration gradients across the membrane. The concentration of sodium is larger outside the membrane, whereas the concentration of potassium and larger anions is greater inside. The combination of these electrical and chemical gradients results in forces that create a resting equilibrium potential. At the nerve cell soma, this resting membrane potential is approximately 70 mV negative inside compared with the outside; distally in the axon it is approximately 90 mV negative.

The membrane of the axon is lined with *voltage-gated sodium channels* (Figure 2–10). These structures are essentially molecular pores with gates that open and close. For many ion channels, gates open in response to molecules that bind to the channel. In the case of the voltage-gated sodium channel, the gate is controlled by a voltage sensor that responds to the level of the membrane potential. If current is injected into the axon, depolarization occurs (i.e., the axon becomes more positive internally). Voltage sensors within the sodium channel respond to the depolarization by opening the gate to the channel and allowing sodium to rush into the axon, driven both by concentration and by electrical gradients. Every time a depolarization of 10 to 30 mV occurs above the resting membrane potential (i.e., *threshold*), it creates an *action potential* and a cycle of positive feedback; further depolarization occurs and more sodium channels open (Figure 2–11). Action potentials are always all-or-none responses, which then propagate away from the initial site of depolarization. The axon does not remain depolarized for long, however, because the opening

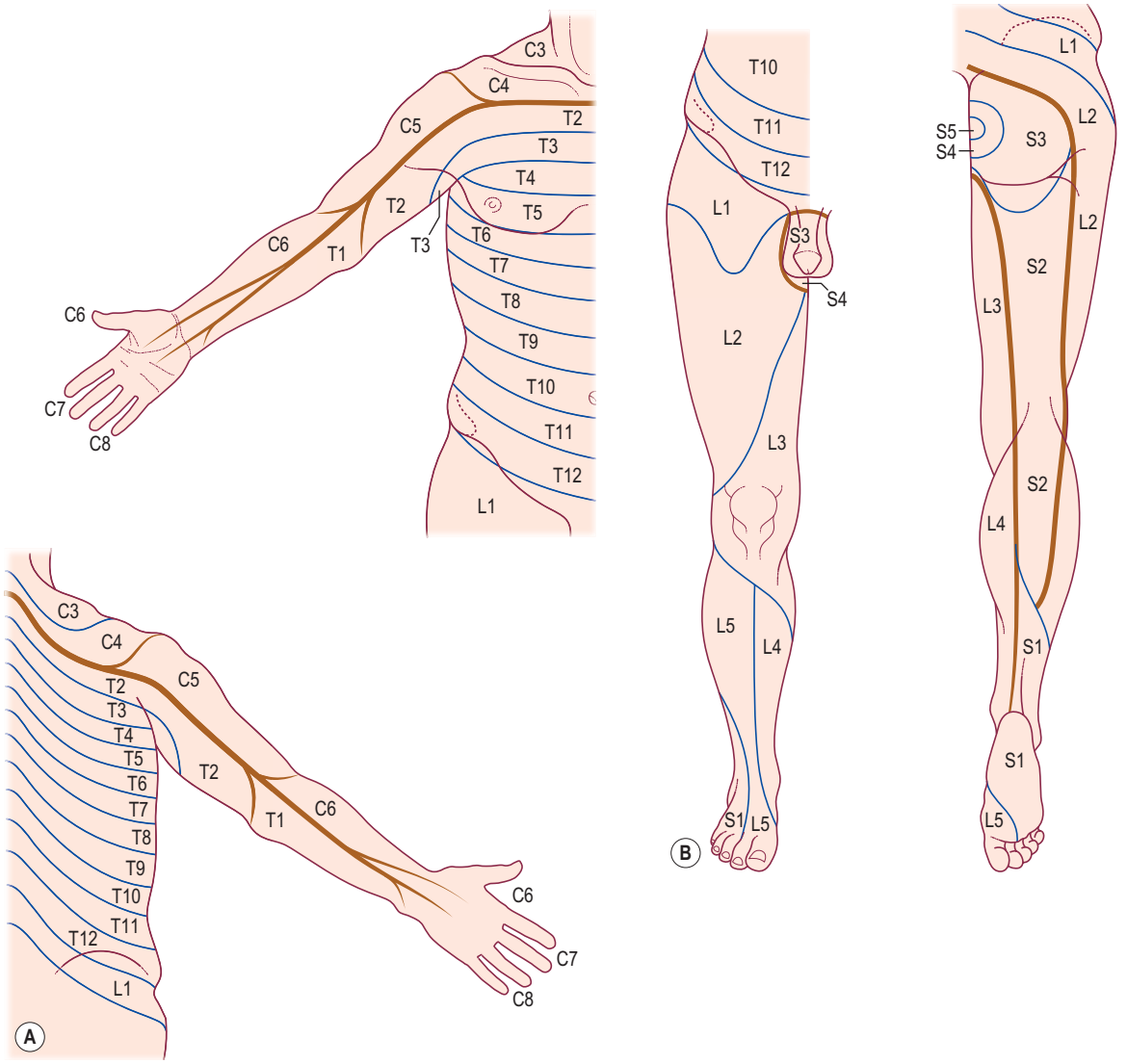
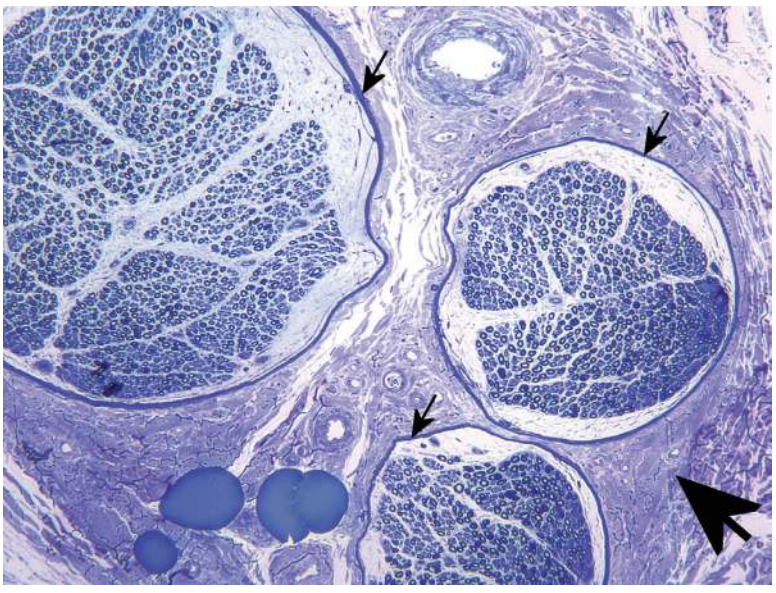


FIGURE 2–7 Dermatomes. The cutaneous area supplied from one spinal segment (i.e., one sensory nerve root) is known as a dermatome. Despite the apparent simplicity of dermatomal charts, in actuality, there is a wide overlap of adjacent dermatomes. Consequently, a nerve root lesion, even if severe, never results in anesthesia but rather altered or decreased sensation.
(From O'Brien M.D., 1986. Aids to the examination of the peripheral nervous system. Baillière Tindall, London.)

FIGURE 2–8 Internal peripheral nerve anatomy. Myelinated fibers are recognized as small dark rings (myelin) with a central clearing (axon) in this one micron thick, semi-thin section of plastic embedded nerve tissue. The endoneurium is present between axons. Axons are grouped into fascicles, surrounded by perineurium (small arrows). Surrounding the entire nerve is the last layer of connective tissue, the epineurium (large arrow).



of the sodium channels is time limited. Sodium channels have a second gate, known as the *inactivation gate*. Inactivation of the sodium channel occurs within 1 to 2 ms. During this time, the membrane is not excitable and cannot be opened (i.e., *refractory period*). The inactivation gate of the sodium channel has been modeled as a "hinged lid." From a practical point of view, the refractory period limits the frequency that nerves can conduct impulses. It also ensures that the action potential continues to propagate in the same direction (i.e., the area of nerve behind the depolarization is refractory when the area ahead is not, so that the impulse will continue forward and will not return backwards).

In addition to sodium channel inactivation, depolarization also results in the opening of potassium channels, which also then drives the membrane voltage more negative. These factors, along with the Na^+/K^+ pump, then reestablish the resting membrane potential.

The conduction velocity of the action potential depends on the diameter of the axon: the larger the axon, the less resistance and the faster the conduction velocity. For typical unmyelinated axons the conduction velocity of an action potential is very slow, typically in the range of 0.2 to 1.5 m/s. Conduction velocity can be greatly increased with the addition of myelin. *Myelin* insulation is present on all fast-conducting fibers and is derived from Schwann cells, the major supporting cells in the peripheral nervous system. Myelin is composed of concentric spirals of Schwann cell membrane (Figure 2–12). For every myelinated fiber, successive segments are myelinated by *single* Schwann cells. Each segment of the axon covered by myelin is termed the "internode." At small gaps between successive internodes, the axon is exposed; these areas are known as the nodes of Ranvier. They are very small, in the range of 1–2 µm in length.

Most of the nerve is effectively insulated with myelin, and depolarization occurs by way of *saltatory conduction*, whereby depolarization occurs only at the nodes of Ranvier. After one node depolarizes, the current jumps to the next adjacent node, and the cycle continues (Figure 2–13). The physiology of normal saltatory conduction was first shown in a series of elegant experiments on normal animal myelinated nerve fibers, recording along the motor root in very small increments, and measuring the current as a function of distance and latency (Figure 2–14). From an electrical point of view, myelin insulates the internode and reduces the capacitance. A lower capacitance results in less current lost as the action potential jumps from node to node. Although more current is needed for saltatory conduction than for continuous conduction, much less nerve membrane has to be depolarized. For unmyelinated fibers, depolarization has to occur over the entire length of the nerve (i.e., continuous conduction), which takes more time than in myelinated fibers. In myelinated fibers, the axonal membrane only needs to depolarize at the nodes of Ranvier; the internodes do not depolarize, but rather the action potential jumps over them. As the internode is approximately 1 mm in length and the node of Ranvier is only 1–2 µm in length, markedly less axonal membrane needs to depolarize in order to propagate an action potential. The lower the total depolarization time, the faster the conduction velocity. In myelinated axons, the density of sodium channels is highest in nodal areas, the areas undergoing depolarization. Myelinated human peripheral nerve fibers typically conduct in the range of 35 to 75 m/s, far faster than could ever be achieved by increasing the diameter of unmyelinated fibers.

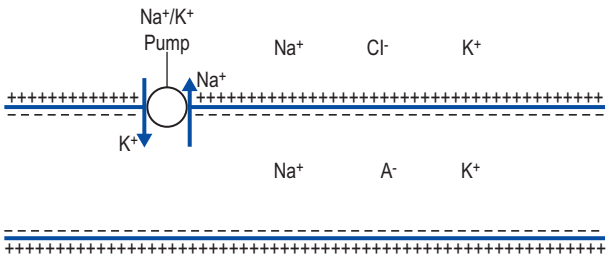


FIGURE 2–9 Resting membrane potential. At rest, the axonal membrane is negatively polarized, inside compared to outside. This resting potential results from the combination of a membrane that is semipermeable to charged particles and an active Na^+/K^+ pump. At rest, the concentration of Na^+ and Cl^- is higher in the extracellular space, with the concentration of K^+ and large anions (A^-) greater inside the axon.

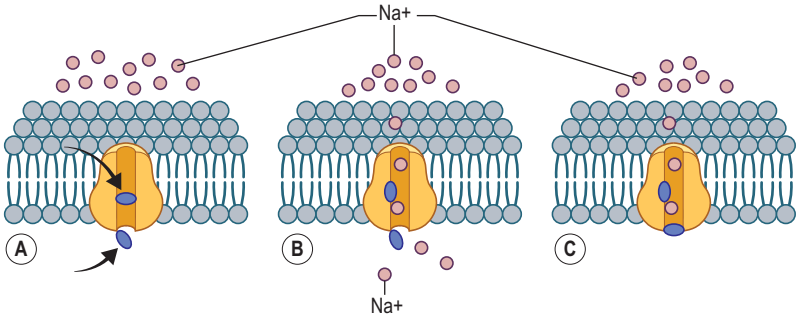


FIGURE 2–10 Voltage-gated sodium channel. The axonal membrane is lined with voltage-gated sodium channels. These channels are molecular pores with gates that open and close; when open, gates are selective for sodium **A**. There are two gates: an activation gate (large arrow) and an inactivation gate (small arrow). If current is injected into the axon, depolarization occurs, and the voltage-gated activation gate opens, allowing the influx of sodium into the axon **B**, driven both by concentration and electrical gradients. However, the opening of the sodium channels is time limited. Inactivation of the sodium channel occurs within 1 to 2 ms **C**. The inactivation gate of the sodium channel has been modeled as a "hinged lid," which closes the end of the channel within 1 to 2 ms of depolarization, preventing further depolarization.

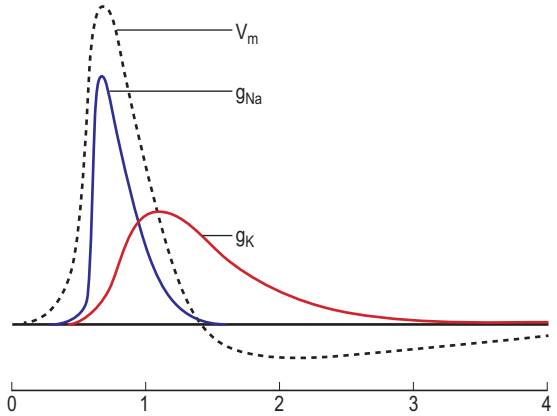


FIGURE 2–11 Action potential. When the resting membrane voltage (V_m) is depolarized to threshold, voltage-gated sodium channels are opened, increasing Na^+ conductance (g_{Na}), resulting in an influx of sodium and further depolarization. The action potential, however, is short lived, due to the inactivation of the sodium channels within 1 to 2 ms and an increase in K^+ conductance (g_k). These changes, along with the Na^+/K^+ pump, allow the axon to reestablish the resting membrane potential.

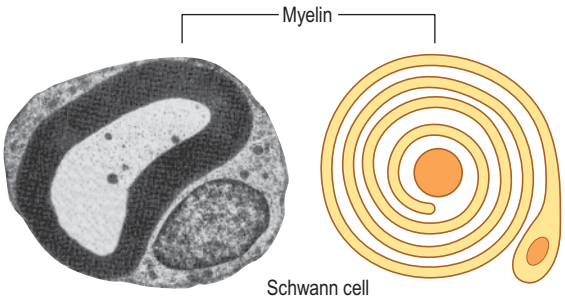


FIGURE 2–12 Schwann cell and the myelin sheath. **Left:** Electron micrograph of a single Schwann cell and myelinated axon. **Right:** Schematic of the same. Myelin insulation is derived from Schwann cells and is present on all fast-conducting fibers, both motor and sensory. Myelin is composed of concentric spirals of Schwann cell membrane, with each Schwann cell supporting a single myelinated axon.

Not all human peripheral nerve fibers are myelinated. Unmyelinated fibers, which conduct very slowly (typically 0.2–1.5 m/s), primarily mediate pain, temperature, and autonomic functions. Schwann cells also support these unmyelinated fibers; however, one Schwann cell typically surrounds several unmyelinated fibers, but without the formation of concentric spirals of myelin.

When an individual axon is depolarized, an action potential propagates down the nerve. Distally, the axon divides into many twigs, each of which goes to an individual muscle fiber. An axon, along with its anterior horn cell and all muscle fibers with which it is connected, is known as a motor unit (Figure 2–15). Depolarization of all the muscle fibers in a motor unit creates an electrical potential known as the *motor unit action potential* (MUAP). Analysis of MUAPs is an important part of every needle EMG examination. When an action potential is generated, all muscle fibers in the motor unit are normally activated, again an all-or-none response. However, before a muscle fiber can

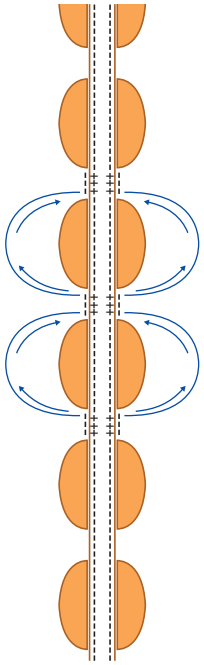


FIGURE 2–13 Saltatory conduction. Myelinated fibers propagate action potentials by way of saltatory conduction. Depolarization only occurs at the small uninsulated areas of membrane between internodes, with the action potential jumping from node to node. Thus, less membrane needs to be depolarized, less time is required, and, consequently, conduction velocity dramatically increases. Most human peripheral myelinated fibers conduct in the range of 35 to 75 m/s.

be activated, the nerve action potential must be carried across the NMJ. The NMJ is essentially an electrical–chemical–electrical link from nerve to muscle. It is formed from two specialized membranes, one on nerve and one on muscle, separated by a thin synaptic cleft (Figure 2–16). As a nerve action potential travels to the presynaptic side of the NMJ, voltage-gated calcium (Ca^+) channels are activated, allowing an influx of Ca^+. Increasing Ca^+ concentration results in the release of acetylcholine, the neurotransmitter at the NMJ. Acetylcholine diffuses across the synaptic cleft to bind to specialized acetylcholine receptors on the muscle membrane. These receptors, when activated, allow an influx of sodium and depolarization of the muscle fiber. As is the case with nerve, once threshold is reached, a muscle fiber action potential is created that spreads throughout the muscle fiber. Following the muscle fiber action potential, a complex set of molecular interactions occurs within the muscle fiber, resulting in increasing overlap of the major muscle fiber filaments: actin and myosin, with the final result of muscle shortening, contraction, and generation of force (Figure 2–17).

CLASSIFICATION

Multiple peripheral nerve classification schemes exist (Table 2–1). Peripheral nerves can be classified based on the following attributes: (1) myelinated or unmyelinated,

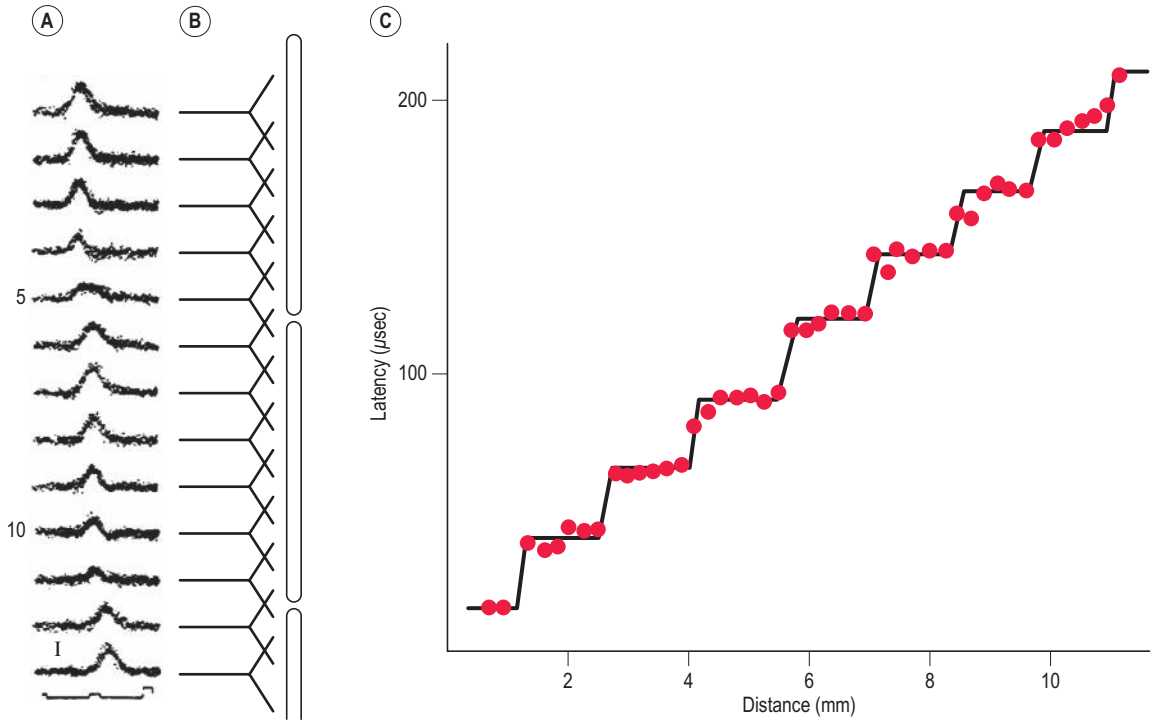


FIGURE 2–14 Demonstration of saltatory conduction. Recording of a normal single fiber from an intact ventral root in a rat: **A:** successive records of external longitudinal current recorded from a single fiber as electrodes were moved along a ventral root in steps of 0–2 mm. **B:** Lines from each record indicate positions of electrodes with respect to underlying nodes and internodes. **C:** Latency to peak of external longitudinal current as a function of distance. Note how the distance/latency graph is a "staircase" configuration. As current proceeds down a normal myelinated axon, the latency (i.e., the conduction time) abruptly increases approximately every 1.0–1.5 mm. This is the depolarization time at the nodes of Ranvier. Conversely, note the flat part of the staircase graph; here the latency stays almost exactly the same despite a change in distance. This is the saltatory conduction jumping from node to node.
(From Rasminsky, M., Sears, T.A., 1972. Internodal conduction in undissected demyelinated nerve fibres. J Physiol 227, 323–350, with permission.)

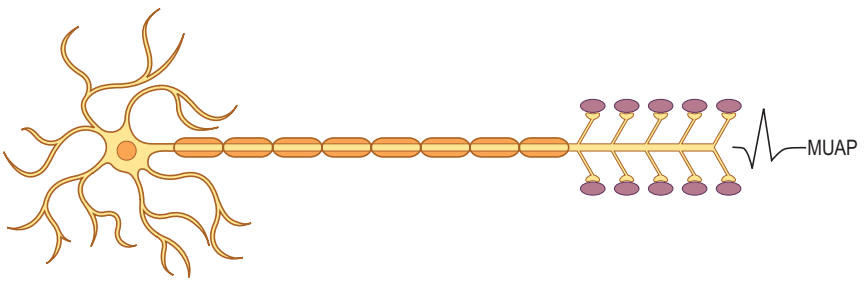


FIGURE 2–15 Motor unit. The motor unit is defined as one axon, its anterior horn cell, and all connected muscle fibers and neuromuscular junctions. A nerve fiber action potential normally always results in depolarization of all the muscle fibers of the motor unit creating an electrical potential known as the motor unit action potential (MUAP). Analysis of motor unit action potentials is a large part of the needle electromyographic examination.

(2) somatic or autonomic, (3) motor or sensory, and (4) diameter.

There are several important points to glean from Table 2–1, some of which are directly relevant to clinical electrodiagnostic testing. First is the direct relationship between fiber diameter and conduction velocity: the larger the diameter, the faster the conduction velocity. The large myelinated fibers are the fibers that are measured in clinical NCSs. Indeed, all routine motor and sensory conduction velocity and latency measurements are from the largest and fastest fibers of the particular peripheral nerve that is being studied. Large-diameter fibers have the most myelin and the least electrical resistance, both of which result in faster conduction velocities. The small myelinated (Aδ, B) and unmyelinated (C) fibers carry autonomic information (afferent and efferent) and somatic pain and temperature sensations. *These fibers are not recorded with standard nerve conduction techniques*. Thus, neuropathies that preferentially affect only small fibers may not reveal any abnormalities on NCSs.

Second, routine sensory conduction studies typically record cutaneous nerves innervating skin. The largest and fastest cutaneous fibers are the Aβ fibers from hair and skin follicles. Note that the size and conduction velocities of

these fibers are similar to those of the muscle efferent fibers from the anterior horn cells that are recorded during routine motor studies. These myelinated fibers have velocities in the range of 35 to 75 m/s.

Third, the largest and fastest fibers in the peripheral nervous system are not recorded during either routine motor or sensory NCSs. These are the muscle afferents, the Aα fibers (also known as Ia fibers), which originate from muscle spindles and mediate the afferent arc of the muscle stretch reflex. *These fibers are recorded only during mixed nerve studies, in which the entire mixed nerve is stimulated and recorded*. Therefore, mixed nerve conduction velocities usually are faster than either routine motor or cutaneous sensory conduction velocities because they contain these Ia fibers. Because the Ia fibers have the largest diameter and accordingly the greatest amount of myelin, they often are affected early by demyelinating lesions such as those found in entrapment neuropathies. For example, in the EDX evaluation of carpal tunnel syndrome, the mixed nerve study from the palm to the wrist often is more sensitive in detecting abnormalities than either the routine motor or sensory conduction study.

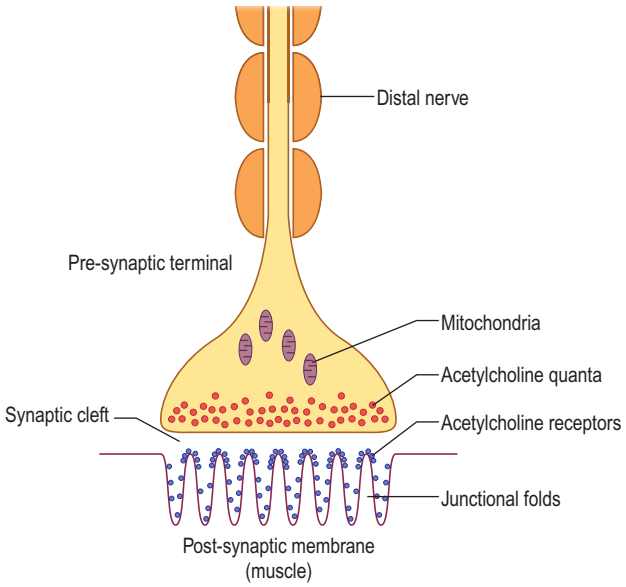


FIGURE 2–16 Neuromuscular junction. The neuromuscular junction is a specialized junction between the terminal axon and muscle fiber. When the nerve action potential invades the presynaptic terminal, acetylcholine is released and diffuses across the synaptic cleft to bind to acetylcholine receptors on the muscle membrane. This binding results in a muscle endplate potential, which, once threshold is reached, causes the generation of a muscle fiber action potential.

RECORDING

All potentials obtained during NCSs and needle EMG result from the extracellular recording of intracellular events, from either nerve or muscle. NCSs usually are performed by recording with surface electrodes over the skin, and EMG potentials by recording with a needle electrode placed within the muscle. In both procedures, intracellular electrical potentials are transmitted through tissue to the recording electrodes. The process of an intracellular electrical potential being transmitted through extracellular fluid and tissue is known as *volume conduction*. Although the theory of volume conduction is complex and beyond the scope of this text, volume-conducted potentials can be modeled as either near-field or far-field potentials. *Near-field potentials* can be recorded only close to their source, and the characteristics of the potential depend on the distance between the recording electrodes and the electrical source (i.e., the *action potential*). With near-field potentials, a response generally is not seen until the source is close to the recording electrodes. The closer the recording electrodes are to the current source, the higher the amplitude. Compound muscle action potentials, sensory nerve action potentials, and MUAPs recorded during routine motor conduction, sensory conduction, and needle EMG studies, respectively, are essentially all volume-conducted near-field potentials.

Volume-conducted, near-field potentials produce a characteristic triphasic waveform as an advancing action potential approaches and then passes beneath and away from a recording electrode (Figure 2–18, top). In practice, most sensory and mixed nerve studies display this triphasic waveform morphology, as do fibrillation potentials and most MUAPs. The electrical correlate of an action potential traveling toward, under, and then away from the recording electrode is an initial positive phase, followed by a negative

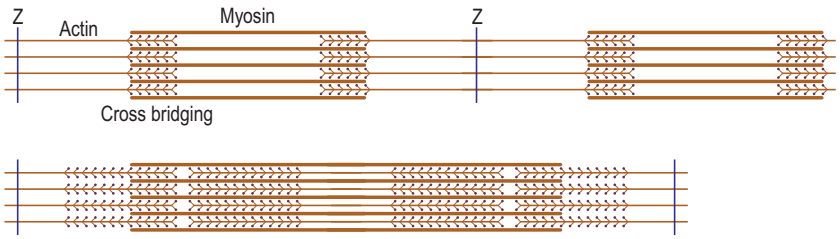


FIGURE 2–17 Actin and myosin. Following a muscle fiber action potential, muscle contraction results from a complex set of molecular interactions, ultimately ending with the overlapping of two interlacing muscle proteins, actin and myosin. This overlap, which occurs along with the formation of energy-dependent cross-bridges, effectively results in shortening of the muscle and the generation of force. Actin filaments are connected by Z lines. The sarcomere, a unit of muscle, is defined from one Z line to the next. The overlapping pattern of actin and myosin filaments gives muscle its striated appearance.

Table 2–1. Peripheral Nerve Classification Schemes

Fiber Type(s)	Name	Subtype	Diameter (mm)	Conduction Velocity (m/s)	Alternative Classification	
Myelinated Somatic Afferent/Efferent						
Cutaneous afferent	A	β δ	6–12 1–5	35–75 5–30	α	
Muscle afferent	A	α β δ	12–21 6–12 1–5	80–120 35–75 5–30	I II III	Ia, Ib
Muscle efferent Anterior horn cells (α and γ motor neurons)	A		6–12	35–75		
Myelinated Autonomic Efferent						
Preganglionic efferent	B		3	3–15		
Unmyelinated Somatic/Autonomic Afferent/Efferent						
Postganglionic efferent	C		0.2–1.5	1–2		
Afferent to dorsal root ganglion (pain)	C		0.2–1.5	1–2	IV	
Sensory Receptor	**Fiber Type**					
Hair follicle	Aβ					
Skin follicle	Aβ					
Muscle spindle	Aa					
Joint receptor	Aβ					
Pain, temperature	Aδ, C					

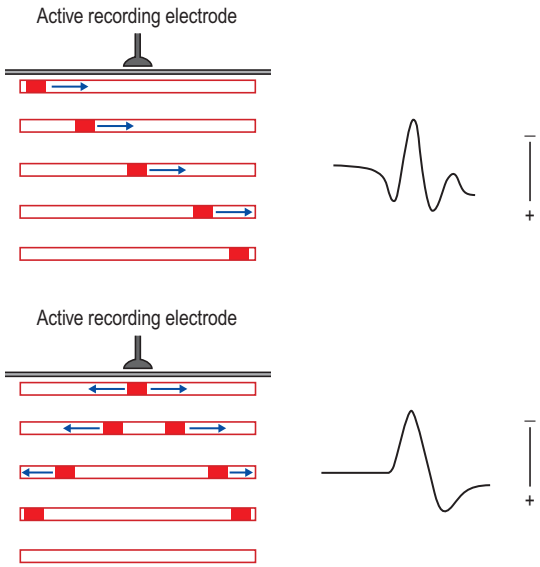


FIGURE 2–18 Volume conduction and waveform morphology. **Top:** An advancing action potential recorded by volume conduction will result in a triphasic potential that initially is positive, then is negative, and finally is positive again. **Bottom:** If the depolarization occurs directly beneath the recording electrode, the initial positive phase will be absent, and a biphasic, initially negative potential will be seen. Note that, by convention, negative is up and positive is down in all nerve conduction and electromyographic traces.

phase and then a trailing positive phase, respectively. The first positive peak represents the time that the action potential is beneath the active electrode; this is the point at which the onset latency should be measured for nerve action potentials. The initial positive peak may be very small or absent with some sensory responses. In that case, the initial negative deflection best marks the true onset of the potential.

If a volume-conducted, near-field action potential begins directly under the recording electrode, the initial deflection will be negative (Figure 2–18, bottom). During routine motor NCSs, this is the expected compound muscle action potential morphology if the active electrode is correctly placed over the motor point (i.e., *endplate*) of the muscle. There is no advancing action potential, as muscle fiber depolarization begins at the endplate; hence, the waveform has no initial positive deflection. This results in a characteristic biphasic potential with an initial negative deflection (Figure 2–19, top). If the electrode is inadvertently placed off the motor point, a triphasic potential with an initial positive deflection will be seen (Figure 2–19, middle). If the depolarization occurs at a distance but never passes under the recording electrode, characteristically only a positive deflection will occur (Figure 2–19, bottom). For example, this pattern is seen when stimulating the median nerve and recording a hypothenar muscle, as might be done during routine motor studies looking for an anomalous

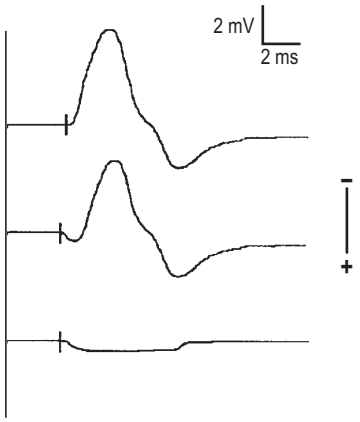


FIGURE 2–19 Volume conduction and motor potentials. With the active recording electrode (G1) over the motor point, depolarization first occurs at that site, with the depolarization subsequently spreading away. The corresponding waveform has an initial negative deflection without any initial positivity (top trace). If the active recording electrode is off the motor point, depolarization begins distally and then travels under and past the active electrode, resulting in an initial positive deflection (middle trace). If the depolarization occurs at a distance and never travels under the recording electrode, only a small positive potential will be seen (bottom trace). Note that, by convention, negative is up and positive is down in all nerve conduction and electromyographic traces.

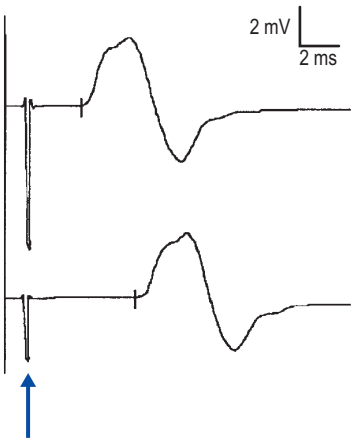


FIGURE 2–20 Near-field and far-field potentials. Median motor study, recording the abductor pollicis brevis muscle, stimulating at the wrist (top trace) and antecubital fossa (bottom trace). At each site, a compound muscle action potential is present, representing a near-field recording of the underlying muscle fiber action potentials. The compound muscle action potential latencies occur at different times, reflecting their different arrival times at the recording electrode. At the start of each trace is the stimulus artifact. The stimulus artifact is an example of a far-field potential, being transmitted instantaneously and seen at the same time, despite the difference in distances between the two stimulation sites.

innervation. The muscle action potential of the median-innervated thenar muscles occurs at a distance but never travels under the recording electrodes located over the hypothenar muscles. The result is a small positive deflection, volume-conducted potential.

The other type of volume-conducted potential is the *far-field potential*. Far-field potentials are electrical potentials that are distributed widely and instantly. Two recording electrodes, one closer and the other farther from the source, essentially see the source at the same time. Although far-field potentials are more often of concern in evoked potential studies, they occasionally are important in NCSs. The stimulus artifact seen at the onset of all NCSs is a good example of a far-field potential (Figure 2–20). The shock artifact is instantly transmitted and is seen at the same time at distal and proximal recording sites. Those potentials whose latencies do not vary with distance from the stimulation site usually are all far-field potentials.

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Basic Nerve Conduction Studies 3

After the history is taken and a directed physical examination is performed, every study begins with the nerve conduction studies (NCSs). The needle electromyography (EMG) examination is performed after the NCSs are completed, because the findings on the NCSs are used in the planning and interpretation of the needle examination which follows.

Peripheral nerves usually can be easily stimulated and brought to action potential with a brief electrical pulse applied to the overlying skin. Techniques have been described for studying most peripheral nerves. In the upper extremity, the median, ulnar, and radial nerves are the most easily studied; in the lower extremity, the peroneal, tibial, and sural nerves are the most easily studied (see Chapters 10 and 11). Of course, the nerves selected for study depend on the patient's symptoms and signs and the differential diagnosis. Motor, sensory, or mixed nerve studies can be performed by stimulating the nerve and placing the recording electrodes over a distal muscle, a cutaneous sensory nerve, or the entire mixed nerve, respectively. The findings from motor, sensory, and mixed nerve studies often complement one another, and yield different types of information based on distinct patterns of abnormalities, depending on the underlying pathology.

MOTOR CONDUCTION STUDIES

Motor conduction studies are technically less demanding than sensory and mixed nerve studies; thus; they usually are performed first. Performing the motor studies first also has other major advantages. It is not uncommon for the sensory responses to be very low in amplitude or absent in many neuropathies. Performing the motor studies first allows one to know where the nerve runs, where it should be stimulated, and how much current is needed, and also gives some information about whether the nerve is normal or abnormal. On the other hand, if the sensory study is done before the motor study, one might spend a lot of unnecessary time stimulating and trying to record a sensory response which is not present. For example, imagine a patient with a moderately severe median neuropathy at the wrist who is sent for an EDX evaluation. If the median motor study is performed first, the correct stimulation site can be confirmed, the amount of current needed to stimulate the median nerve will be known, and one will also know that the median nerve is abnormal, before doing the median sensory study. Then, when performing the median sensory study, one is confident of where to stimulate the nerve and how much current is needed. In this case, if no sensory response is present, one can have a high degree of certainty that the response is truly absent, and move along to the next nerve to be studied. However, if the sensory conduction study is done first, and is absent, it will not be as obvious if the absent response is due to a technical problem, or is truly absent. One can waste a lot of time unnecessarily trying to figure this out. Do the motor conduction study first; your study will be more efficient, and the patient will tolerate the study much better.

Motor responses typically are in the range of several millivolts (mV), as opposed to sensory and mixed nerve responses, which are in the microvolt (μV) range. Thus, motor responses are less affected by electrical noise and other technical factors. For motor conduction studies, the gain usually is set at 2 to 5 mV per division. Recording electrodes are placed over the muscle of interest. In general, the *belly–tendon montage* is used. The active recording electrode (also known as G1) is placed on the center of the muscle belly (over the motor endplate), and the reference electrode (also known as G2) is placed distally, over the tendon to the muscle (Figure 3–1). The designations G1 and G2 remain in the EMG vernacular, referring to a time when electrodes were attached to grids (hence the G) of an oscilloscope. The stimulator then is placed over the nerve that supplies the muscle, with the cathode placed closest to the recording electrode. It is helpful to remember "black to black," indicating that the black electrode of the stimulator (the cathode) should be facing the black recording electrode (the active recording electrode). For motor studies, the duration of the electrical pulse usually is set to 200 ms. Most normal nerves require a current in the range of 20 to 50 mA to achieve supramaximal stimulation. As current is slowly increased from a baseline 0 mA, usually by 5 to 10 mA increments, more of the underlying nerve fibers are brought to action potential, and subsequently more muscle fiber action potentials are generated. The recorded potential, known as the *compound muscle action potential* (CMAP), represents the summation of all underlying individual muscle fiber action potentials. When the current is increased to the point that the CMAP no longer

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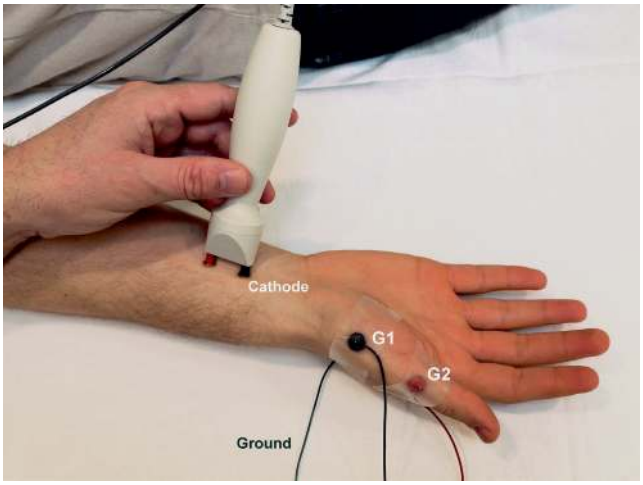

FIGURE 3–1 Motor conduction study setup. Median motor study, recording the abductor pollicis brevis muscle, stimulating the median nerve at the wrist. In motor studies, the "belly–tendon" method is used for recording. The active recording electrode (G1) is placed on the center of the muscle, with the reference electrode (G2) placed distally over the tendon.

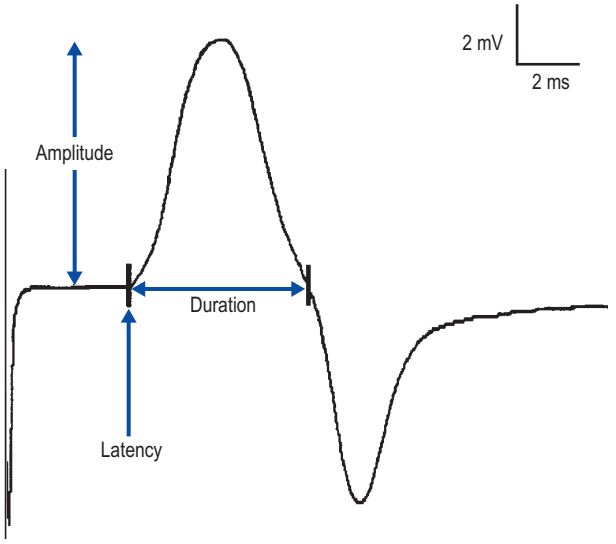

FIGURE 3–2 Compound muscle action potential (CMAP). The CMAP represents the summation of all the underlying muscle fiber action potentials. With recording electrodes properly placed, the CMAP is a biphasic potential with an initial negative deflection. Latency is the time from the stimulus to the initial negative deflection from baseline. Amplitude is most commonly measured from baseline to negative peak but also can be measured from peak to peak. Duration is measured from the initial deflection from baseline to the first baseline crossing (i.e., negative peak duration). In addition, negative CMAP area (i.e., the area above the baseline) is calculated by most modern computerized electromyographic machines. Latency reflects only the fastest conducting motor fibers. All fibers contribute to amplitude and area. Duration is primarily a measure of synchrony.

increases in size, one presumes that all nerve fibers have been excited and that supramaximal stimulation has been achieved. The current is then increased by another 20% to ensure supramaximal stimulation.

The CMAP is a biphasic potential with an initial negativity, or upward deflection from the baseline, if the recording electrodes have been properly placed with G1 over the motor endplate. For each stimulation site, the latency, amplitude, duration, and area of the CMAP are measured (Figure 3–2). A motor conduction velocity can be calculated after two sites, one distal and one proximal, have been stimulated.

Latency

The latency is the time from the stimulus to the initial CMAP deflection from baseline. Latency represents three separate processes: (1) the nerve conduction time from the stimulus site to the neuromuscular junction (NMJ), (2) the time delay across the NMJ, and (3) the depolarization time across the muscle. Latency measurements usually are made in milliseconds (ms), and reflect only the fastest conducting motor fibers.

Amplitude

CMAP amplitude is most commonly measured from baseline to the negative peak and less commonly from the first negative peak to the next positive peak. CMAP amplitude reflects the number of muscle fibers that depolarize. Although low CMAP amplitudes most often result from loss of axons (as in a typical axonal neuropathy), other causes of a low CMAP amplitude include conduction block from demyelination located between the stimulation site and the recorded muscle, as well as some NMJ disorders and myopathies.

Area

CMAP area also is conventionally measured as the area above the baseline to the negative peak. Although the area cannot be determined manually, the calculation is readily performed by most modern computerized EMG machines. Negative peak CMAP area is another measure reflecting the number of muscle fibers that depolarize. Differences in CMAP area between distal and proximal stimulation sites take on special significance in the determination of conduction block from a demyelinating lesion (see section on Conduction Block).

Duration

CMAP duration usually is measured from the initial deflection from baseline to the first baseline crossing (i.e., negative peak duration), but it also can be measured from the initial to the terminal deflection back to baseline. The former is preferred as a measure of CMAP duration because when CMAP duration is measured from the initial to terminal deflection back to baseline, the terminal CMAP returns to baseline very slowly and can be difficult to mark precisely. Duration is primarily a measure of synchrony (i.e., the extent to which each of the individual muscle fibers fire at the same time). Duration characteristically increases in conditions that result in slowing of some motor fibers but not others (e.g., in a demyelinating lesion).

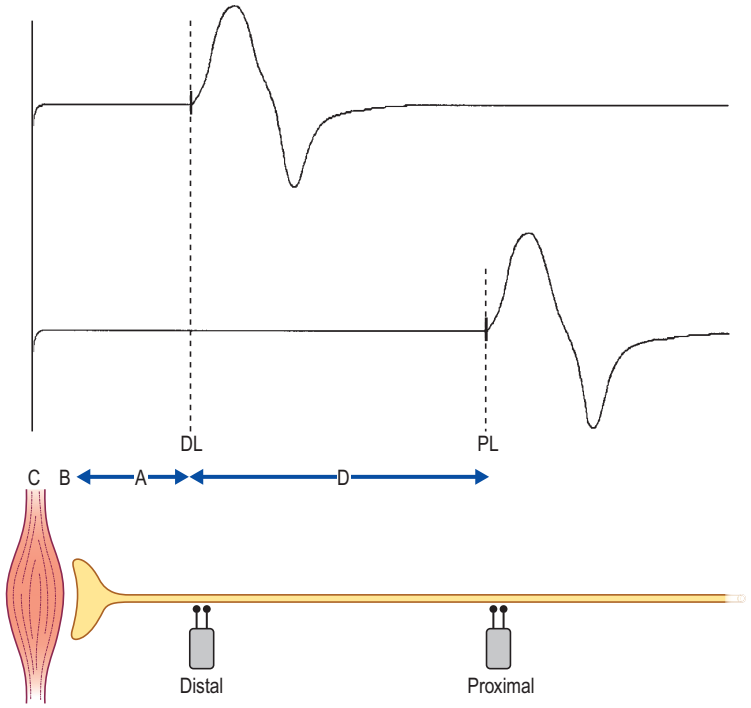

FIGURE 3–3 Motor conduction velocity (CV) calculation. **Top:** Median motor study, recording abductor pollicis brevis, stimulating wrist and elbow. DL, distal motor latency; PL, proximal motor latency. The only difference between distal and proximal stimulations is the latency, with PL being longer than DL. **Bottom:** DL represents three separate times: the nerve conduction time from the distal stimulation site to the neuromuscular junction (NMJ) (A), the NMJ transmission time (B), and the muscle depolarization time (C). Accordingly, DL cannot be used alone to calculate a motor conduction velocity. Two stimulations are necessary. PL includes the nerve conduction time from the distal stimulation site to the neuromuscular junction (A), the NMJ transmission time (B), and the muscle depolarization time (C), as well as the nerve conduction time between the proximal and distal stimulation sites (D). If DL (A+B+C) is subtracted from PL (A+B+C+D), only the nerve conduction time between the distal and proximal stimulation sites (D) remains. The distance between those two sites can be measured, and a conduction velocity can be calculated (distance/time). Conduction velocity reflects only the fastest conducting fibers in the nerve being studied.

Conduction Velocity

Motor conduction velocity is a measure of the speed of the fastest conducting motor axons in the nerve being studied, which is calculated by dividing the distance traveled by the nerve conduction time. However, motor conduction velocity cannot be calculated by performing a single stimulation. The distal motor latency is more than simply a conduction time along the motor axon; it includes not only (A) the conduction time along the distal motor axon to the NMJ, but also (B) the NMJ transmission time and (C) the muscle depolarization time. Therefore, to calculate a true motor conduction velocity, without including NMJ transmission and muscle depolarization times, two stimulation sites must be used, one distal and one proximal.

When the nerve is stimulated proximally, the resulting CMAP area, amplitude, and duration are, in general, similar to those of the distal stimulation waveform. The only major difference between CMAPs produced by proximal and distal stimulations is the latency. The proximal latency is longer than the distal latency, reflecting the longer time and distance needed for the action potential to travel. The proximal motor latency reflects four separate times, as opposed to the three components reflected in the distal motor latency measurement. In addition to (A) the nerve conduction time between the distal site and the NMJ, (B) the NMJ transmission time, and (C) the muscle depolarization time, the proximal motor latency also includes (D) the nerve conduction time between the proximal and distal stimulation sites (Figure 3–3). Therefore, if the distal motor latency (containing components A+B+C) is subtracted from the proximal motor latency (containing components A+B+C+D), the first three components will cancel out. This leaves only component D, the nerve conduction time between the proximal and distal stimulation sites, without the distal nerve conduction, NMJ transmission, and muscle depolarization times. The distance between these two sites can be approximated by measuring the surface distance with a tape measure. A conduction velocity then can be calculated along this segment: (distance between the proximal and distal stimulation sites) divided by (proximal latency−distal latency). Conduction velocities usually are measured in meters per second (m/s).

It is essential to note that both latency and conduction velocity reflect only the fastest conducting fibers in the nerve being studied. By definition, conduction along these fibers arrives first and thus it is these fibers that are the ones measured. The many other slower conducting fibers participate in the CMAP area and amplitude but are not

reflected in either the latency or conduction velocity measurements.

SENSORY CONDUCTION STUDIES

In contrast to motor conduction studies, in which the CMAP reflects conduction along motor nerve, NMJ, and muscle fibers, in sensory conduction studies only nerve fibers are assessed. Because most sensory responses are very small (usually in the range of 1 to 50 μV), technical factors and electrical noise assume more importance. For sensory conduction studies, the gain usually is set at 10 to 20 μV per division. A pair of recording electrodes (G1 and G2) are placed in line over the nerve being studied, at an interelectrode distance of 2.5 to 4 cm, with the active electrode (G1) placed closest to the stimulator. Recording ring electrodes are conventionally used to test the sensory nerves in the fingers (Figure 3–4). For sensory studies, an electrical pulse of either 100 or 200 ms in duration is used, and most normal sensory nerves require a current in the range of 5 to 30 mA to achieve supramaximal stimulation. This is less current than what is usually required for motor conduction studies. Thus, sensory fibers usually have a lower threshold to stimulation than do motor fibers. This can easily be demonstrated on yourself; when slowly increasing the stimulus intensity, you will feel the paresthesias (sensory) before you feel or see the muscle start to twitch (motor). As in motor studies, the current is slowly increased from a baseline of 0 mA, usually in 3 to 5 mA increments, until the recorded sensory potential is maximized. This potential, the *sensory nerve action potential* (SNAP), is a compound potential that represents the summation of all the individual sensory fiber action potentials. SNAPs usually are biphasic or triphasic potentials. For each stimulation site, the onset latency, peak latency, duration, and amplitude are measured (Figure 3–5). Unlike motor studies, a sensory conduction velocity can be calculated with one stimulation site alone, by taking the measured distance between the stimulator and active recording electrode and dividing by the onset latency. No NMJ or muscle time needs to be subtracted out by using two stimulation sites.

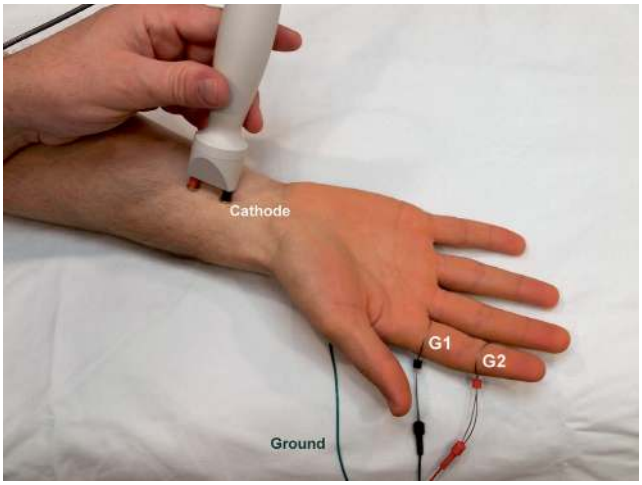

FIGURE 3–4 Sensory conduction study setup. Median sensory study, antidromic technique. Ring electrodes are placed over the index finger, 3 to 4 cm apart. The active recording electrode (G1) is placed more proximally, closest to the stimulator. Although the entire median nerve is stimulated at the wrist, only the cutaneous sensory fibers are recorded over the finger.

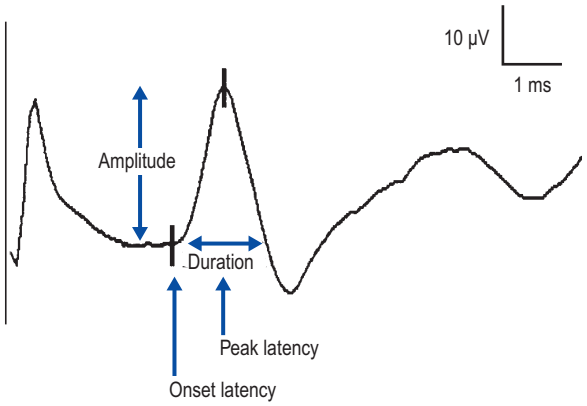

FIGURE 3–5 Sensory nerve action potential (SNAP). The SNAP represents the summation of all the underlying sensory fiber action potentials. The SNAP usually is biphasic or triphasic in configuration. Onset latency is measured from the stimulus to the initial negative deflection for biphasic SNAPs (as in the waveform here) or to the initial positive peak for triphasic SNAPs. Onset latency represents nerve conduction time from the stimulus site to the recording electrodes for the largest cutaneous sensory fibers in the nerve being studied. Peak latency is measured at the midpoint of the first negative peak. Amplitude most commonly is measured from baseline to negative peak but also can be measured from peak to peak. Duration is measured from the initial deflection from baseline to the first baseline crossing (i.e., negative peak duration). Only one stimulation site is required to calculate a sensory conduction velocity, as sensory onset latency represents only nerve conduction time.

Onset Latency

The onset latency is the time from the stimulus to the initial negative deflection from baseline for biphasic SNAPs or to the initial positive peak for triphasic SNAPs. Sensory onset latency represents nerve conduction time from the stimulus site to the recording electrodes for the largest cutaneous sensory fibers in the nerve being studied.

Peak Latency

The peak latency is measured at the midpoint of the first negative peak. Although the population of sensory fibers represented by the peak latency is not known (in contrast to the onset latency, which represents the fastest conducting fibers in the nerve being studied), measurement of peak latency has several advantages. The peak latency can be ascertained in a straightforward manner; there is practically no interindividual variation in its determination. In contrast, the onset latency can be obscured by noise or by the stimulus artifact, making it difficult to determine precisely. In addition, for some potentials, especially small ones, it may be difficult to determine the precise point of deflection from baseline (Figure 3–6). These problems do not occur in marking the peak latency. Normal values exist for

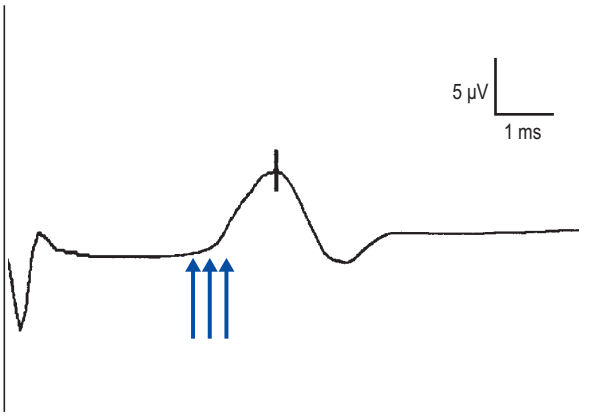

FIGURE 3–6 Sensory nerve action potential (SNAP) onset and peak latencies. Onset and peak latency measurements each have their own advantages and disadvantages. Onset latency represents the fastest conducting fibers and can be used to calculate a conduction velocity. However, for many potentials, especially small ones, it is difficult to precisely place the latency marker on the initial deflection from baseline (blue arrows: possible onset latencies). Marking the peak latency is straightforward, with nearly no inter-examiner variation. However, the population of fibers represented by peak latency is unknown; it cannot be used to calculate a conduction velocity.

peak latencies for the most commonly performed sensory studies stimulated at a standard distance. Note that the peak latency cannot be used to calculate a conduction velocity.

Amplitude

The SNAP amplitude is most commonly measured from baseline to negative peak, but it can also be measured from the first negative peak to the next positive peak. The SNAP amplitude reflects the sum of all the individual sensory fibers that depolarize. Low SNAP amplitudes indicate a definite disorder of peripheral nerve.

Duration

Similar to the CMAP duration, SNAP duration is usually measured from the onset of the potential to the first baseline crossing (i.e., negative peak duration), but it also can be measured from the initial to the terminal deflection back to baseline. The former is preferred given that the SNAP duration measured from the initial to terminal deflection back to baseline is difficult to mark precisely, because the terminal SNAP returns to baseline very slowly. The SNAP duration typically is much shorter than the CMAP duration (typically 1.5 vs. 5–6 ms, respectively). Thus, duration is often a useful parameter to help identify a potential as a true nerve potential rather than a muscle potential (Figure 3–7).

Conduction Velocity

Unlike the calculation of a motor conduction velocity, which requires two stimulation sites, sensory conduction velocity can be determined with one stimulation, simply by

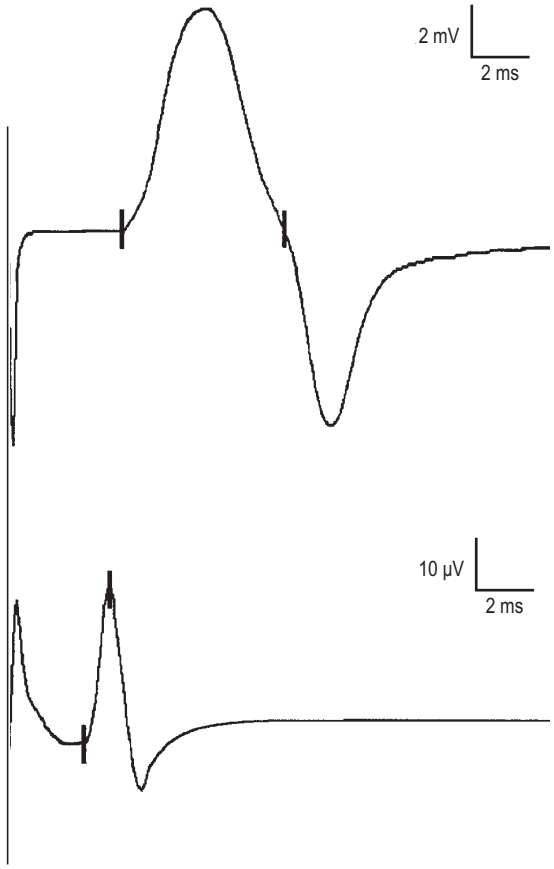

FIGURE 3–7 Compound muscle action potential (CMAP) and sensory nerve action potential (SNAP) comparison. CMAPs **(top)** and SNAPs **(bottom)** both are compound potentials but are quite different in terms of size and duration. CMAP amplitude usually is measured in millivolts, whereas SNAPs are small potentials measured in the microvolt range (note different gains between the traces). CMAP negative peak duration usually is 5 to 6 ms, whereas SNAP negative peak duration is much shorter, typically 1 to 2 ms. When both sensory and motor fibers are stimulated (such as when performing antidromic sensory or mixed studies), these differences (especially duration) usually allow an unknown potential to be recognized as either a nerve or muscle potential.

dividing the distance traveled by the onset latency. Essentially, distal conduction velocity and onset latency are the same measurement; they differ only by a multiplication factor (i.e., the distance). Sensory conduction velocity represents the speed of the fastest, myelinated cutaneous sensory fibers in the nerve being studied.

Sensory conduction velocity along proximal segments of nerve can be determined by performing proximal stimulation and calculating the conduction velocity between proximal and distal sites, in a manner similar to the calculation for motor conduction velocity: (distance between the proximal and distal stimulation sites) divided by (proximal latency − distal latency). However, proximal sensory studies result in smaller amplitude potentials and often are more difficult to perform, even in normal subjects, because of the normal processes of phase cancellation and temporal dispersion (see later). Note that one can also determine the sensory conduction velocity from the proximal site to the

recording electrode by simply dividing the total distance traveled by the proximal onset latency.

Special Considerations in Sensory Conduction Studies: Antidromic versus Orthodromic Recording

When a nerve is depolarized, conduction occurs equally well in both directions away from the stimulation site. Consequently, sensory conduction studies may be performed using either antidromic (stimulating toward the sensory receptor) or orthodromic (stimulating away from the sensory receptor) techniques. For instance, when studying median sensory fibers to the index finger, one can stimulate the median nerve at the wrist and record the potential with ring electrodes over the index finger (antidromic study). Conversely, the same ring electrodes can be used for stimulation, and the potential recorded over the median nerve at the wrist (orthodromic study). Latencies and conduction velocities should be identical with either method (Figure 3–8), although the amplitude generally is higher in antidromically conducted potentials.

In general, the antidromic technique is superior for several reasons, but each method has its advantages and disadvantages. Most important, the amplitude is higher with antidromic than with orthodromic recordings, which makes it easier to identify the potential. The SNAP amplitude is directly proportional to the proximity of the recording electrode to the underlying nerve. For most antidromically conducted potentials, the recording electrodes are closer to the nerve. For example, in the antidromically conducted median sensory response, the recording ring electrodes are placed on the finger, very close to the underlying digital nerves just beneath the skin from which the potential is recorded. When the montage is reversed for orthodromic recording, there is more tissue (e.g., the transverse carpal ligament and other connective tissues) at the wrist separating the nerve from the recording electrodes. This results in attenuation of the recorded sensory response, resulting in a much lower amplitude. The higher SNAP amplitude obtained with antidromic recordings is the major advantage of using this method. The antidromic technique is especially helpful when recording very small potentials, which often occur in pathologic conditions. Furthermore, because the antidromic potential generally is larger than the orthodromic potential, it is less subject to noise or other artifacts.

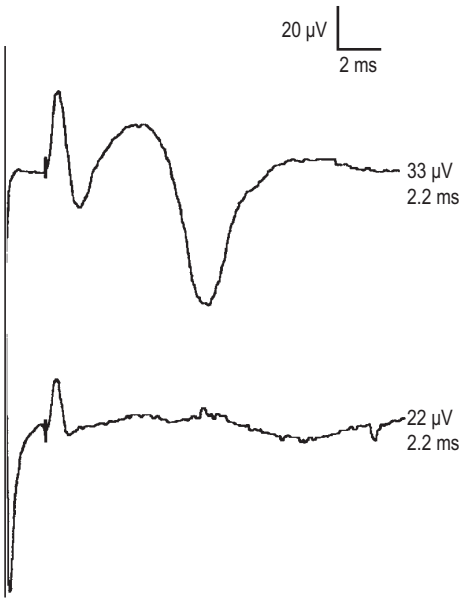

FIGURE 3–8 Antidromic and orthodromic sensory studies. Median sensory nerve action potential (SNAPs). **Top trace:** Antidromic study, stimulating wrist, recording index finger. **Bottom trace:** Orthodromic study, stimulating index finger, recording wrist. Latencies and conduction velocities are identical for both. The antidromic method has the advantage of a higher-amplitude SNAP but is followed by a large volume-conducted motor potential. If the SNAP is absent in an antidromic study, care must be taken not to confuse the volume-conducted motor potential as the sensory potential. Note the difference in duration between SNAP and CMAP, which helps discriminate between the SNAP and the volume-conducted motor potential that follows.

However, the antidromic method has some disadvantages (Figure 3–9). Since the entire nerve is often stimulated, including the motor fibers, this frequently results in the SNAP being followed by a volume-conducted motor potential. It usually is not difficult to differentiate between the two, because the SNAP latency typically occurs earlier than the volume-conducted motor potential. However, problems occur if the two potentials have a similar latency or, more importantly, if the sensory potential is absent. When the latter occurs, one can mistake the first component of the volume conducted motor potential for the SNAP, where none truly exists. It is in this situation that measuring the duration of the potential can be helpful in distinguishing a sensory from a motor potential. If one is still not sure, performing an orthodromic study will settle the issue, as no volume conducted motor response will occur with an orthodromic study. In this case, the antidromic and orthodromic potentials should have the same onset latency.

Lesions Proximal to the Dorsal Root Ganglion Result in Normal Sensory Nerve Action Potentials

Peripheral sensory fibers are all derived from the dorsal root ganglia cells, the primary sensory neurons. These cells have a unique anatomic arrangement: they are bipolar cells located outside the spinal cord, near the intervertebral foramina. Their central processes form the sensory nerve roots, whereas their peripheral projections ultimately become peripheral sensory nerves. Any lesion of the nerve root, even if severe, leaves the dorsal root ganglion and its peripheral axon intact, although essentially disconnected from its central projection. *Accordingly, SNAPs remain normal in lesions proximal to the dorsal root ganglia, including lesions of the nerve roots, spinal cord, and brain* (Figure 3–10). It is not uncommon, in the EMG lab, for a patient to have sensory symptoms or sensory loss but to have normal SNAPs in that distribution. This combination of clinical and electrical findings should always suggest the

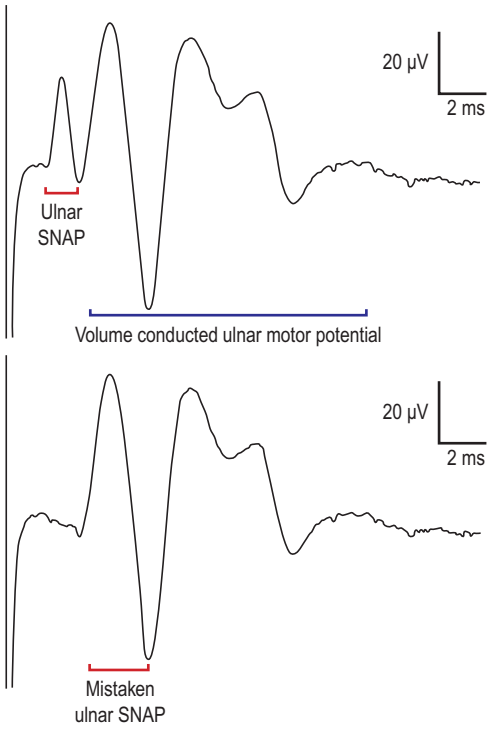

FIGURE 3–9 Misinterpretation error with antidromic sensory studies. In an antidromic study, the entire nerve is stimulated, including both sensory and motor fibers, which frequently results in the SNAP being followed by a volume-conducted motor potential. **Top:** Normal antidromic ulnar sensory response, stimulating the wrist and recording the fifth digit. Notice the ulnar SNAP, which is followed by the large, volume-conducted motor response. One can recognize the SNAP by its characteristic shape, and especially by its brief negative peak duration of approximately 1.5 ms. Also, notice that the SNAP usually occurs earlier than the volume-conducted motor response. **Bottom:** If the sensory response is absent, and an antidromic study is performed, one might mistake the first component of the volume-conducted motor response for the SNAP. The key to not making this mistake is to note the longer duration of the motor potential, which often has a higher amplitude and slowed latency/conduction velocity. In this case, the negative peak duration of this mistaken potential is approximately 2.5 ms. In some cases, one still may not be certain. In those situations, performing the study orthodromically will settle the issue as no volume-conducted motor potential will occur with an orthodromic study. The onset latencies of the orthodromic and antidromic potentials should be the same. The problem with an orthodromic study is that the amplitude is often much lower than with the antidromic method. (Note: Sensory responses are normally very low, in the microvolt range.)

possibility of a lesion proximal to the dorsal root ganglia, although rarely other conditions can produce the same situation.

The situation is quite different for motor fibers. The primary motor neurons, the anterior horn cells, are located in the ventral gray matter of the spinal cord. Axons from the motor neurons form the motor roots and, ultimately, the motor fibers in the peripheral nerves. Lesions of the motor roots effectively disconnect the peripheral motor fibers from their primary neurons, resulting in degeneration of motor fibers throughout the peripheral nerve. Consequently, a nerve root lesion often results in abnormalities on motor NCSs and especially needle EMG.

Proximal Stimulation: Normal Temporal Dispersion and Phase Cancellation

During routine motor conduction studies, the CMAPs recorded by proximal and distal stimulations are nearly identical in configuration. If measured carefully, the proximal CMAP duration may increase slightly, and both the area and amplitude may fall slightly. If the same proximal and distal stimulation sites are used for sensory studies, however, the proximal SNAP varies greatly from the distal one in terms of duration, area, and amplitude. The duration of the proximal potential is markedly increased, and the amplitude and area are greatly reduced compared to the distal potential (Figure 3–11). These changes are normal findings that result from a combination of temporal dispersion and phase cancellation.

For both sensory and motor studies, the recorded potential (SNAP, CMAP) is a *compound* potential. In the case of sensory studies, many individual sensory fibers depolarize and summate to create the SNAP. Within any sensory nerve, there are large, medium, and smaller myelinated fibers, which depolarize and conduct at slightly different velocities. In general, the larger fibers depolarize before the smaller ones. Likewise, there is a normal variation in the size of individual sensory fiber action potentials, with larger fibers generally having larger amplitudes. Temporal dispersion occurs as these individual nerve fibers fire at slightly different times (i.e., larger, faster fibers depolarize before smaller, slower ones). Temporal dispersion normally is more prominent at proximal stimulation sites because the slower fibers progressively lag behind the faster fibers (Figure 3–12). This is analogous to a marathon race in which one runner runs a 5-minute mile and the other a 6-minute mile. At the beginning of the race, both runners are very close to each other (less dispersion), but by the end of the race they are far apart (greater dispersion).

With proximal stimulation, there is a greater lag time between the faster and slower conducting fibers, leading to increased duration and temporal dispersion of the waveform. If temporal dispersion alone were at work, the amplitude would decrease as the potential was spread out, but the area would be preserved. This would indeed be the case if each sensory fiber action potential were monophasic in configuration. However, single sensory fiber action potentials usually have either a biphasic or triphasic configuration. A single, large sensory myelinated fiber has a negative duration of about 0.5 ms, approximately half the normal duration of the distal SNAP (typical duration is 1.3 ms). This implies that after the first 0.5 ms, the trailing positive phase of the fastest potential overlaps with the leading negative phases of the slower fibers. When overlap occurs between the positive phase of one sensory fiber action potential and the negative phase of another, phase cancellation occurs, resulting in a smaller summated potential. This results in a drop of area, as well as a further drop in amplitude.

Although temporal dispersion and phase cancellation usually are thought of as occurring at proximal stimulation

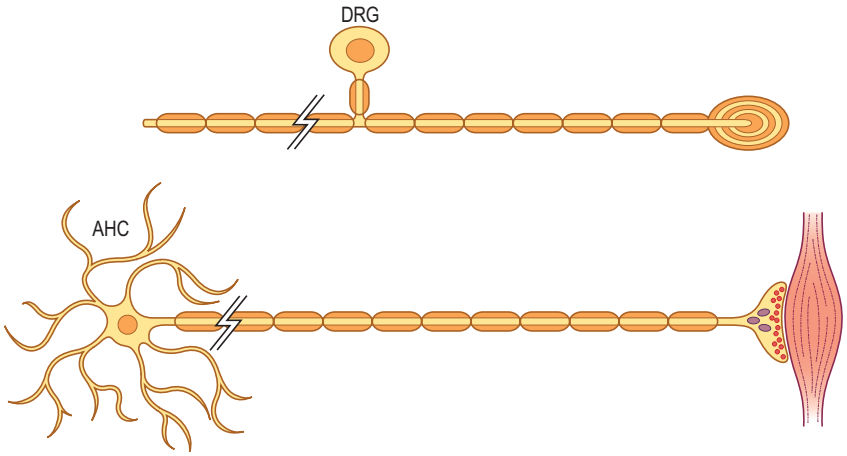

FIGURE 3–10 Nerve root lesions and nerve conduction studies. Anatomic differences between sensory and motor nerve fibers result in different patterns of nerve conduction abnormalities in nerve root lesions. The sensory nerve **(top)** is derived from the dorsal root ganglia (DRG). The DRG are bipolar cells whose central processes form the sensory roots and distal processes continue as the peripheral sensory nerve fibers. The motor nerve **(bottom)** is derived from the anterior horn cell (AHC), which resides in the ventral gray matter of the spinal cord. Lesions of the nerve roots separate the peripheral motor nerve from its neuron, the AHC, but leave the DRG and its distal processes intact. Thus, nerve root lesions may result in degeneration of the motor fibers distally and, accordingly, abnormalities on motor nerve conduction studies and/or needle electromyogram. However, the distal sensory nerve remains intact in lesions of the nerve roots, as the lesion is proximal to the DRG. Thus, results of sensory conduction studies remain normal.

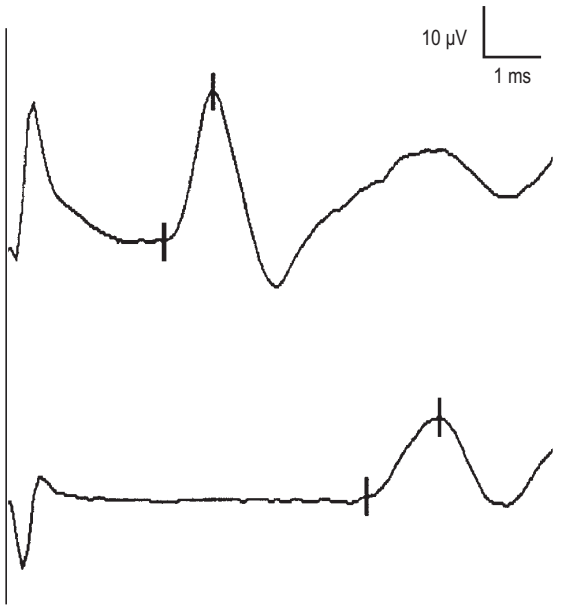

FIGURE 3–11 Proximal sensory studies. Normal median sensory study, recording index finger, stimulating wrist **(top trace)** and elbow **(bottom trace)**. Note that in normal subjects, proximal stimulation results in sensory nerve action potentials (SNAPs) that are longer in duration and lower in amplitude and area. This occurs as a result of normal temporal dispersion and phase cancellation. If the SNAP is small at the distal stimulation site, it may be difficult or impossible to obtain a potential with proximal stimulation.

sites, the effect is present to some degree even with distal stimulation. For example, the median SNAP is higher in amplitude and shorter in duration when stimulating in the palm and recording the index finger than when stimulating at the usual distal site in the wrist. This is because some normal temporal dispersion and phase cancellation occur even at the usual distal stimulation sites. The effects of temporal dispersion are not as apparent with distal stimulation, however, because the slower fibers do not have as much time to lag behind, and phase cancellation is less prominent. This results in a distal potential with a larger amplitude and area than the more proximal potential. At proximal stimulation sites, phase cancellation results in a potential with a smaller amplitude and area and a longer duration.

Temporal dispersion and phase cancellation also occur in motor studies but are much less marked (Figure 3–12). The CMAP is the summation of many individual motor unit action potentials (MUAPs). An individual MUAP has a negative peak duration of 5 to 6 ms, very similar to the CMAP duration. With such similar durations, most MUAPs are in phase with each other. In addition, the range of normal conduction velocities is smaller for motor than for sensory fibers. Because the slowest motor fibers do not lag as far behind the fastest fibers with proximal stimulation, the effects of temporal dispersion and phase cancellation are not as marked for motor as they are for sensory fibers.

MIXED CONDUCTION STUDIES

In many respects, mixed NCSs are comparable to sensory studies. Both studies measure compound nerve action potentials, which are stimulated and recorded in a similar manner. However, for mixed nerve studies, the potential reflects both motor and sensory fiber action potentials generated along the nerve. Although theoretically any mixed nerve can be studied, in practice, the median, ulnar, and distal tibial nerves are most often selected for examination. These mixed nerve studies are used most often in the electrodiagnosis of median neuropathy at the wrist, ulnar neuropathy at the elbow, and tibial neuropathy across the tarsal tunnel, respectively.

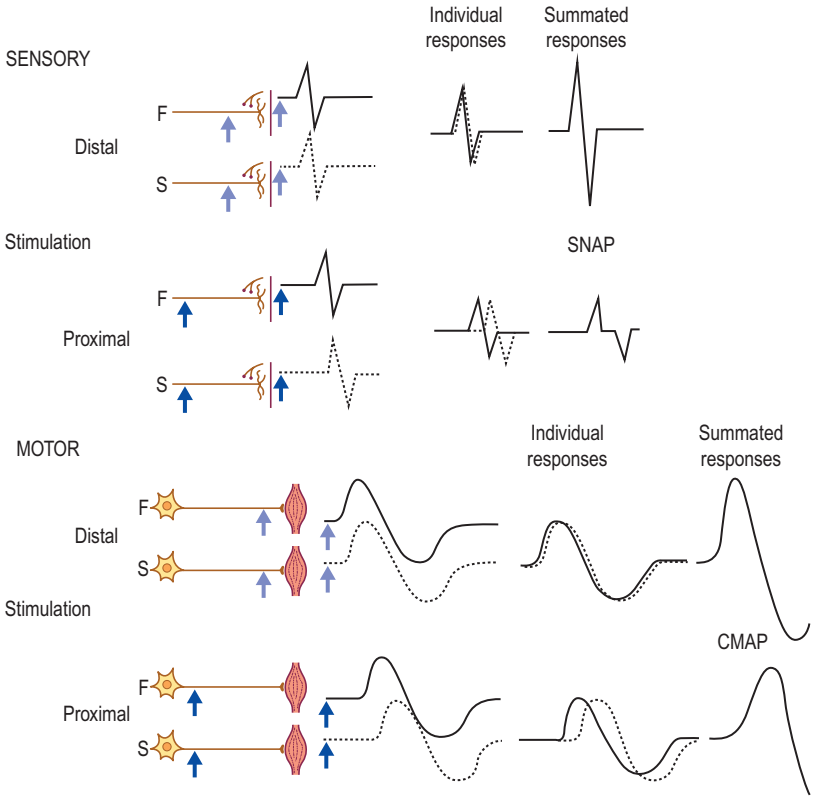

FIGURE 3–12 Temporal dispersion and phase cancellation in nerve conduction studies. Sensory nerve action potentials (SNAPs) and compound muscle action potentials (CMAPs) both are compound potentials, representing the summation of individual sensory and muscle fiber action potentials, respectively. In each case, there are fibers that conduct faster (F) and those that conduct more slowly (S). With distal stimulation, fast and slow fiber potentials arrive at the recording site at approximately the same time. However, with proximal stimulation, the slower fibers lag behind the faster fibers. For sensory fibers **(top traces),** the amount of temporal dispersion at proximal stimulation sites results in the negative phase of the slower fibers overlapping with the positive trailing phase of fastest fibers. These superimposed positive and negative phases cancel each other out, resulting in a decrease in area and amplitude, beyond the decrease in amplitude and increase in duration from the effects of temporal dispersion alone. The effects of temporal dispersion and phase cancellation are less prominent for motor fibers **(bottom traces).** The duration of individual motor fiber potentials is much longer than that of single sensory fibers. Thus, for the same amount of temporal dispersion, there is much less overlap between negative and positive phases of motor fiber action potentials.
(From Kimura, J., Machida, M., Ishida, T., et al., 1986. Relationship between size of compound sensory or muscle action potentials, and length of nerve segment. Neurology 36, 647, with permission of Little, Brown and Company.)

At first glance, one might presume that mixed nerve studies, which record motor and sensory fibers in combination, offer little advantage over routine motor and sensory studies performed independently. During routine motor or sensory NCSs, however, the largest and fastest fibers in the body are not recorded. These fibers are the sensory muscle afferents, the Ia fibers, which supply the muscle spindles. *These largest fibers are recorded only during mixed nerve studies, wherein the entire mixed nerve is stimulated and also recorded*. Mixed nerve conduction velocities usually are faster than either routine motor or cutaneous sensory conduction velocities because they include these Ia fibers. Furthermore, because the Ia fibers have the largest diameter, and accordingly the greatest amount of myelin, they often are the fibers earliest affected by demyelinating lesions, such as occur in entrapment neuropathies.

For a mixed NCS, the settings are similar to those used for sensory conduction studies. The gain usually is set at 10 to 20 μV per division because the responses are quite small (usually in the range of 5 to 100 μV). A pair of recording electrodes (G1 and G2) is placed in line over the mixed nerve, at an interelectrode distance of 2.5 to 4 cm, with the active electrode (G1) closest to the stimulator (Figure 3–13). The recorded potential, the mixed nerve action potential (MNAP), is a compound potential that represents the summation of all the individual sensory and motor fiber action potentials. MNAPs usually are biphasic or triphasic potentials. Onset latency, peak latency, duration, amplitude, and conduction velocity are measured using methods similar to those used in sensory conduction studies.

PRINCIPLES OF STIMULATION

Use Supramaximal Stimulation

In order to obtain correct and reproducible data during NCSs, it is essential that all fibers within a nerve are stimulated at all locations. If the current is too low, not all fibers will be depolarized (submaximal stimulation).

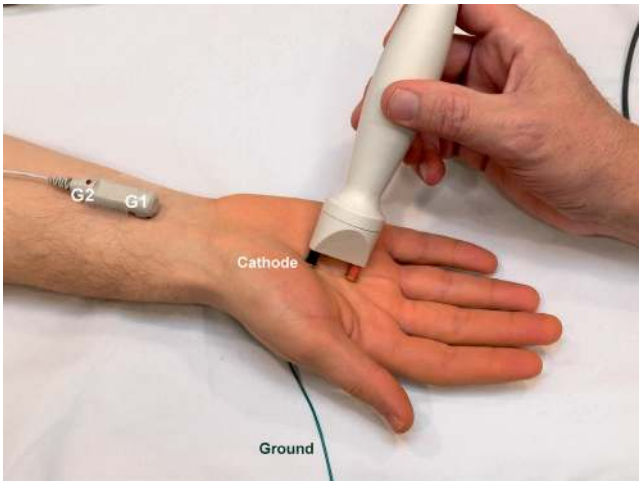

FIGURE 3–13 Mixed nerve study setup. Median mixed study, stimulating median nerve in the palm, recording median nerve at the wrist. The active recording electrode (G1) faces the cathode of the stimulator. Mixed studies stimulate and record all motor and sensory fibers, including the muscle afferents, the Ia fibers, which are not recorded in either routine sensory or motor conduction studies.

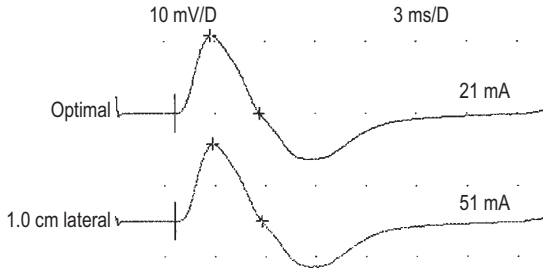

FIGURE 3–14 Optimal stimulator position and supramaximal stimulation. In this example, the median nerve is stimulated at the wrist while recording the abductor pollicis brevis muscle. In the top trace, the stimulator has been placed in the optimal location directly over the nerve. In the lower trace, the stimulator has been moved 1 cm lateral to that position. Supramaximal stimulation is then achieved. Note that in both examples, the resultant compound muscle action potential is identical. However, the current needed to obtain supramaximal stimulation, when stimulating laterally, is more than twice that needed at the optimal position.

Conversely, if it is too high, current may spread and depolarize nearby nerves (co-stimulation). Different degrees of current intensity are required in different individuals and in different anatomic locations in order to depolarize all nerve fibers. For instance, some nerves lie just under the skin (e.g., ulnar nerve at the elbow), whereas others are much deeper (e.g., tibial nerve at the popliteal fossa). At each stimulation site, it is essential that supramaximal stimulation be used to ensure that all axons within a given nerve are depolarized. To achieve supramaximal stimulation, the current intensity is slowly increased until the amplitude of the recorded potential reaches a plateau. The current intensity then is increased an additional 20 to 25% to ensure that the potential no longer increases. It is only at this point that supramaximal stimulation is achieved. This procedure needs to be used at all locations. *One of the most common mistakes in performing NCSs is to stop increasing the current once the potential is within the normal range. In this case, the potential may be "normal" but not supramaximal.*

Optimize the Stimulation Site

One may be tempted to routinely use higher stimulation intensities in order to assure supramaximal stimulation. However, this practice can lead to technical errors due to the spread of the stimulus to nearby adjacent nerves, in addition to causing pain to the patient (see Chapter 8). One of the most useful techniques to master is placement of the stimulator at the optimal location directly over the nerve, which yields the highest CMAP amplitude with the least stimulus intensity (Figure 3–14). This technique is easily learned. The stimulator is placed over a site where the nerve is expected to run, based on anatomic landmarks. The stimulus intensity is slowly increased until the first small submaximal potential is recorded. At this point, the stimulus current is held constant, and the stimulator is moved parallel to the initial stimulation site, both slightly laterally and then slightly medially (Figure 3–15). The position that yields the highest response is the position closest to the nerve. Because the stimulus intensity is low, this procedure is not painful for the patient. Once the optimal position is determined, the current is increased to supramaximal. It often is surprising how little current is required to obtain supramaximal stimulation using this technique, leading to many fewer technical errors and better patient tolerance and cooperation.

IMPORTANT BASIC PATTERNS

Several basic patterns of nerve conduction abnormalities can be recognized, depending on the underlying pathology. For example, abnormalities noted in motor conduction studies may be seen with disorders of the anterior horn cell, nerve root, nerve, NMJ, or muscle. In contrast, sensory or mixed nerve conduction abnormalities always imply a primary disorder of the peripheral nerve.

Neuropathic Lesions

Neuropathic lesions can be divided into those that primarily affect either the axon or the myelin sheath. Axonal loss may be seen after physical disruption of the nerve or as a result of numerous toxic, metabolic, or genetic conditions that can damage the metabolic machinery of the axon. Demyelination resulting from loss or dysfunction of the myelin sheath is seen most often in entrapment or compressive neuropathies. Otherwise, demyelination occurs in only a limited number of conditions, some of which are genetic (e.g., Charcot–Marie–Tooth polyneuropathy), some toxic (e.g., diphtheria), and others the consequence of a presumed immunologic attack on the myelin (e.g.,

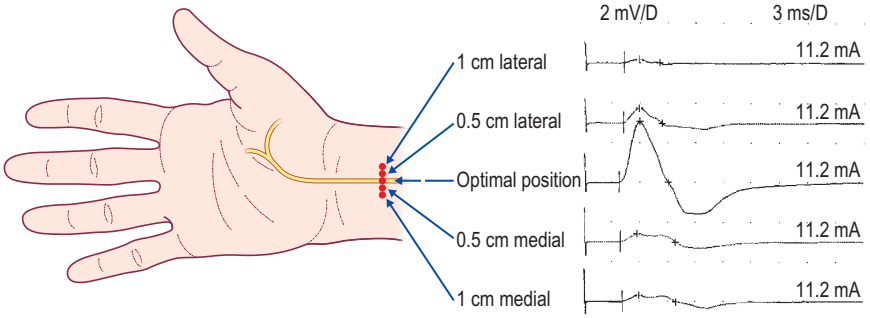

FIGURE 3–15 Optimizing the stimulator position over the nerve. The stimulator is placed over a site where the nerve is expected to run, based on anatomic landmarks. The stimulus intensity is slowly increased until the first small submaximal potential is recorded. At this point, the stimulus current is held constant, and the stimulator is moved parallel to the initial stimulation site, both slightly laterally and then slightly medially. Note in this example that moving the stimulator by very small increments (0.5 cm) markedly changes the amplitude of the compound muscle action potential. The optimal site is the one with the largest potential, which is directly over the nerve. Because the stimulus intensity is low (in this case, 11.2 mA), this procedure of optimizing the stimulator site is not painful for the patient. Once the optimal position is determined, the current is increased to supramaximal. Using this technique markedly reduces the amount of current necessary to achieve supramaximal stimulation, reduces a host of possible technical errors as well as patient discomfort, and increases efficiency.

Guillain–Barré syndrome). *In neuropathic lesions, one of the key pieces of diagnostic information obtained from NCSs is the differentiation of a primary axonal loss lesion from a primary demyelinating lesion.*

Axonal Loss

Axonal loss is the most common pattern seen on NCSs. *Reduced amplitude is the primary abnormality associated with axonal loss*. Amplitudes of the CMAP, SNAP, and MNAPs reflect the number of underlying motor, sensory, and mixed nerve axons, respectively. As axons are lost, the amplitudes of these potentials decrease. The best way to assess the amount of axonal loss is to compare the amplitude of a potential with a previous baseline value, a normal control value, or the contralateral (asymptomatic) side. *Note that although axonal loss lesions generally result in reduced amplitudes, the corollary is not necessarily true: reduced amplitudes do not necessarily imply an axonal loss lesion* (see the next two sections on Demyelination and Conduction Block).

In axonal loss lesions, conduction velocity and distal latency are normal, provided that the largest and fastest conducting axons remain intact. The typical pattern associated with axonal loss is one of reduced amplitudes with preserved latencies and conduction velocities (Figure 3–16B). Mild slowing of distal latency and conduction velocity may occur if the largest and fastest conducting axons are lost. Marked slowing, however, does not occur. To understand this concept and the possible range of slowing in axonal loss lesions, consider the examples shown in Figure 3–17. Every nerve contains a normal range of myelinated fibers with different axonal diameters and conduction velocities. In the median nerve, for instance, the largest-diameter (and accordingly the fastest) myelinated fibers conduct at a velocity of approximately 65 m/s. At the other end of the normal range, there are slower fibers that conduct as slowly as 35 m/s. The vast majority of fibers lie between these two extremes. However, whereas all fibers contribute to amplitude and area, only the fastest conducting fibers contribute to the conduction velocity and latency measured by routine NCSs.

In lesions associated with axonal loss, one can consider two possible extremes of conduction velocity abnormalities. At one extreme, there may be severe loss of axons with only a few of the fastest fibers remaining (Figure 3–17B). While amplitude markedly decreases, the conduction velocity and distal latency remain normal, due to the preservation of the fastest conducting fibers. At the other extreme, if all axons are lost except for a few of the normal most slowly conducting fibers (Figure 3–17C), the amplitude will also fall dramatically. In addition, conduction velocity will drop, but only as low as 35 m/s (approximately 75% of the lower limit of normal), reflecting the conduction velocity of the slowest conducting fibers. Greater slowing cannot occur in a pure axonal loss lesion because normal myelinated fibers do not conduct any more slowly than this. Latencies become prolonged in a similar fashion, but there is a limit to this prolongation, such that the latencies generally do not exceed 130% of the upper limit of normal. In general, axonal loss lesions result in a pattern somewhere between these two extremes. When there is random dropout of fibers, the amplitude falls, the conduction velocity slows slightly, and the distal latency mildly prolongs (Figure 3–18).

Thus, with axonal loss lesions, (1) amplitudes decrease, (2) conduction velocities are normal or slightly decreased but never below 75% of the lower limit of normal, and (3) distal latencies are normal or slightly prolonged but never greater than 130% of the upper limit of normal.

The only exception to these criteria for axonal loss lesions occurs in hyperacute axonal loss lesions, such as might occur following a nerve transection. In such a case, results of NCSs performed within 3 to 4 days of an acute axonal loss lesion remain normal, provided both stimulation and recording are done distal to the lesion. Between days 3 to 10, the process of wallerian degeneration occurs: the nerve

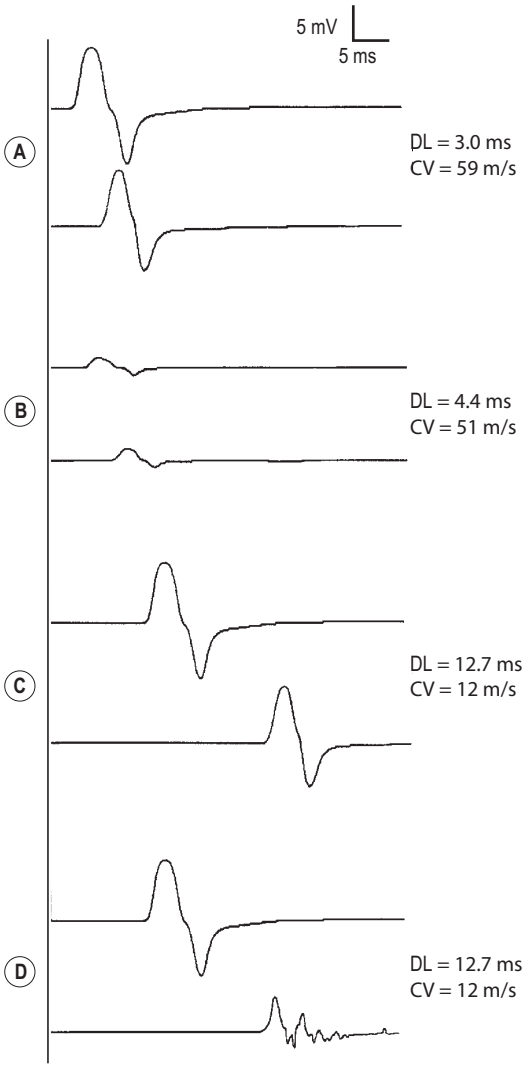

FIGURE 3–16 Patterns of nerve conduction abnormalities. Depending on whether the underlying nerve pathology is axonal loss or demyelination, different patterns of abnormalities are seen on nerve conduction studies. **A:** Normal study. Note the normal distal latency (DL) <4.4 ms, amplitude >4 mV, and conduction velocity (CV) >49 m/s. **B:** Axonal loss. In axonal loss lesions, amplitudes decrease; CV is normal or slightly slowed, but not <75% of the lower limit of normal; and DL is normal or slightly prolonged, but not >130% of the upper limit of normal. The morphology of the potential does not change between proximal and distal sites. **C:** Demyelination resulting in uniform slowing is most often associated with inherited conditions (e.g., Charcot–Marie–Tooth polyneuropathy). CV is markedly slowed (<75% lower limit of normal) and DL is markedly prolonged (>130% of the upper limit of normal). However, there usually is no change in configuration between proximal and distal stimulation sites. **D:** Demyelination with conduction block/temporal dispersion. Marked slowing of conduction velocity and distal latency, but also with change in potential morphology (conduction block/temporal dispersion) between distal and proximal stimulation sites, is most often associated with acquired causes of demyelination. This pattern may be seen in Guillain–Barré syndrome or other acquired demyelinating conditions.

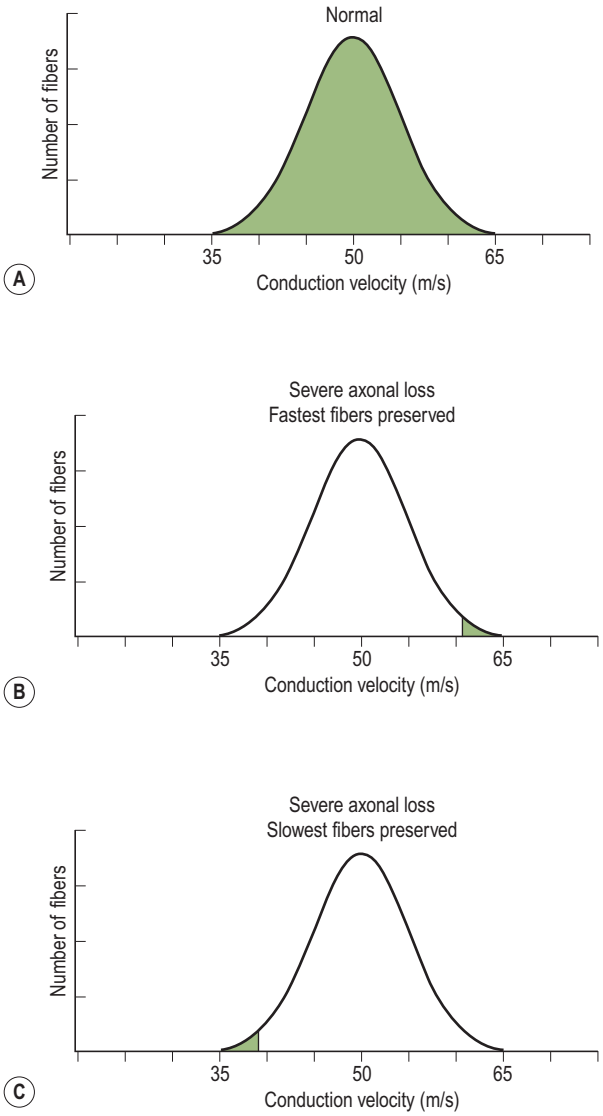

FIGURE 3–17 Conduction velocity slowing and axonal loss lesions. Every nerve contains a normal range of myelinated fibers with different axonal diameters and conduction velocities. For example, in the normal median nerve (**A**), the fastest myelinated fibers conduct at a velocity of approximately 65 m/s. At the other end of the normal range, there are slower fibers that conduct as slowly as 35 m/s. Whereas all fibers contribute to amplitude and area, only the fastest conducting fibers contribute to the conduction velocity and latency measured by routine nerve conduction studies. In lesions associated with axonal loss, there is a range of possible conduction velocity slowing. At one extreme (**B**), severe axonal loss may occur with sparing of only a few of the fastest fibers remaining (outlined in green). While amplitude markedly decreases, conduction velocity and distal latency remain normal, due to the preservation of the fastest conducting fibers. At the other extreme (**C**), if all axons are lost, except for a few of the slowest conducting fibers (outlined in green), the amplitude also falls dramatically. However, conduction velocity can only drop as low as 35 m/s (≈75% of the lower limit of normal). Greater slowing cannot occur in a pure axonal loss lesion because normal myelinated fibers do not conduct any slower than this. Latencies also prolong in a similar fashion, but there is a limit to this prolongation, generally no greater than 130% of the upper limit of normal. Thus, with axonal loss lesions, (1) amplitudes decrease, (2) conduction velocities are normal or slightly decreased, but never below 75% of the lower limit of normal, and (3) distal latencies are normal or slightly prolonged, but never greater than 130% of the upper limit of normal.

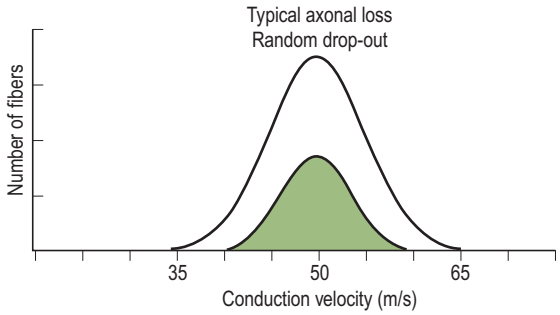

FIGURE 3–18 Typical axonal loss pattern. With random dropout of fibers from axonal loss (outlined in green), the normal distribution of nerve fibers and their associated conduction velocities changes to a smaller bell-shaped curve. In this case, the amplitude decreases while the conduction velocity and distal latency slightly slow. This is the more typical pattern of axonal loss than the extreme examples shown in Figure 3–17, where only a few of either the fastest or slowest normal fibers remain after severe axonal loss.

distal to the transection undergoes degeneration, resulting in a low amplitude potential both distally and proximally. The process of wallerian degeneration is earlier for motor fibers (typically between days 3–5) compared to sensory fibers (typically between days 6–10). Once wallerian degeneration is complete, the typical pattern of axonal loss will be seen on NCSs.

A unique situation occurs if stimulation is performed distal and proximal to an acute axonal loss lesion during the first 3 days after the nerve insult. In this case, the amplitude will be normal with distal stimulation, but reduced with proximal stimulation. This pattern simulates conduction block, a pattern typically associated with demyelination but, in fact, is best termed *pseudo-conduction block*. This type of acute axonal loss pattern is distinctly unusual, and in common practice, is seen only in two situations: (1) acute trauma/transection of a nerve, or (2) nerve infarction, as occurs most classically in vasculitic neuropathy. In such situations, the only way to differentiate an acute axonal loss lesion resulting in pseudo-conduction block from a true demyelinating conduction block is to repeat the study after an additional week, when wallerian degeneration is complete. In the case of an axonal loss lesion, the typical axonal pattern will be present after 1 week (low amplitudes, normal or slightly prolonged latencies, normal or slightly slow conduction velocity) whereas in a true demyelinating lesion, the conduction block pattern will persist.

Demyelination

Myelin is essential for saltatory conduction. Without myelin, nerve conduction velocity is either markedly slowed or blocked (Figure 3–16C and D). On NCSs, demyelination is associated with marked slowing of conduction velocity (slower than 75% of the lower limit of normal), marked prolongation of distal latency (longer than 130% of the upper limit of normal), or both. Conduction velocities and latencies slower than these cutoff values imply primary demyelination; such values are not seen with axonal loss lesions, even in severe lesions associated with loss of the fastest conducting fibers. This is because there are simply no normal myelinated axons that conduct this slowly (n.b., there are small myelinated Aδ pain fibers that conduct in this range, but these fibers are neither stimulated nor recorded with routine nerve conduction techniques). *Essentially, any motor, sensory, or mixed nerve conduction velocity that is slower than 35 m/s in the arms or 30 m/s in the legs signifies unequivocal demyelination*. Only in the rare case of regenerating nerve fibers after a complete axonal injury (e.g., nerve transection) can conduction velocities be this slow and not signify a primary demyelinating lesion.

Occasionally, the electromyographer will encounter conduction velocity slowing that approaches these cutoff values. When this occurs, interpretation of whether the slowing represents demyelination or axonal loss is aided by knowledge of the amplitude of the potential. A conduction velocity near the cutoff value where the amplitude is normal usually represents demyelination, whereas a borderline velocity with a markedly reduced amplitude most often implies severe axonal loss. Consider the following example:

Median motor study	Conduction velocity (m/s)	Distal motor amplitude (mV)
Case 1	35	7
Case 2	35	0.2

In this example, both cases have a conduction velocity of 35 m/s, which is right at the cutoff value for slowing of the median nerve in the demyelinating range (i.e., 75% of the lower limit of normal). In case 1 the amplitude is normal, and the conduction velocity likely represents demyelination. In case 2, however, the amplitude is very low at 0.2 mV and is accompanied by the same slowed conduction velocity. This markedly low amplitude implies that there has likely been severe axonal loss. In this situation, the severely slowed conduction velocity most likely represents severe axonal loss, with loss of the fastest and intermediate conducting fibers and preservation of the more slowly conducting fibers. Using more than one piece of information for interpretating EDX findings is a recurring theme in EDX studies: it is often not one piece of information that leads to a correct interpretation and diagnosis, but putting several pieces of data together.

Amplitude changes associated with demyelination are variable. At first glance, it might appear that reduced amplitudes are always a marker of axonal loss rather than demyelination. This is not completely true, however, and depends on two conditions:

- whether sensory or motor studies are performed
- whether or not *conduction block* is present, and if present, where the stimulation site is in relationship to the conduction block.

Sensory amplitudes often are low or absent in demyelinating lesions. Sensory amplitudes are reduced due to the normal processes of temporal dispersion and phase cancellation. These are exaggerated by demyelinative slowing,

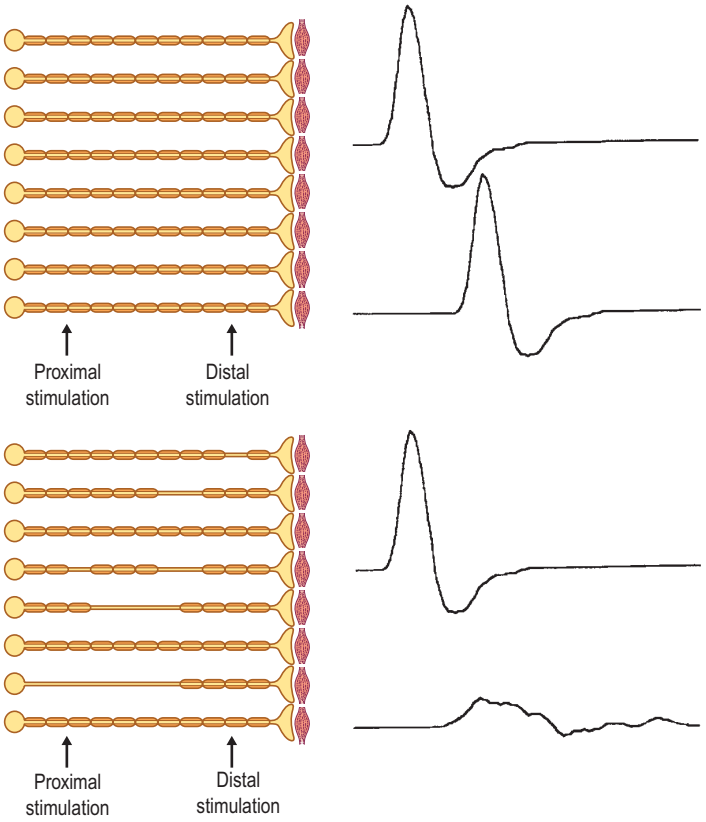

FIGURE 3–19 Model of conduction block. In acquired demyelinating lesions, demyelination is often a patchy, multifocal process. When the nerve is stimulated proximal to the conduction block, the compound muscle action potential (CMAP) drops in amplitude and area and becomes dispersed **(bottom).** In a normal nerve **(top),** the CMAP morphology usually is similar between distal and proximal stimulation sites.
(Adapted from Albers, J.W., 1987. Inflammatory demyelinating polyradiculoneuropathy. In: Brown, W.F., Bolton, C.F., (Eds.), Clinical electromyography. Butterworth-Heinemann, Stoneham, MA, with permission.)

which further lowers sensory amplitudes by changing the range of conduction velocities, thereby increasing the temporal dispersion and phase cancellation. Think again about the analogy of two marathon runners: one running at 13 miles per hour and another at 6.5 miles per hour. To complete the marathon of 26 miles, the first runner takes 2 hours, and the second takes 4 hours. Thus, they finish 2 hours apart. Consider this normal temporal dispersion. Now, imagine that both runners run half as fast as their normal speed, 6.5 miles per hour and 3.25 miles per hour. Consider this demyelination. It will take the first runner 4 hours to complete the marathon, and the second runner, 8 hours. Now, the two runners finish 4 hours apart. Thus, they are more temporally dispersed than normal. In the world of nerve conductions, more temporal dispersion results in more phase cancellation (i.e., negative phases of some fiber action potentials cancelling out positive phases of other fiber action potentials), and thus lower or absent sensory potentials.

Conduction Block

Reduced amplitudes in demyelinating lesions are seen when conduction block is present, as occurs in acquired demyelination (Figure 3–19). If a conduction block is present in a demyelinating lesion, then the site of stimulation and the location of the conduction block will determine the CMAP amplitude (Figure 3–20). The amplitude will be low if the nerve is stimulated proximal to the conduction block. If the conduction block is present between the normal distal stimulation site and the recording electrodes, both the distal and proximal CMAP amplitudes will be low and may simulate an axonal loss lesion (Figure 3–20, top). In this situation, it may be difficult to prove that a conduction block is present. If the conduction block is present between distal and proximal stimulation sites, which is the usual situation, the CMAP amplitude will be normal distally, below the block, but will be decreased at the proximal stimulation site, above the block (Figure 3–20, middle). Finally, if both the proximal and distal stimulation sites are distal to, or below the block, the CMAP amplitudes will remain normal both distally and proximally (Figure 3–20, bottom).

In demyelinating lesions, the crucial question that often must be addressed is how much of a drop in either amplitude or area is needed to properly identify a conduction block. From studies of normal subjects, CMAP amplitude and area generally do not decrease by more than 20%, and CMAP duration generally does not increase by more than 15%, when recorded from the typical distal and proximal stimulation sites (i.e., wrist to elbow, ankle to knee).*

*The only normal exception to these findings occurs during routine tibial motor studies. The tibial CMAP often is smaller in amplitude and area, and more dispersed, when stimulating at the popliteal fossa than when stimulating at the ankle. The reason for this finding is not completely clear, although, in some cases, supramaximal stimulation is difficult to achieve at the popliteal fossa. In practice, one should always be cautious calling a proximal drop in amplitude or area a conduction block during routine tibial motor studies. A drop in amplitude up to 50% may be seen in normal subjects when stimulating the tibial nerve at the popliteal fossa.

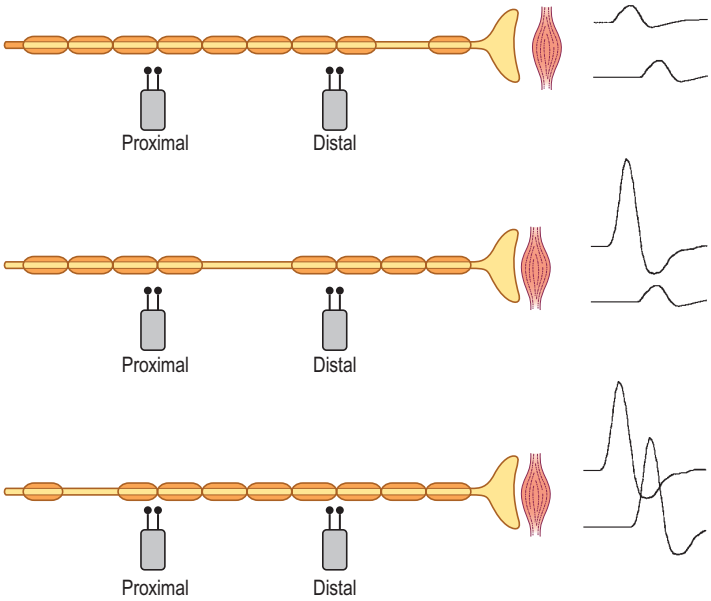

FIGURE 3–20 Compound muscle action potential (CMAP) amplitude and conduction block location. In demyelinating lesions, the site of stimulation and the presence and location of the conduction block will determine the CMAP amplitude. **Top:** If a conduction block is present between the usual distal stimulation site and the muscle, amplitudes will be low at both distal and proximal stimulation sites, the pattern usually associated with axonal loss lesions. **Middle:** If a conduction block is present between distal and proximal stimulation sites, a normal CMAP amplitude will be recorded with distal stimulation and a reduced CMAP amplitude will be recorded with proximal stimulation. **Bottom:** If a conduction block is proximal to the most proximal stimulation site, the nerve remains normal distally, although effectively disconnected from its proximal segment. This results in normal CMAP amplitudes both distally and proximally. Late responses may be abnormal (see Chapter 4).

These studies imply that any drop in either CMAP amplitude or area of more than 20% denotes conduction block, and any increase in CMAP duration of more than 15% signifies abnormal temporal dispersion. The effects of normal temporal dispersion, of course, depend on the distance. If more proximal stimulation is performed than in routine motor studies (e.g., axilla or Erb's point stimulation), these values must be modified. In general, for Erb's point stimulation, the cutoff values are doubled (i.e., area or amplitude drop of more than 40%, duration increase of more than 30%). In a similar vein, any abrupt drop in either CMAP area or amplitude over a short segment, even if <20%, and especially if associated with slowing, usually implies conduction block.

Although these guidelines regarding conduction block are useful, sophisticated studies using computer simulation techniques have questioned the proper electrophysiologic criteria for conduction block. Use of these techniques has shown that many of the amplitude and area criteria once considered diagnostic of motor conduction block in demyelinating lesions actually overlap with the amplitude and area drop that can be seen from a combination of temporal dispersion and phase cancellation alone, without conduction block.

In normal motor studies, temporal dispersion and phase cancellation generally do not lead to an appreciable drop in the proximal CMAP amplitude and area for the reasons discussed earlier. In demyelinating lesions, however, the conduction velocities may be very slow, and temporal dispersion and phase cancellation become more prominent for motor fibers. Using computer simulation models, CMAP *area* has been demonstrated to fall by 50%, and amplitude even farther, solely from the effects of temporal dispersion and phase cancellation in demyelinating lesions, without any conduction block (Figure 3–21). *Thus, the criteria of more than a 50% drop in area between proximal and distal stimulation sites should be used to define electrophysiologic conduction block. Of course, it is important to remember that both conduction block as well as abnormal temporal dispersion and phase cancellation signify acquired demyelination.*

In any patient with a peripheral nerve disorder, the presence of demyelination is a key finding for several reasons. In entrapment neuropathies, the exact localization of the lesion can be accomplished only by demonstrating focal

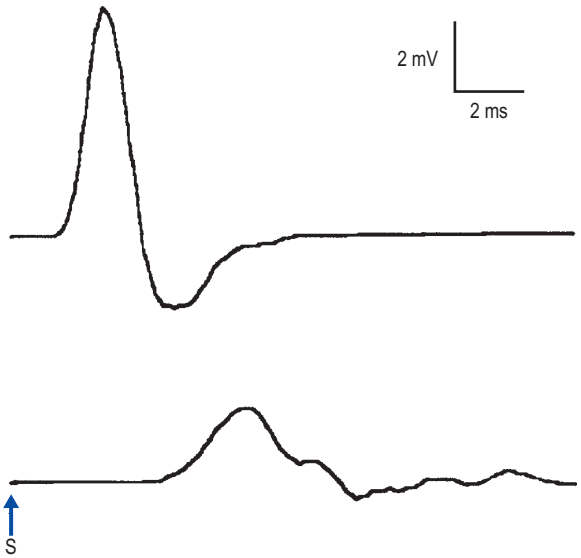

FIGURE 3–21 Temporal dispersion without conduction block. A marked drop in proximal compound muscle action potential (CMAP) amplitude usually means conduction block. In the figure above, there is no conduction block between distal and proximal stimulation sites. The drop in amplitude was entirely due to abnormal temporal dispersion from a demyelinating lesion. To differentiate conduction block from abnormal temporal dispersion requires a drop in area >50%, which is not seen here.
(From Rhee, E.K., England, J.D., Sumner, A.J., 1990. A computer simulation of conduction block: effects produced by actual block versus interphase cancellation. Ann Neurol 28, 146, with permission of Little, Brown and Company.)

Table 3–1. Radial Motor Studies Across the Spiral Groove

Patient No.	Radial CMAP (involved side)		Radial CMAP (contralateral side)	
	Below Spiral Groove (mV)	Above Spiral Grove (mV)	Below Spiral Groove (mV)	Above Spiral Grove (mV)
1	4	0.5	5	4.8
2	1	0.5	5	4.8

CMAP, compound muscle action potential.

demyelination, either by conduction velocity slowing or by conduction block across the lesion site. In addition, the relative degree of conduction block across a lesion site indicates how much weakness and sensory loss are due to demyelination rather than axonal loss. This factor has direct implications for prognosis and the time course of recovery. For example, contrast two patients (Table 3–1), each of whom has a severe wrist drop from a radial neuropathy across the spiral groove ("Saturday night palsy").

In both patients, there is a drop in amplitude across the spiral groove on the involved side. In patient 1, the distal CMAP amplitude (below the spiral groove) is slightly smaller than that on the contralateral, asymptomatic side. This comparison implies only a small amount of axonal loss (4 vs. 5 mV). However, there is a large drop in amplitude (4 vs. 0.5 mV) across the spiral groove, which implies that most of the patient's weakness is secondary to conduction block. Conduction block signifies demyelination; therefore, the prognosis is good. The patient will likely recover quickly over several weeks as remyelination occurs. Contrast this situation with that of patient 2, in whom there is a marked loss of CMAP amplitude below the spiral groove compared with the contralateral side (1 vs. 5 mV). This implies significant axonal loss. Although there is some conduction block across the spiral groove (1 vs. 0.5 mV), most of this patient's weakness is secondary to axonal loss, which implies a longer and possibly less complete recovery process.

Box 3–1. Demyelinating Neuropathies

Hereditary

- Charcot–Marie–Tooth, Type I (CMT1)†
- Charcot–Marie–Tooth, Type IV (CMT4)†
- Charcot–Marie–Tooth, X-linked (CMTX)†
- Dejerine–Sottas disease‡
- Refsum disease
- Hereditary neuropathy with liability to pressure palsy (HNPP)
- Metachromatic leukodystrophy
- Krabbe disease
- Adrenoleukodystrophy
- Cockayne syndrome
- Niemann–Pick disease
- Cerebrotendinous xanthomatosis
- Mitochondrial neurogastrointestinal encephalomyopathy (MNGIE)

Acquired

- Acute inflammatory demyelinating polyradiculoneuropathy (AIDP, the most common variant of Guillain–Barré syndrome)
- Chronic inflammatory demyelinating polyradiculoneuropathy (CIDP)
  - Idiopathic
  - Associated with human immunodeficiency virus (HIV) infection
  - Associated with MGUS (especially IgM)
  - Associated with anti-MAG antibodies
  - Associated with osteosclerotic myeloma
  - Associated with Waldenström macroglobulinemia
- Multifocal motor neuropathy with conduction block ($\pm GM_1$ antibodies)
- Diphtheria
- Toxic (i.e., amiodarone, perhexiline, arsenic, glue sniffing, buckthorn shrub poisoning)

Although the list of demyelinating neuropathies is short compared to the differential for axonal neuropathies, it usually can be quickly narrowed even further by clinical history, age of onset, and the presence or absence of systemic and central nervous system features. From a practical point of view, the differential diagnosis of a subacute/chronic demyelinating neuropathy in an adult is likely either an inherited neuropathy (CMT type I) or CIDP and one of its variants. MGUS, monoclonal gammopathy of undetermined significance; MAG, myelin associated glycoprotein.

†The nomenclature of demyelinating Charcot–Marie–Tooth inherited polyneuropathies is complex. Type 1 refers to autosomal dominant, Type 4 to autosomal recessive, and Type X to X-linked. Each type has several subtypes based on the specific genetic defect. Although the conduction velocities are in the demyelinating range, CMTX in males may have more intermediate conduction velocities (e.g., 25–38 m/s) than the more common CMT1 group. In female carriers of CMTX, conduction velocities are only slightly slow or in the normal range.

‡Dejerine–Sottas disease is a historical term used to denote a severe demyelinating neuropathy in children. Formerly considered a distinct entity with autosomal recessive inheritance, genetic analysis has demonstrated that Dejerine–Sottas is a syndrome caused by either recessive inheritance or *de novo* mutations with autosomal dominant inheritance. The recessive forms are now incorporated into the CMT4 group, but the de novo autosomal dominant mutations are on the same genes implicated for CMT1, but with the genetic defect resulting in a much more severe demyelinating neuropathy.

Finally, the presence of demyelination in a patient with polyneuropathy has special significance because very few polyneuropathies show primarily demyelinating features on NCSs (Box 3–1). In patients with demyelinating polyneuropathies, the presence of conduction block at non-entrapment sites often can be used to differentiate between acquired and inherited conditions. In patients with inherited demyelinating polyneuropathies (e.g., Charcot–Marie–Tooth polyneuropathy, Type I), there is uniform slowing of conduction velocity without the

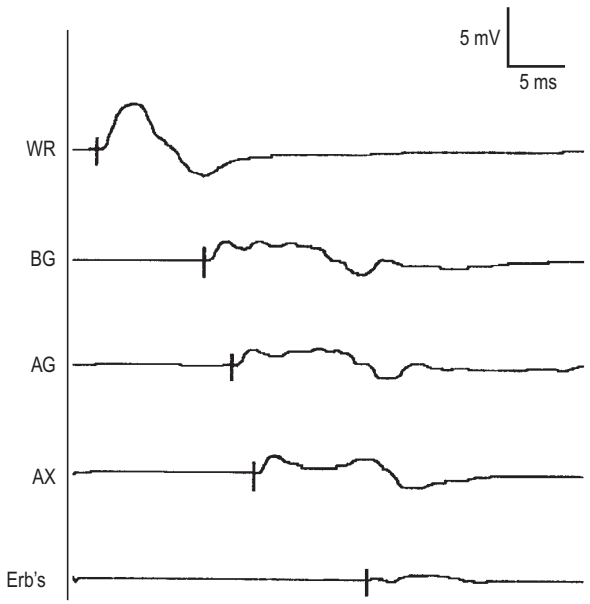

FIGURE 3–22 Conduction block and chronic inflammatory demyelinating polyneuropathy (CIDP). Ulnar motor study in a patient with CIDP, recording abductor digiti minimi, stimulating wrist (WR), below groove (BG), above groove (AG), axilla (AX), and Erb's point. Note the conduction block/temporal dispersion pattern between wrist and below elbow, and between axilla and Erb's point. Conduction block and abnormal temporal dispersion are markers of acquired demyelination. They do not occur in inherited demyelinating neuropathies, except in common areas of entrapment or compression.

presence of conduction blocks. This is in contrast to acquired demyelinating polyneuropathies (e.g., Guillain–Barré syndrome, chronic inflammatory demyelinating polyneuropathy), in which demyelination often is patchy and focal, resulting in conduction block on NCSs (Figure 3–22).

Myopathy

In myopathic disorders, sensory conduction studies are always normal unless there is a superimposed neuropathic condition. Because most myopathies primarily affect proximal muscles and most motor conduction studies record distal muscles, CMAP amplitudes and distal latencies are also generally normal. However, some rare myopathic disorders preferentially affect distal muscles, and in such situations CMAP amplitudes may be low. The same is true if the myopathy is severe and generalized (e.g., critical illness myopathy). Even in these situations, however, the distal latencies and conduction velocities will remain normal.

Neuromuscular Junction Disorders

As in myopathic disorders, sensory studies are normal in disorders of the NMJ. Abnormalities of the CMAP may be seen depending on whether the NMJ pathology is presynaptic or postsynaptic. In postsynaptic disorders (e.g., myasthenia gravis), the motor studies, including the CMAP amplitude, usually are completely normal. However, the situation is different in presynaptic disorders (e.g., Lambert–Eaton myasthenic syndrome, botulism). In these conditions, CMAP amplitudes usually are low at rest, with normal latencies and conduction velocities. To demonstrate a disorder of NMJ transmission, repetitive nerve stimulation, exercise testing, or both need to be performed (see Chapter 6).

Suggested Readings

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4 Late Responses

Nerve conduction studies are most often used to assess distal nerve segments, with routine stimulation seldom done above the elbow or knee. Few studies can be easily performed to assess the more proximal nerve segments (plexus and roots). In the arm, surface stimulation can be performed proximally in the axilla and at Erb's point, although technical factors limit these studies, especially at Erb's point. Needle stimulation or high-voltage stimulators, both of which have technical limitations, often are needed to study proximal nerve segments at the root level. In the electromyography (EMG) laboratory, two late responses, the F response and the H reflex, are used routinely to study the more proximal nerve segments. Each has its advantages and limitations (Table 4–1). Although both are usually

Table 4–1. Late Responses: F Response and H Reflex

	F Response	H Reflex
Afferent	Motor	Sensory (Ia muscle spindle)
Efferent	Motor	Motor
Synapse	No	Yes
Nerves studied	All	Tibial–soleus (median-FCR, femoral-quads)
Stimulation	Supramaximal	Submaximal, long duration pulse (1 ms)
Configuration	Usually polyphasic Amplitude 1–5% CMAP Varies with each simulation	Triphasic and stable At low stimulation intensity, H is present without M As stimulation is increased, H and M increase At high stimulation, H decreases and M increases
Measurements	Minimal latency Chronodispersion Persistence	Minimal latency H/M ratio (maximal H/maximal M amplitude)
Major uses	Early Guillain–Barré syndrome C8–T1, L5–S1 radiculopathy Polyneuropathy Internal control (entrapment neuropathy)	Early polyneuropathy S1 radiculopathy Early Guillain–Barré syndrome Tibial and sciatic neuropathy, sacral plexopathy
Normal values	≤32 ms median/ulnar* ≤56 ms peroneal/tibial* Compare to F estimate Compare symptomatic to asymptomatic side Chronodispersion <4 ms (median/ulnar) <6 ms (peroneal/tibial) Persistence >50%	≤34 ms* Leg length nomogram Height nomogram ≤1.5 ms difference side to side H/M ratio ≤50%
Miscellaneous	In normals, peroneal F waves may be absent or impersistent F responses may be absent in sleeping or sedated patients F responses may be absent with low-amplitude distal CMAPs May be enhanced by Jendrassik maneuver	Electrical correlate of the ankle jerk Must be present if ankle jerk is present May be present even if ankle jerk is absent May be enhanced by Jendrassik maneuver

CMAP, compound muscle action potential. FCR, flexor carpi radialis.
*Assumes median height, normal conduction velocity and distal latency.

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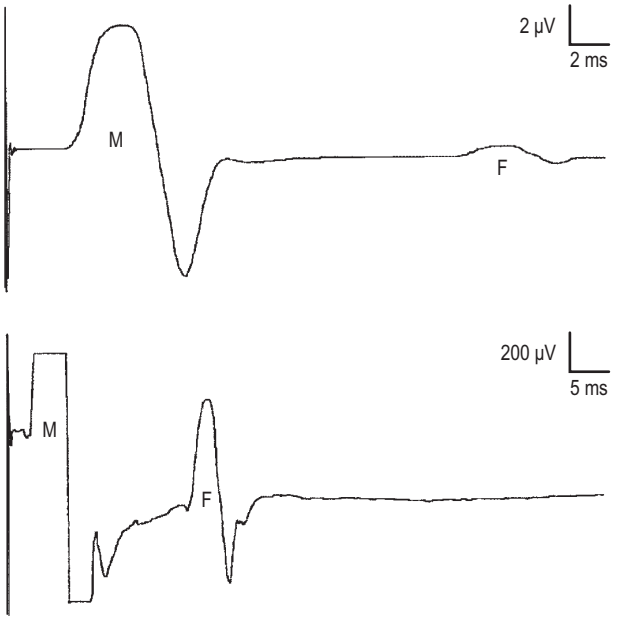

FIGURE 4–1 Normal F response. Stimulating the median nerve at the wrist, recording abductor pollicis brevis. F, F response; M, direct motor response (i.e., compound muscle action potential). Note that to accurately measure the F response, the gain must be increased to 200 µV and the sweep to either 5 or 10 ms **(bottom trace).** With these settings, the F response is well seen, but the M response saturates the amplifier and becomes distorted.

thought of as assessing only the proximal nerve segments, in reality they travel the entire nerve segment from distal to proximal and back. Thus, they are most useful when routine nerve conduction studies, which assess distal segments, are normal and the late responses are abnormal, a situation that implies a proximal lesion.

F RESPONSE

The F response is a late motor response that occurs after the compound muscle action potential (CMAP, also known as the direct motor [M] potential) (Figure 4–1). The F response derives its name from the word "foot" because it was first recorded from the intrinsic foot muscles. In the upper extremity, when the median or ulnar nerves are stimulated at the wrist, the F response usually occurs at a latency of 25 to 32 ms. In the lower extremity, when the peroneal or tibial nerves are stimulated at the ankle, the F response usually occurs at a latency of 45 to 56 ms. If the stimulator is moved proximally, the latency of the CMAP increases as expected, but the latency of the F response actually decreases (Figure 4–2). This is due to the circuitry of the F response, which is initially antidromic toward the spinal cord. Thus, with more proximal stimulation, the action potential has less distance to travel, hence the shorter latency. During a routine motor nerve conduction study, one usually thinks of the action potential as traveling down the nerve across the neuromuscular junction (NMJ) to subsequently depolarize the muscle. When stimulated,

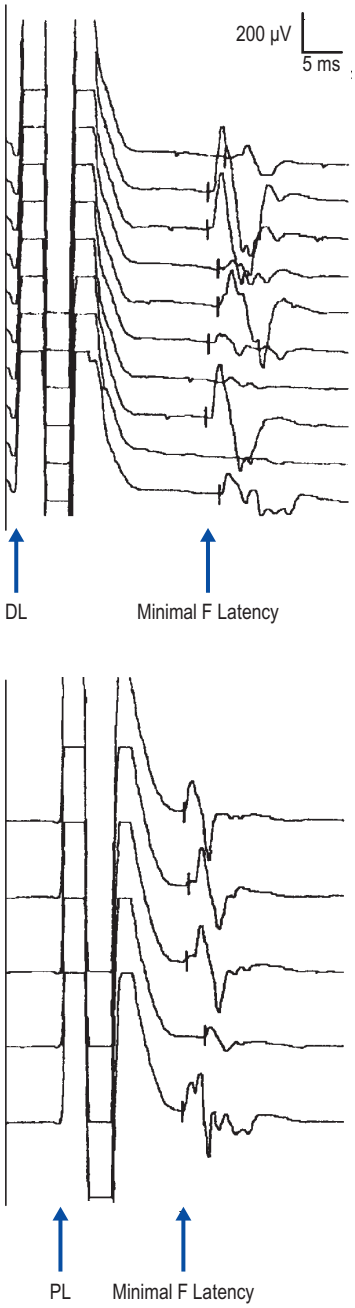

FIGURE 4–2 Normal F responses, distal and proximal stimulation. Median F responses recording abductor pollicis brevis, stimulating wrist **(top trace)** and elbow **(bottom trace).** DL, distal compound muscle action potential (CMAP) latency; PL, proximal CMAP latency. Note with proximal stimulation, the proximal CMAP latencies increase as expected, but the F response latencies decrease, due to the F response traveling a shorter distance antidromically to the spinal cord.

however, the nerve conducts well in both directions. The F response is derived by antidromic travel up the nerve to the anterior horn cell, with backfiring of a small population of anterior horn cells, resulting in orthodromic travel back down the nerve past the stimulation site to the muscle (Figure 4–3). The F response is actually a small CMAP, representing 1 to 5% of the muscle fibers. The F response

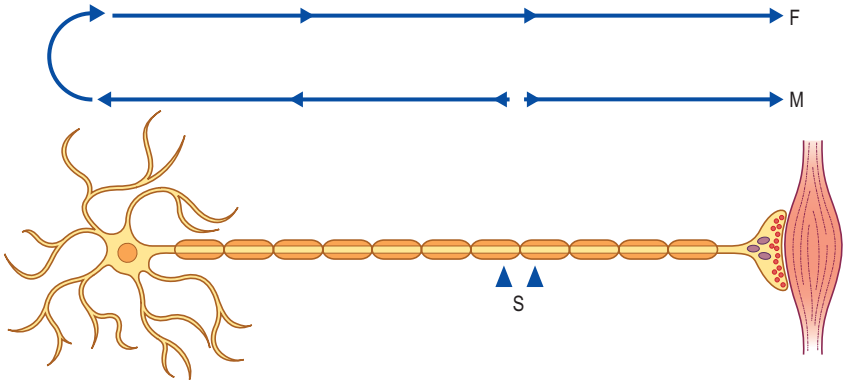

FIGURE 4–3 F response circuitry. When a nerve is stimulated distally (S), depolarization occurs both orthodromically and antidromically. The direct muscle response (M) occurs from orthodromic travel. The F response (F) is derived from antidromic travel to the anterior horn cell, backfiring of some anterior horn cells, and orthodromic travel back down the nerve past the stimulation site to the muscle.

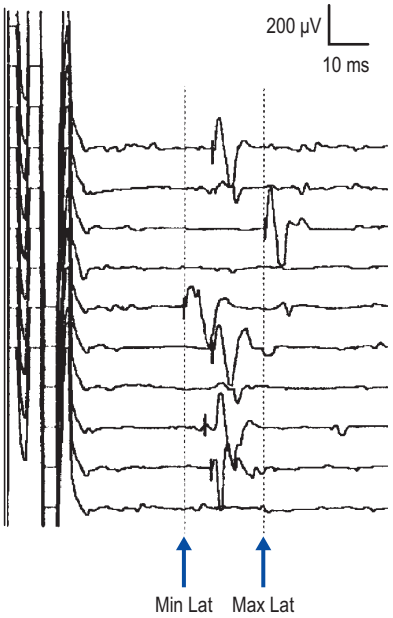

FIGURE 4–4 F response measurements. F responses, ten rastered traces. Minimal latency is the shortest (fastest) of the ten responses, representing the largest, fastest conducting fibers. Chronodispersion is the difference between the minimal and maximal latency F response. F wave persistence is the number of F responses obtained per number of stimulations. In this case, F responses are absent in traces 4 and 10; persistence=80%.

circuitry, both afferent and efferent, is therefore pure motor. There is no synapse, so it is not a true reflex. In conditions that selectively affect the sensory nerves or sensory nerve roots, the F responses are completely normal.

Each F response varies slightly in latency, configuration, and amplitude because a different population of anterior horn cells is activated with each stimulation. Presumably, the shortest latency represents the largest and fastest conducting motor fibers. Several measurements can be made on the F responses, with the most common being the minimal (or fastest) F response latency (Figure 4–4). F wave persistence is a measure of the number of F waves obtained per the number of stimulations. Normal F wave persistence is between 80 and 100%, and always above 50% with the exception of the peroneal F responses (see below). F wave chronodispersion is a measure of the difference between the minimal (fastest) and maximal (slowest) F response latency. Normal chronodispersion is up to 4 ms in the upper extremities and up to 6 ms in the lower extremities. F responses can be obtained from any motor nerve. The only notable exception to this is the peroneal nerve, wherein F responses may be difficult to elicit even in normal subjects. Note also that F responses may be absent or impersistent in all nerves in sleeping or sedated patients. In these situations, absent or impersistent F responses are not necessarily a sign of pathology. F responses are best obtained with distal stimulation. With proximal stimulation, they often are superimposed on the terminal CMAP and may be more difficult to identify.

F Response Procedure

To obtain an F response, the setup is essentially the same as that for a routine motor conduction study using distal stimulation. Several adjustments must be made to the EMG machine to record F responses, however. The gain should be increased to 200 µV (because the amplitude of the F response is quite low), and the sweep speed should be increased to 5 or 10 ms, depending on the length of the nerve being studied. Supramaximal stimulation must always be used, and the stimulator should be turned around so that the cathode is more proximal (Figure 4–5). Although F responses typically can be obtained with the stimulator in the standard position (cathode distal), there is the theoretical possibility of anodal block (wherein the nerve hyperpolarizes under the anode, blocking antidromic travel of the action potential from the depolarization site under the cathode). One should stimulate at a rate no faster than once every two seconds (0.5 Hz). This is done in order to avoid the effects of the previous stimulus on a subsequent response. In addition, stimulating at this rate is much more comfortable for the patient and avoids the "temporal summation of pain" that occurs when the stimulation frequency

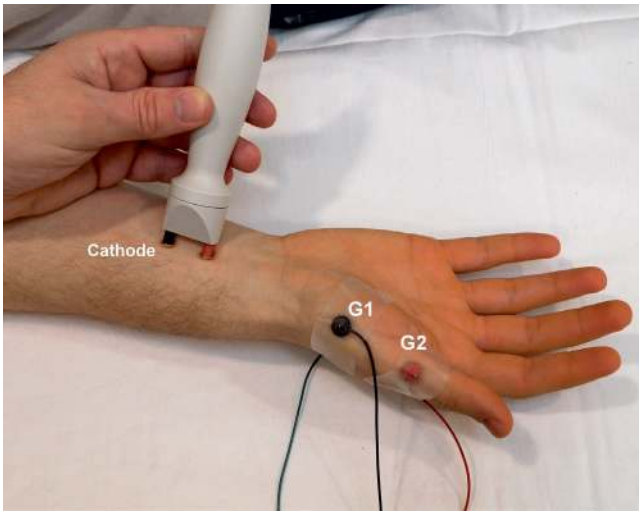

FIGURE 4–5 F response setup. Setup for median nerve shown. Recording electrodes are placed as in routine motor studies. The nerve is stimulated supramaximally distally with the cathode placed proximally to avoid the theoretic possibility of anodal block.

is too fast (i.e., the patient is stimulated again before recovering from the discomfort of the previous one).

Because each F response varies in latency and amplitude, it is important to obtain at least ten F responses, preferably on a rastered trace. Indeed, the normal values of F waves are based on doing at least ten stimulations. If one is unable to obtain an F response, first ensure that the nerve has been stimulated supramaximally. Second, the Jendrassik (reinforcement) maneuver can be of help in "priming" the anterior horn cells. The patient can be asked to make a fist with the contralateral hand or clench the teeth prior to each stimulation. This maneuver often will elicit an F response where one was not present at rest. It should be noted that one should not do the Jendrassik maneuver unless the F responses are difficult to elicit. Paradoxically, performing a Jendrassik maneuver when not necessary can actually decrease the likelihood of obtaining F responses.*

Of the various F response measurements (minimal latency, chronodispersion [maximal minus minimal F response latency], and F wave persistence [Figure 4–6]), the minimal F wave latency is the most reliable and useful measurement, although occasionally side-to-side differences in F wave persistence and chronodispersion help in identifying an abnormality. Unfortunately, because F responses are quite small, there is often some inherent error in placing the latency markers. It is best to place the latency marker on the F response at the point where it departs from the baseline, with either a positive or negative deflection. In addition, superimposing the rastered traces once all the responses are obtained is often helpful in determining the minimal latency.

It is important to emphasize that although F responses usually are thought of as assessing the proximal nerve segments, they actually check the entire nerve. For example,

*Action potentials generated from the anterior horn cell normally originate near the axon hillock (the area where the axon meets the anterior horn cell). Both inhibitory and excitatory postsynaptic potentials are summed together at the axon hillock. If threshold is reached, an action potential is generated that normally runs down the length of the axon. The Jendrassik maneuver is thought to enhance motor neuron excitability (i.e., it results in excitatory postsynaptic potentials). For the F response to occur, the depolarization must travel antidromically into the axon hillock and motor neuron, and then travel out of the dendritic tree to return to "backfire" the axon hillock a second time. If the axon hillock and motor neuron are at a very high level of excitability (i.e., from the Jendrassik maneuver), then it is possible that the motor neuron depolarization will occur so rapidly that when the depolarization returns to "backfire" the axonal hillock it may still be refractory and unable to initiate another discharge. Thus, if the motor neuron is not close to threshold, a Jendrassik maneuver will be helpful in priming the motor neuron to facilitate the generation of an F response; however, if the motor neuron is too primed, it can actually inhibit the generation of the F response.

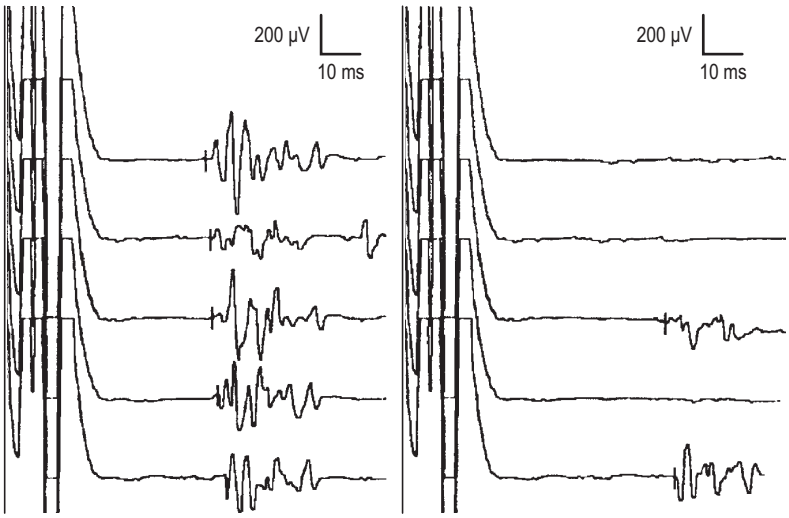

FIGURE 4–6 F response abnormalities. Tibial F responses, five rastered traces. **Left:** Right leg. **Right:** Left leg. The minimal F response is prolonged in the left leg, and the responses are impersistent, consistent with a proximal lesion (e.g., S1 radiculopathy).

any nerve with a prolonged distal motor latency on routine nerve conduction studies will also have prolonged F responses, because the F response must travel through the distal segment of nerve as well as the proximal segment. This situation is commonly seen in patients with median neuropathy at the wrist, wherein the median minimal F latency is often prolonged; in this situation, the depolarization travels antidromically from the stimulation site at the wrist up the nerve to the anterior horn cell, and then back down the nerve to the point of stimulation. However, once the depolarization proceeds past the point of stimulation, through the area of slowing at the wrist, this results in prolongation of the F response. Likewise, if there is generalized conduction velocity slowing from a polyneuropathy, the F response will also be slowed, reflecting the slowed conduction velocity of the entire nerve. The F response latency is shorter in the arms than in the legs, reflecting the shorter length of nerve traveled. Therefore, it should be no surprise that taller patients have longer F responses than do shorter patients. Thus, the distal motor latency, the conduction velocity, and the height of the patient must all be taken into account before a prolonged F response is interpreted as indicating a proximal nerve lesion.

The F Estimate

One of the more useful calculations to perform is that of the F estimate. The F estimate takes into account the distal motor latency, the conduction velocity, and the patient's limb length in determining whether a prolonged F response is truly due to a lesion of the proximal nerve segment, or merely reflects an abnormal distal motor latency or conduction velocity or an unusually tall patient. The F estimate is calculated by determining the theoretical time it should take for the F response to occur, taking into account all of these variables (Figure 4–7). First, one must calculate the time it takes for the F response to go from the stimulation site to the anterior horn cells in the spinal cord, by dividing the distance between those sites by the motor nerve conduction velocity. Second, there is a brief turnaround time at the anterior horn cell, which has been estimated experimentally to be approximately 1 ms. Third, the time it takes the F response to travel back down the nerve from the anterior horn cell to the distal stimulation site is the same as the time it takes to travel up the nerve. Finally, the time it takes the F response to travel from the stimulation site to the muscle is the distal motor latency. Therefore, if one knows the motor nerve conduction velocity and the distal motor latency (from the routine motor conduction study), one can measure the distance between the stimulation site and spinal cord to calculate the F estimate. The distance between the stimulation site and the spinal cord can be approximated by measuring from the xiphoid process to the ankle stimulation site for the peroneal and tibial studies, and from the C7 spinous process to the wrist stimulation site for the median and ulnar studies.

$$\text{F estimate} = (2D/CV) \times 10 + 1\,\text{ms} + DL$$

where D is the distance from the stimulation site to the spinal cord (cm), CV is the conduction velocity (m/s), DL is the distal motor latency (ms), and 10 is the conversion factor to milliseconds. The turnaround time of 1 ms at the anterior horn cell is added to the equation. The actual measured minimal F wave latency is usually slightly shorter than the F estimate. This is because the conduction velocity used in the equation is measured from the distal nerve segment (forearm or leg), which is then used to estimate the entire conduction velocity up to the anterior horn cell. However, the conduction velocity in more proximal segments of nerve tends to be slightly faster, due to a combination of larger nerve fiber diameter and warmer temperature in the proximal nerve segments. Therefore, if the measured minimal F response is prolonged compared

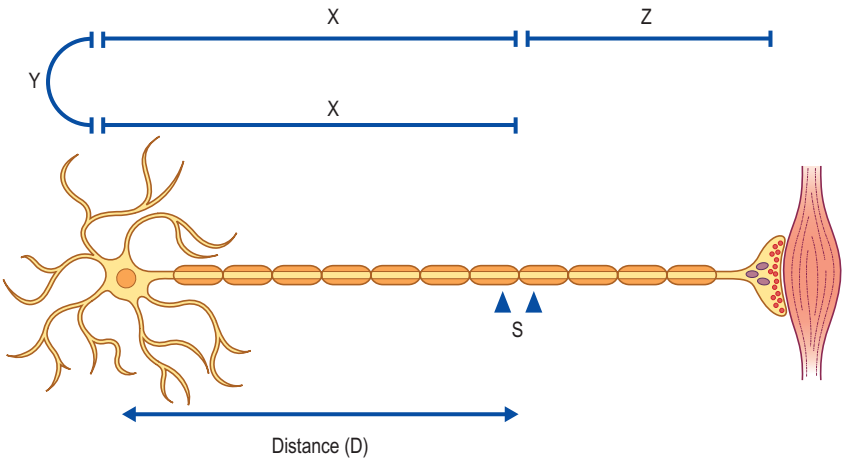

FIGURE 4–7 F estimate calculation. *X* is the time from the stimulation site (S) to the spinal cord; *Y* is the turnaround time at the anterior horn cell; *Z* is the time from the stimulation site to the muscle. Theoretical F estimate=2*X*+*Y*+*Z*. *X* can be calculated by measuring the distance between the stimulation site and the spinal cord (*D*), which then is divided by the conduction velocity of the nerve. *Z* is the distal latency. The turnaround time, *Y*, has been estimated experimentally as 1 ms. Thus, the F estimate=(2*D*/*CV*)×10+1 ms+*DL* (a conversion factor of 10 is needed to obtain an answer in milliseconds).

to the F estimate, this implies a delay in the proximal nerve segments out of proportion to what would be expected for the distal motor latency, the motor conduction velocity, and the limb length of the patient.

Unfortunately, the usefulness of F responses is quite limited, because of their lack of specificity in determining the site or cause of a lesion. They do, however, serve a useful purpose in testing the entire nerve circuit, and can be used as a good internal control for other nerve conduction abnormalities. For instance, in most polyneuropathies, the F responses are expected to be slightly prolonged. In distal entrapment neuropathies, such as carpal tunnel syndrome, the F responses typically are prolonged. F responses have their greatest usefulness in identifying early polyradiculopathy such as occurs in Guillain–Barré syndrome. Guillain–Barré syndrome, which is an acquired demyelinating polyradiculoneuropathy, commonly begins with demyelination of the nerve roots. Early in Guillain–Barré syndrome, the routine motor nerve conduction studies may be entirely normal, with prolonged or absent F responses, a pattern that implies proximal demyelination. It is also important to remember that F responses are generally not seen in nerves where the CMAP amplitude is severely reduced. Because the F response is 1 to 5% of the amplitude of the CMAP, F responses often are unobtainable or very low in amplitude and difficult to measure, if the CMAP amplitudes are severely reduced. For instance, if the tibial F responses are absent in a patient whose CMAP amplitude is only 200 μV, this does not imply a proximal lesion but rather reflects the low chance of eliciting an F response from a nerve with such severe axonal loss. One should not try to obtain F responses in a motor nerve with an absent CMAP, and one can make a strong argument against even trying to obtain them in a motor nerve if the CMAP amplitude is very low, as an absent F response in this setting does not have significance.

One would assume that F responses should have their greatest usefulness in the diagnosis of radiculopathy or plexopathy. Unfortunately, from a practical point of view, their usefulness in the diagnosis of these disorders is limited. First, F responses can only check the nerve or nerve roots that innervate the muscle being recorded. In the upper extremity, where the median and ulnar nerves typically are recorded, their distal muscles (i.e., abductor pollicis brevis, abductor digiti minimi) are innervated by the C8 and T1 nerve roots. Radiculopathy from a herniated disk or spondylosis only rarely affects those nerve roots, compared with the more commonly affected C5, C6, and C7 nerve roots. A lesion of the C5, C6, or C7 nerve root would not be expected to show any F wave abnormality recording the distal median and ulnar muscles. Thus, F responses have potential usefulness only in assessing possible C8–T1 radiculopathies in the upper extremity and L5–S1 radiculopathies in the lower extremity (distal recorded peroneal and tibial muscles are L5–S1 innervated).

Second, if a radiculopathy predominantly affects sensory nerve root fibers (as often occurs with initial symptoms of pain and radiating paresthesias), the F response, which measures motor fibers, will be normal. Third, if a small segment of the nerve is demyelinated, this likely will be diluted out in the F response latency, which includes the entire length of the nerve, most of which is conducting at a normal velocity. Finally, for the F responses to be completely absent or for the minimal latency to be delayed, all or at least most of the motor nerve fibers must be involved. However, this is rarely the case in radiculopathy or plexopathy, unless the lesion is markedly severe. For instance, if half of the nerve fibers are affected, a normal minimal F wave latency may still be recorded, reflecting the remaining unaffected fibers, unless all of the fastest conducting fibers have been affected. In addition, because all muscles are supplied by at least two, if not three, myotomes, fibers from the uninvolved myotomes are still available to conduct a normal F response. For example, in a severe C8 radiculopathy, the median and ulnar F waves would still be normal because both the abductor pollicis brevis (median innervated) and abductor digiti minimi (ulnar innervated) are innervated by both C8 and T1 nerve roots, allowing T1 fibers to conduct normal F responses.

As in most other nerve conduction studies, comparison of the symptomatic to the asymptomatic side often is helpful when evaluating F responses. Finally, it is important to reemphasize that if the distal nerve conductions are normal, a prolonged F response may occur in proximal neuropathy, plexopathy, or radiculopathy, and the finding cannot be used to differentiate among those possibilities.

H REFLEX

The H reflex derives its name from Paul Hoffmann, who first evoked the response in 1918. The H response is distinctly different from the F response in that it is a true reflex with a sensory afferent, a synapse, and a motor efferent segment. Likewise, several other properties differentiate the H and F responses (Table 4–1). Unlike the F response that can be elicited from all motor nerves, the distribution of the H reflex is much more limited. In newborns, H reflexes are widely present in motor nerves, but beyond the age of two, they can only be routinely elicited by stimulating the tibial nerve in the popliteal fossa and recording the gastroc–soleus muscle. Although there are techniques for obtaining an H reflex from the femoral nerve recording the quadriceps muscle and from the median nerve recording the flexor carpi radialis muscle, both of these have significant limitations.

The circuitry of the H reflex involves the Ia muscle spindles as sensory afferents and the alpha motor neurons and their axons as efferents (Figure 4–8). If a low submaximal stimulus with a long duration pulse is applied to a nerve, it is possible to relatively selectively activate the Ia fibers. Several adjustments must be made to the EMG machine to record an H reflex, similar to those made for the F response. The gain must be increased initially to 200 to 500 μV. The typical H reflex latency is approximately 30 ms, so the sweep speed must be increased to 10 ms.

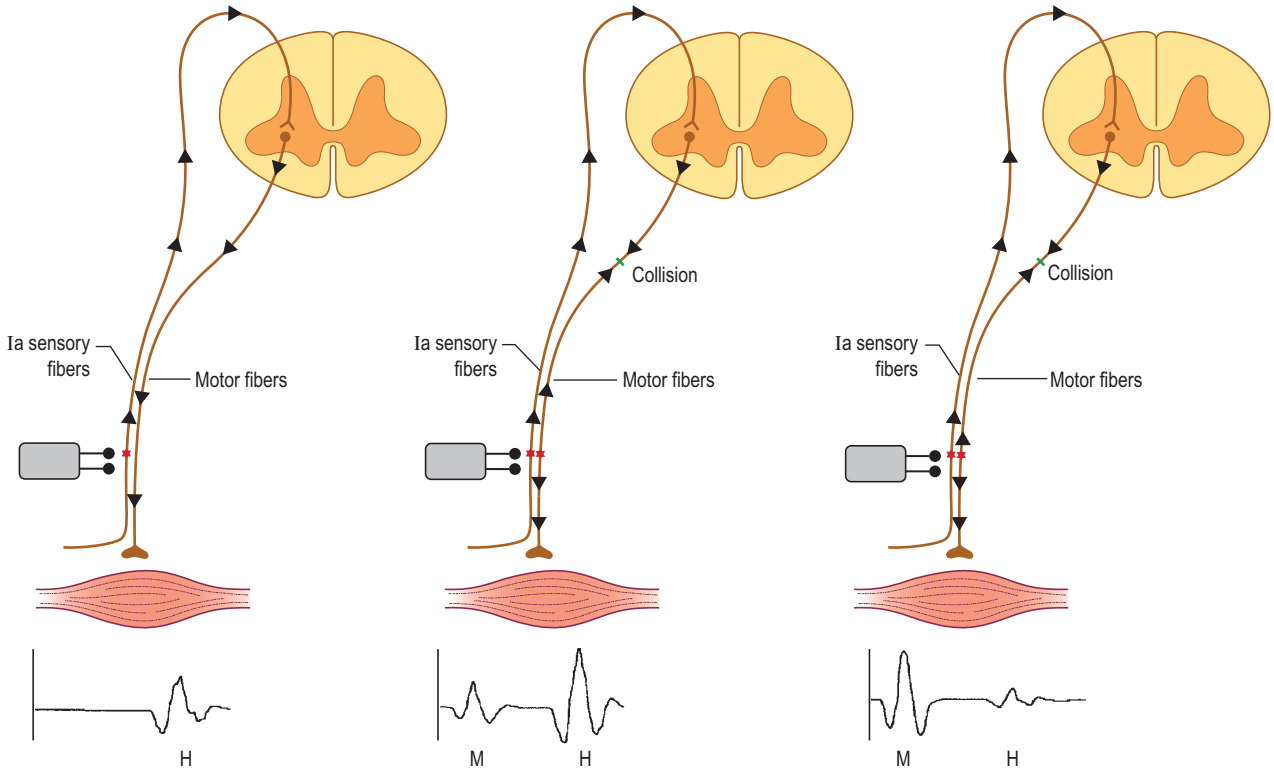

FIGURE 4–8 H reflex circuitry. The afferent loop is formed from Ia sensory fibers and the efferent loop from motor axons, with an intervening synapse in the spinal cord. At low stimulation intensity **(left),** the Ia sensory fibers are selectively activated, yielding an H reflex without a direct motor (M) potential. With increasing stimulation **(middle),** more Ia sensory fibers are activated, as are some of the motor fibers. The motor fiber stimulation results in a small M potential and some collision proximally of the descending H reflex by the antidromic motor volley. At higher stimulation **(right),** the selective activation of the Ia sensory fibers is lost. Both sensory and motor fibers are stimulated at high levels. The higher motor stimulation results in an increasingly larger M potential. However, the H reflex decreases in size as there is greater collision proximally of the descending H reflex from the antidromic motor volley.

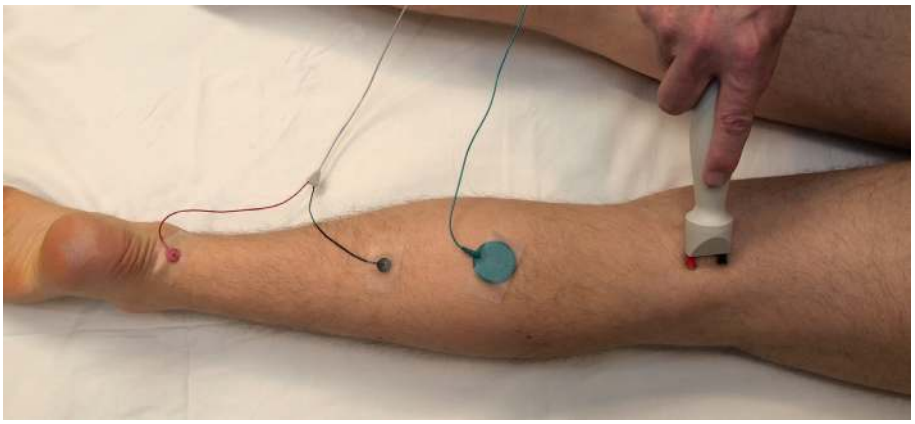

FIGURE 4–9 H reflex setup. To record the H reflex, G1 is placed over the soleus, two to three fingerbreadths distal to where it meets the two bellies of the gastrocnemius muscle, with G2 over the Achilles tendon. The tibial nerve is stimulated submaximally in the popliteal fossa, with the cathode placed proximal to the anode.

Most important, the stimulus duration must be increased to 1 ms in order to selectively stimulate the Ia fibers. The recording montage consists of G1 placed over the soleus and G2, the reference electrode, placed over the Achilles tendon (Figure 4–9). Although the H reflex can be recorded over any portion of the gastrocnemius and soleus muscles, the optimal location that yields the largest H reflex has been studied. If one draws a line from the popliteal fossa posteriorly to the Achilles tendon where the medial malleolus flares out and then divides that line into eight equal parts, the optimal location is at the fifth or sixth segment distally, over the soleus (Figure 4–10). This location is approximately two to three fingerbreadths distal to where the soleus meets the two bellies of the gastrocnemius. The

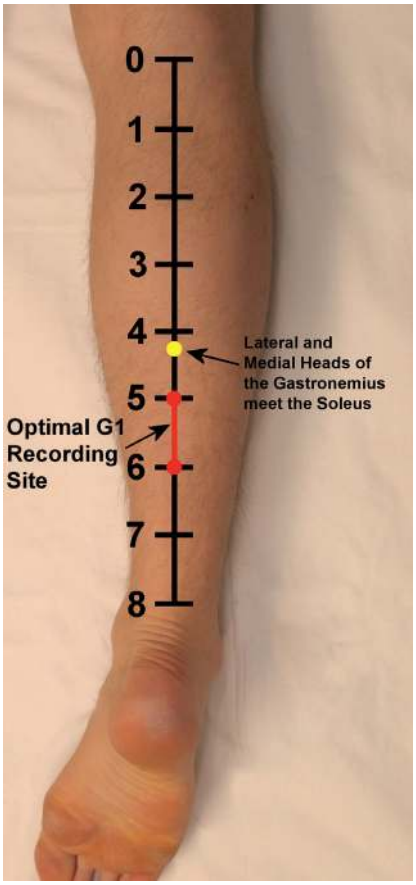

FIGURE 4–10 Optimal recording location for the H reflex. If one draws a line from the popliteal fossa posteriorly to the Achilles tendon where the medial malleolus flares out and then divides that line into eight equal parts, the optimal location for placing the active recording electrode (G1) is at the fifth or sixth segment distally. This location over the soleus is approximately two to three fingerbreadths distal to where the soleus meets the two bellies of the gastrocnemius.

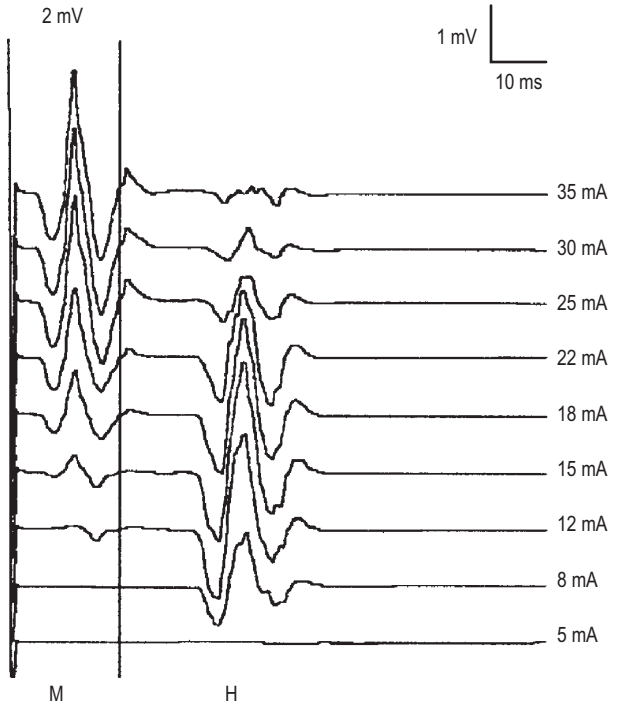

FIGURE 4–11 H reflex. Note at low stimulation intensities, an H reflex is present without a direct motor (M) response. With increasing stimulation, the H wave grows and the M response appears. At higher stimulation, the M potential continues to grow and the H reflex diminishes, due to collision between the H reflex and antidromic motor potentials.

tibial nerve is stimulated in the popliteal fossa, with the cathode placed proximally and beginning at very low stimulus intensities. One should stimulate at a rate no faster than once every 2 seconds (0.5 Hz) in order to avoid the effects of a previous stimulus on a subsequent response. As the current is slowly increased, an H reflex (which usually is triphasic) first appears at a latency of 25 to 34 ms. H reflexes are routinely recorded with the muscle at rest. If an H reflex cannot be elicited, having the patient slightly plantar flex the ankle can be used to enhance the H reflex. If that is not helpful, the Jendrassik maneuver, as described earlier for the F response, can be used to prime the anterior horn cells. As the stimulus intensity is slowly increased, the H reflex continues to increase in amplitude and decrease in latency. As the stimulus intensity is increased further, a direct motor (M) potential appears along with the H reflex. As the stimulus intensity is increased still further, the M potential grows in size and the H reflex decreases in size.

Obtaining the H reflexes on a rastered trace, which can be superimposed once all the responses are obtained, may be helpful in determining the minimal latency, which is generally also associated with the largest amplitude. It is best to place the latency marker on the H reflex at the point where it departs from the baseline, which most often is a positive (i.e., downward) deflection. At supramaximal stimulation, the H reflex disappears, and the M potential is seen followed by an F response, which has now replaced the H reflex. The explanation for these events is as follows. Initially, with very low stimulation, the H reflex appears without the M potential (Figure 4–11) because only the Ia afferents are selectively stimulated at low stimulus intensities. As the Ia afferents are stimulated, the sensory action potential travels orthodromically to the spinal cord, across the synapse, creating a motor potential that travels orthodromically down the motor nerve to the muscle, in turn creating the H reflex. The motor axons have not been directly stimulated at this point; therefore, there is no M potential. As the stimulus intensity is increased, both the Ia afferents and the motor axons are directly stimulated. At this point, the orthodromically traveling motor action potentials create the M potential, but the motor action potentials also travel antidromically toward the spinal cord (Figure 4–8). These antidromically traveling potentials collide with the orthodromically traveling H reflex potentials, resulting in a decrease in the size of the H reflex. At supramaximal stimulation, both the Ia afferents and the motor axons are stimulated at high levels, and there is greater collision proximally of the descending H reflex. The H reflex then disappears, often replaced by the F response, and the M potential increases in size.

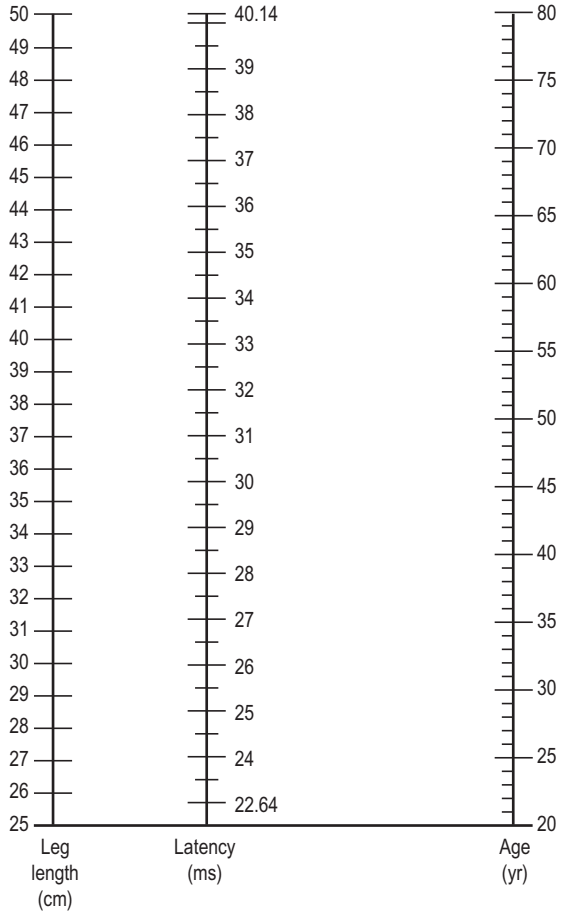

FIGURE 4–12 H latency reference values. Normal H latencies are based on leg length and age. Leg length is measured between the stimulation site in the popliteal fossa and the medial malleolus.
(Reprinted with permission from Braddom, R.I., Johnson, E.W., 1974. Standardization of the H-reflex and diagnostic use in S1 radiculopathy. Arch Phys Med Rehabil 55, 161.)

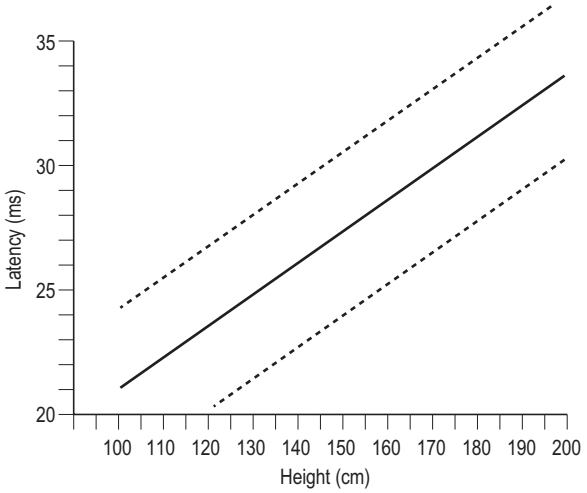

FIGURE 4–13 H latency reference values. Normal H reflex latencies are based on height.
(From Lachman, T., Shahani, B.T., Young, R.R., 1980. Late responses as aids to diagnosis in peripheral neuropathy. J Neurol Neurosurg Psychiatry 43, 56, courtesy of the BMJ Publishing Group.)

Typically the H reflex with the shortest latency is measured and compared with a set of normal controls for height (Figures 4–12 and 4–13). Comparison with the contralateral side is more useful in assessing a unilateral lesion; any difference of more than 1.5 ms is considered significant. Of course, both H reflexes must be acquired using the same distance for the stimulating and recording electrodes, in order for a side-to-side difference to be considered significant. In addition, the maximal amplitude of the H response (often measured peak to peak) can be compared with the maximal amplitude of the M potential (measured peak to peak) to calculate an H/M ratio (Table 4–1), see below.

The H reflex can be useful in a couple of situations. First, the response is the electrical correlate of the S1 tendon ankle reflex. If the ankle reflex is present clinically, an H reflex should always be present. If the ankle reflex is absent, however, an H reflex may still be present in some cases. Any lesion that might decrease the ankle reflex might also prolong the H reflex. Thus, one may see a prolonged H reflex in polyneuropathy, proximal tibial and sciatic neuropathy, lumbosacral plexopathy, and lesions of the S1 nerve root. One should keep in mind that bilaterally absent H reflexes in the elderly are not necessarily abnormal, and correlate with the common clinical finding of absent ankle reflexes in a significant number of elderly patients. In addition, the H/M ratio is a crude assessment of anterior horn cell excitability. The H/M ratio often increases in upper motor neuron lesions. Likewise, the presence of H reflexes in other muscles in an adult should suggest a central disorder.

AXON REFLEX

The axon reflex (A wave), although not a true reflex, is another late potential that often is recognized during the recording of F responses. The axon reflex typically occurs between the F response and the direct motor (M) response (Figure 4–14). An axon reflex is identified as a small motor potential that is identical in latency and configuration with each successive stimulation. This is in contrast to the F response, which varies slightly in latency and configuration from stimulation to stimulation. It often is useful to acquire these potentials on a rastered trace, which can be superimposed. Axon reflexes, unlike F responses, superimpose perfectly on one another. Axon reflexes typically are seen in reinnervated nerves, especially when a submaximal stimulus is given.

An axon normally divides into its terminal divisions very close to the muscle, which usually is distal to the common distal stimulation sites for most nerves studied in the EMG laboratory. In reinnervated nerves, however, terminal branching points from collateral sprouting may occur proximal to the distal stimulation site. It is in this latter situation, with submaximal stimulation, that an axon reflex may occur. As a nerve is stimulated, the action potential travels both distally and proximally. If the proximally

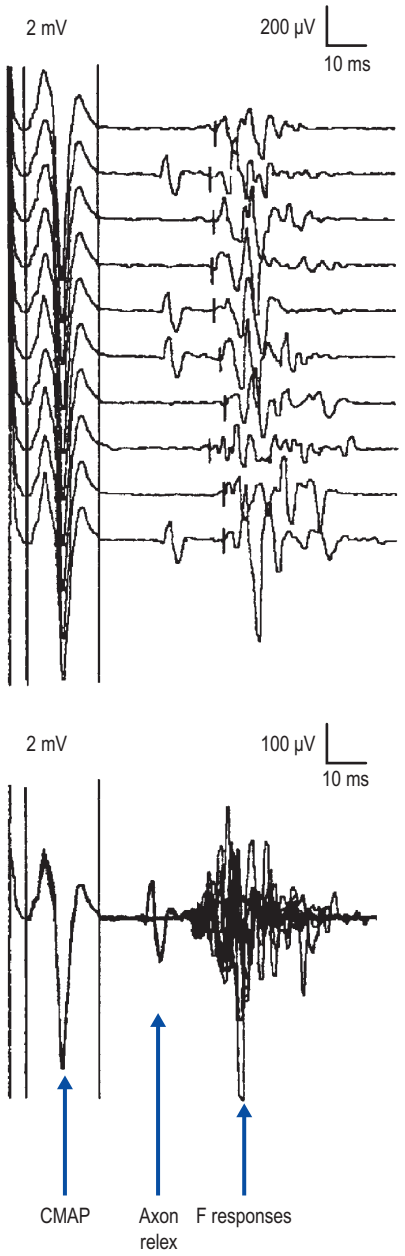

FIGURE 4–14 Axon reflex. Tibial F responses, ten rastered traces. Note that in traces 2, 5, 6, and 10, there is an additional potential, the axon reflex, that occurs between the compound action potential and the F response **(top).** When superimposed **(bottom),** the axon reflexes superimpose perfectly, in contrast to the F waves, which differ in configuration and latency in each trace.

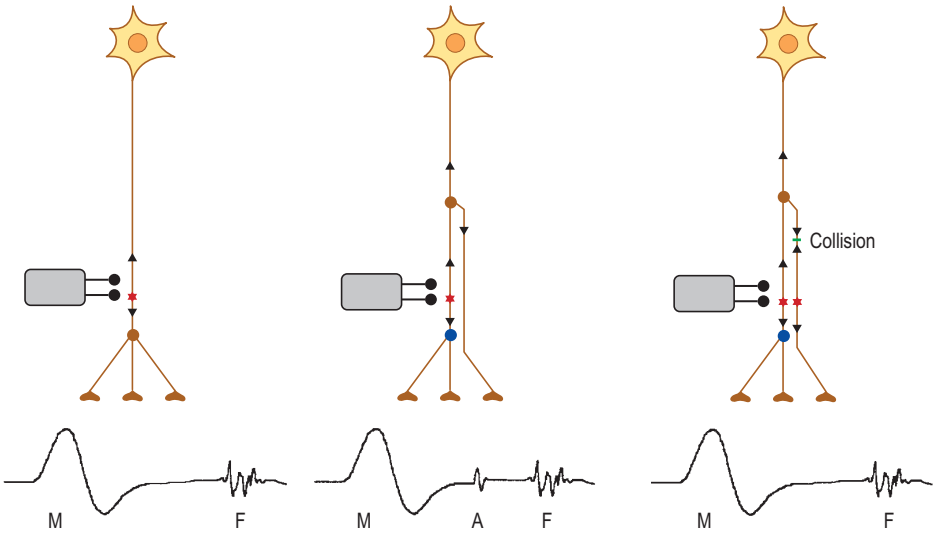

FIGURE 4–15 Axon reflex circuit. **Left:** Normally, the axon divides into its terminal divisions close to the muscle. When stimulation occurs distally, orthodromic travel results in a direct motor (M) potential, while antidromic travel results in an F response as usual. **Middle:** Following denervation, collateral sprouts may grow from the more proximal axon to reinnervate denervated muscle fibers. The antidromic pulse may pass a collateral branching point to a nerve fiber and travel orthodromically back down the branching nerve fiber to the muscle to create the axon reflex. This occurs in the situation where all the distal nerve fibers have not been supramaximally stimulated, and there is no antidromic pulse to collide with the action potential traveling down the collateral fibers. Because the length of nerve traveled for the axon reflex is less than that traveled for the F response, the axon reflex usually occurs before the F response. It is identified by its identical latency and configuration with each successive stimulation. **Right:** With supramaximal stimulation, the axon reflex often is eliminated, due to collision between the orthodromically traveling axon reflex and the antidromic volley from the reinnervated sprout.

traveling antidromic pulse passes a terminal branching point, the pulse might then travel back down that branching nerve fiber to the muscle to create an axon reflex, which occurs after the M potential but before the F response (Figure 4–15). With supramaximal stimulation, the antidromic volley usually collides with the orthodromically traveling axon reflex, and the axon reflex is not seen. If all the distal nerve fibers have not been supramaximally stimulated, however, there may be no antidromic volley in the branching fibers to collide with the orthodromically traveling axon reflex, in which case the potential is free to travel back down the branching fiber to the muscle, creating the axon reflex. Axon reflexes are important to identify because they often suggest reinnervation along the nerve, as well as the possibility that the stimulation is not supramaximal. Most important, axon reflexes should not be confused with the F response, which usually occurs later. Rarely, the axon reflex will follow rather than precede the F response, if the regenerating collateral fibers are conducting very slowly.

Although axon reflexes are most often associated with reinnervation following axonal loss lesions, they also can be seen in demyelinating neuropathies. Most classic is Guillain–Barré syndrome, where they are often seen in the first several days of the illness. Their etiology in this setting remains a topic of debate, but has been speculated to occur from ephaptic spread from one nerve fiber to another at a point of inflammation and demyelination (ephaptic meaning direct spread from one nerve membrane to another).

Suggested Readings

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5 Blink Reflex

Few routine electrophysiologic tests are available to evaluate the cranial nerves and their proximal segments other than visual and brainstem evoked potentials. However, cranial nerves V (trigeminal) and VII (facial), along with their connections in the pons and medulla, can be assessed electrically with the blink reflex. The blink reflex is essentially the electrical correlate of the clinically evoked corneal reflex. Like the H reflex, the blink reflex is a true reflex, with a sensory afferent limb, intervening synapses, and a motor efferent. Blink reflexes are useful in detecting abnormalities anywhere along the reflex arc, including peripheral and central pathways. Accordingly, neuropathies or compressive lesions of the peripheral facial or trigeminal nerves may be detected, as well as central lesions in the brainstem, including those caused by brainstem strokes and multiple sclerosis.

ANATOMY

The afferent limb of the blink reflex is mediated by sensory fibers of the supraorbital branch of the ophthalmic division of the trigeminal nerve (cranial nerve V_1) and the efferent limb by motor fibers of the facial nerve (cranial nerve VII). Just as with the corneal reflex, ipsilateral electrical stimulation of the supraorbital branch of the trigeminal nerve elicits a facial nerve (eye blink) response bilaterally. Stimulation of the ipsilateral supraorbital nerve results in an afferent volley along the trigeminal nerve to both the main sensory nucleus of V (mid-pons) and the nucleus of the spinal tract of V (lower pons and medulla) in the brainstem. Through a series of interneurons in the pons and lateral medulla, the nerve impulse next reaches the ipsilateral and contralateral facial nuclei, from which the efferent signal travels along the facial nerve bilaterally (Figure 5–1).

The blink reflex has two components, an early R1 and a late R2 response. The R1 response is usually present ipsilaterally to the side being stimulated, whereas the R2 response is typically present bilaterally. The R1 response is thought to represent the disynaptic reflex pathway between the main sensory nucleus of V in the mid-pons and the ipsilateral facial nucleus in the lower pontine tegmentum. The R2 responses are mediated by a multisynaptic pathway between the nucleus of the spinal tract of V in the ipsilateral pons and medulla and interneurons forming connections to the ipsilateral and contralateral facial nuclei.

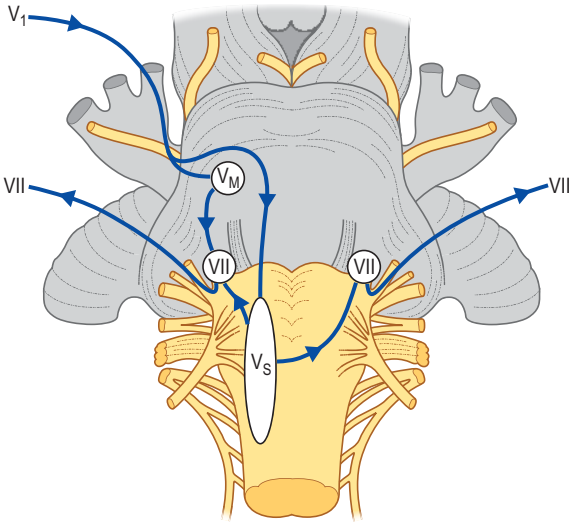

FIGURE 5–1 Blink reflex anatomy. The afferent loop of the blink reflex is mediated by the first division of the trigeminal nerve (V_1), which synapses with both the main sensory nucleus of cranial nerve V (V_M) in the mid-pons and the nucleus of the spinal tract of cranial nerve V (V_S) in the medulla. The earlier R1 potential is mediated by a disynaptic connection between the main sensory nucleus and the ipsilateral facial motor nucleus (VII). The later R2 responses are mediated by a multisynaptic pathway between the nucleus of the spinal tract of cranial nerve V and both ipsilateral and contralateral facial nuclei (VII). The efferent pathway for both R1 and R2 is mediated via the facial nerve to the orbicularis oculi muscles. (Modified from Chusid JC. Correlative neuroanatomy and functional neurology, 18th ed. Stamford, CT: Appleton & Lange, 1982, with permission.)

The earlier R1 response usually is stable and reproducible, with biphasic or triphasic morphology. In a small percentage of normal individuals, the R1 response cannot be reliably elicited on either side. The R2 responses, on the other hand, are polyphasic and variable from stimulation to stimulation. With repeated stimulation, the R2 responses tend to habituate.

BLINK REFLEX PROCEDURE

The patient should be in a relaxed state, lying supine on the examining table, with the eyes either open or gently closed (Box 5–1). Recording is performed simultaneously from both sides of the face using a two-channel recording apparatus. Surface recording electrodes are placed over the

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inferior orbicularis oculi muscles bilaterally (Figure 5–2). For recording the compound motor action potential from the orbicularis oculi muscle, the active recording electrode (G1) is best placed below the eye just lateral and inferior to the pupil at mid-position. The corresponding reference electrodes (G2) are placed just lateral to the lateral canthus bilaterally. Alternatively, recording can be done with small concentric needle electrodes placed in the orbicularis oculi bilaterally. The ground electrode is placed on the mid-forehead or chin.

Box 5–1. Blink Response Procedure

1. The patient should be in a relaxed state, lying supine on the examining table, with the eyes either open or gently closed.
2. Recording from both orbicularis oculi muscles is performed simultaneously.
3. Active recording electrodes are placed below the eye just lateral and inferior to the pupil at mid-position, with the reference electrodes placed just lateral to the lateral canthus.
4. A ground electrode is placed over the mid-forehead or chin.
5. Sweep speed set at 5 or 10 ms/division.
6. Sensitivity set at 100 or 200 μV/division.
7. Motor filter settings are 10 Hz and 10 kHz.
8. Stimulate each supraorbital nerve (preferably with pediatric prong stimulator) over medial eyebrow, recording orbicularis oculi bilaterally. Allow several seconds between successive stimulations to prevent habituation.
9. For each side, 4–6 stimuli are obtained on a rastered tracing and superimposed to determine the shortest response latencies.

Because typical R1 and R2 latencies are 10 to 12 ms and 30 to 40 ms, respectively, the sweep speed should be set at 5 or 10 ms per division. Initial sensitivity should be set at 100 or 200 μV per division because the amplitudes of both R1 and R2 are quite small. The filter settings are the same as for a motor conduction study (10 Hz, 10 kHz). The supraorbital nerve (branch of the ophthalmic division of the trigeminal nerve) is stimulated ipsilaterally, with the stimulator placed in the superior orbital fissure. In some patients, a small pediatric bipolar prong stimulator or bar electrode can be used for stimulation. The stimulation site is found over the medial supraorbital ridge and can be felt as a slight depression in the bony ridge over the eyebrow. An electrical pulse of 100 ms duration is used. The current is turned up in small increments (usually 3–5 mA) from a baseline of 0 mA until supramaximal stimulation is reached, resulting in the shortest latency and highest amplitude potentials. The nerve is easily stimulated with low currents. Typically, no more than 15 to 25 mA is needed to obtain supramaximal stimulation.

Once supramaximal stimulation is achieved, four to six responses are obtained on a rastered tracing and superimposed to determine the shortest response latencies. To prevent habituation, it is best to wait several seconds between successive stimulations. Because R1 is stable, its latency is easily marked. It is best to place the latency marker on the R1 potential at the point where it departs

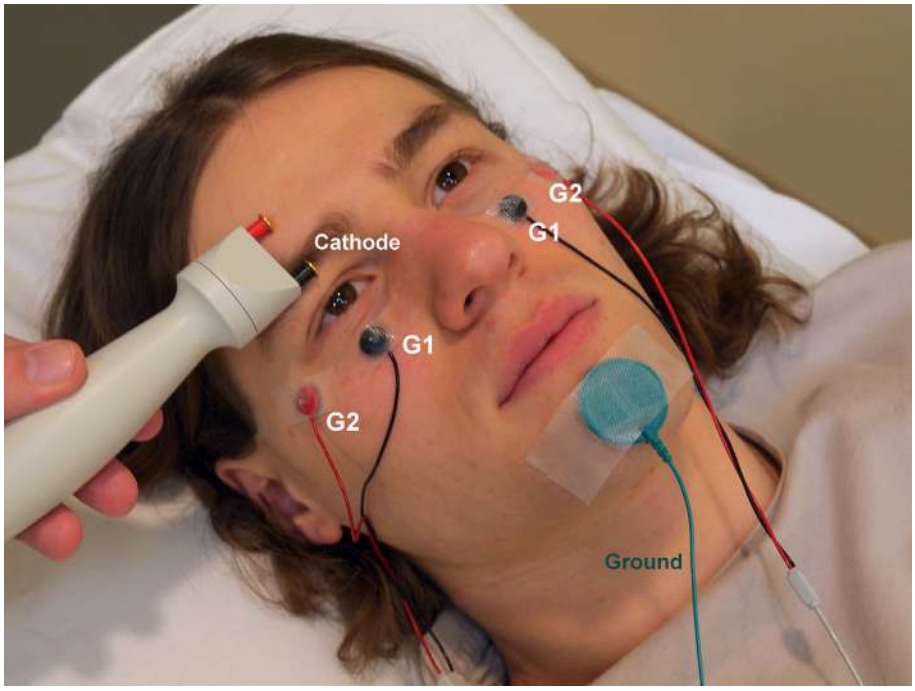

FIGURE 5–2 Blink reflex procedure. Both orbicularis oculi muscles are recorded simultaneously. The active recording electrodes (G1) are placed below the eye inferior and slightly lateral to the pupil at mid-position, with the reference recording electrodes (G2) placed just lateral to the lateral canthus. For each side, the ipsilateral supraorbital nerve is stimulated over the medial eyebrow. Recording and stimulation sites are shown for a right-sided blink reflex.

from the baseline with either a positive or negative deflection. Measurement of R2 latencies is more difficult because the potential varies in latency and morphology from stimulation to stimulation. With several traces superimposed, the shortest R2 latency is selected. It is extremely important that the patient be in a relaxed state to eliminate any signal noise, which could obliterate or confound one or both components of the blink reflex (especially R2). Turning up the speaker is very helpful to provide auditory feedback to the patient; this helps with muscle relaxation and thereby reduces signal noise. *The stimulator should never be set on repetitive stimulation, because it is important to ensure electrical silence before each stimulation.*

The blink reflex usually is elicited by stimulation of the supraorbital nerve, a branch of cranial nerve V_1. In a small number of individuals, stimulation of the infraorbital nerve, a branch of cranial nerve V_2, may result in a response. The reflex can also be elicited with a glabellar tap, using a specially devised reflex hammer that automatically triggers the oscilloscope sweep, although the reflex is not as easily evoked in this manner. Please note that using this technique, mechanical stimulation over the forehead elicits an R1 response bilaterally.

In a normal individual, electrical stimulation elicits an R1 response on the side ipsilateral to the stimulation and R2 responses bilaterally (Figure 5–3). R1 latency reflects conduction time along the fastest fibers of the afferent pathway of the ipsilateral trigeminal nerve to the main sensory nucleus of V, across disynaptic pathways in the pons to the facial nerve nucleus, and along the efferent pathway of the ipsilateral facial nerve. R2 latency is a measure of conduction time along the fastest fibers of the afferent pathway of the ipsilateral trigeminal nerve to the nucleus of the spinal tract of V, across multiple synapses in the pons and lateral medulla to both the ipsilateral and contralateral facial nerve nuclei, and along the efferent pathways of the facial nerves bilaterally

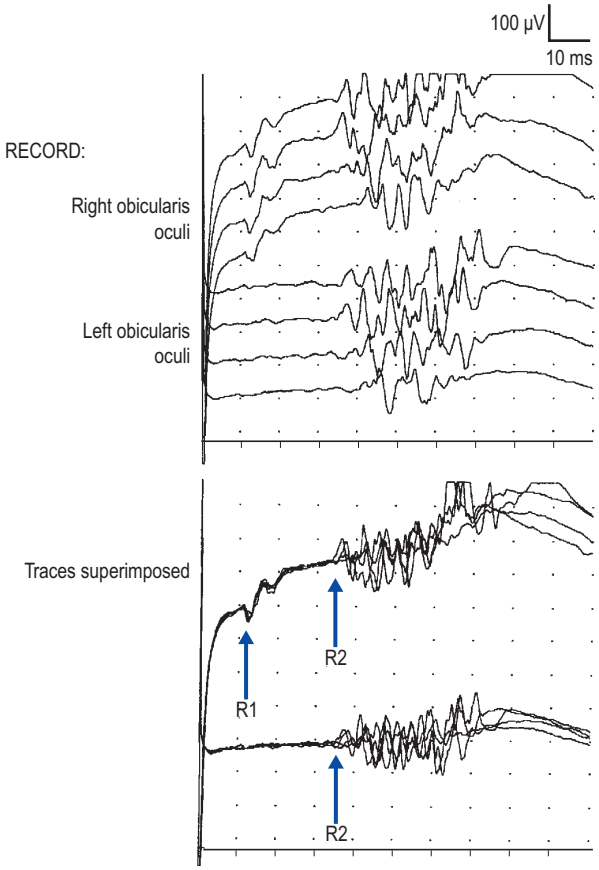

FIGURE 5–3 Normal blink reflex. Stimulating the right side, recording both orbicularis oculi muscles in a normal subject. On the ipsilateral side, an early R1 potential is present at 11 ms and a late R2 potential at 34 ms. R1 usually is a biphasic or triphasic potential and stable from stimulation to stimulation. The R2 potential is variable and usually polyphasic. On the contralateral side, only a late R2 potential is seen at 35 ms. Superimposing several traces is useful to help determine the shortest R2 latencies.

PATTERNS OF ABNORMALITIES

For each blink response, the absolute latencies of R1 and R2 are compared with normal control values as well as with those found on the contralateral side. In normal subjects (Figure 5–4A), the absolute R1 latency is <13 ms, the ipsilateral R2 latency <41 ms, and the contralateral R2 latency <44 ms. For side-to-side comparisons, the difference between the R1 latencies should be <1.2 ms, the difference between ipsilateral R2 latencies should be <5 ms, and the difference between contralateral R2 latencies should be <7 ms. Many different patterns of abnormalities can occur, depending on the site or sites of the lesion(s). The basic abnormal patterns are as follows:

1. *Unilateral trigeminal lesion* (Figure 5–4B and C). Stimulating the affected side, there will be a delay or absence of all potentials (ipsilateral R1 and R2, contralateral R2). Stimulating the unaffected side results in normal potentials, including the ipsilateral R1 and R2 and the contralateral R2. *Clinical correlate:* This pattern of a trigeminal sensory neuropathy is most often seen in association with connective tissue diseases or in some toxic neuropathies.
2. *Unilateral facial lesion* (Figure 5–4D and E). Stimulating the affected side results in a delay or absence of the ipsilateral R1 and R2, but a normal contralateral R2. Stimulating the unaffected side results in a normal ipsilateral R1 and R2, but a delayed or absent contralateral R2. In this pattern, all potentials on the affected side are abnormal, regardless of which side is stimulated. *Clinical correlate:* This pattern of a unilateral facial lesion has a large differential diagnosis, including infectious, inflammatory, granulomatous, and structural lesions. However, it is most often seen as an idiopathic, post-infectious syndrome (i.e., Bell's palsy).
3. *Unilateral mid-pontine lesion* (main sensory nucleus V and/or lesion of the pontine interneurons to the ipsilateral facial nerve nucleus) (Figure 5–4F). Stimulating the affected side results in an absent or

delayed R1, but an intact ipsilateral and contralateral R2. Stimulating the unaffected side results in all normal potentials, including R1 and ipsilateral and contralateral R2. C*linical correlate:* This pattern denotes an intrinsic lesion within the pons, most often stroke, demyelination, or a structural lesion.

4. *Unilateral medullary lesion* (nucleus of the spinal tract of V and/or lesion of the medullary interneurons to the ipsilateral facial nerve nucleus) (Figure 5–4G). Stimulating the affected side results in a normal R1 and contralateral R2, but an absent or delayed ipsilateral R2. Stimulating the unaffected side results in normal ipsilateral R1 and R2 potentials, but a delayed or absent contralateral R2. If there is a more extensive lesion in the medulla involving medullary interneurons to the contralateral facial nerve, stimulating the affected side will result in a normal R1, but both the ipsilateral and contralateral R2 potentials will be absent or delayed. Stimulating the unaffected side results in the same pattern. C*linical correlate:* This pattern denotes an intrinsic lesion within the medulla, most often stroke, demyelination, or a structural lesion.
5. *Demyelinating peripheral neuropathy* (Figures 5–4H and 5–5). Axonal neuropathies rarely affect the blink reflex because typical axonal distal dying-back neuropathies are unlikely to affect the fibers that mediate the blink reflex, which are so proximal. However, in demyelinating neuropathies, all potentials of the blink response may be markedly delayed or absent, reflecting slowing of either or both motor and sensory pathways.

With an understanding of the anatomy of the blink reflex circuitry and the basic abnormal patterns outlined

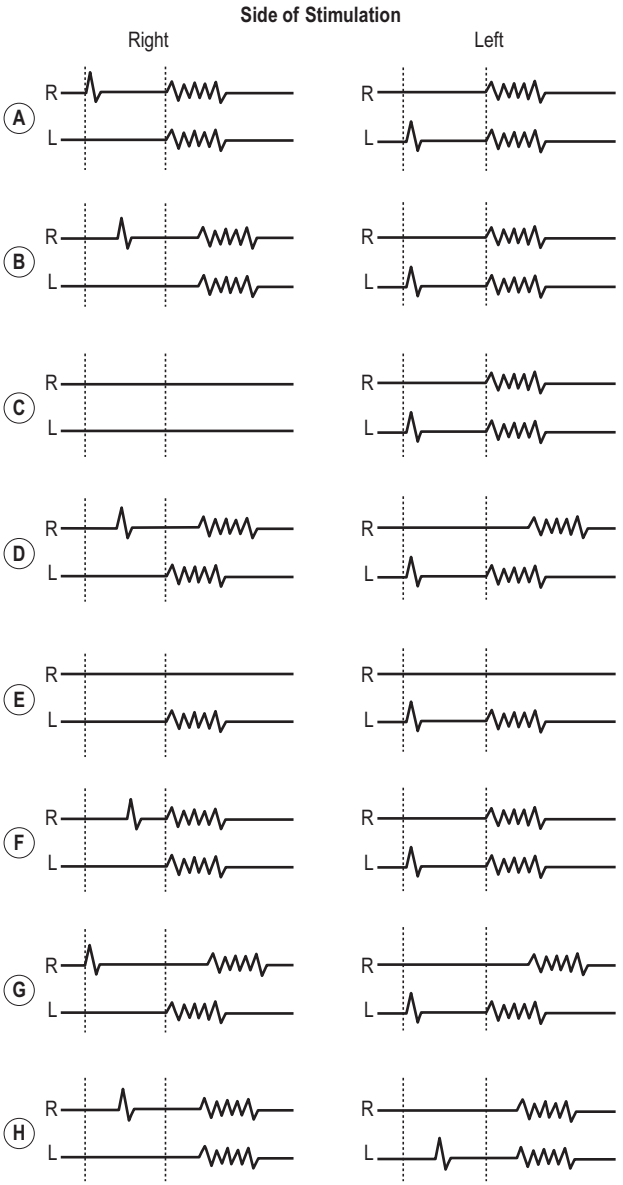

FIGURE 5–4 Blink reflex patterns of abnormalities. **A:** Normal pattern. Recording both orbicularis oculi muscles, stimulating the supraorbital nerve on each side results in an ipsilateral R1 (early) and bilateral R2 (late) potential. **B:** Incomplete right trigeminal lesion. Stimulating the affected right side, there is a delay of all potentials, including the ipsilateral R1 and R2 and contralateral R2. Stimulating the unaffected side results in all normal potentials. **C:** Complete right trigeminal lesion. Stimulating the affected right side, all potentials are absent. Stimulating the unaffected side results in all normal potentials. **D:** Incomplete right facial lesion. Stimulating the affected side results in delay of the ipsilateral R1 and R2, but a normal contralateral R2. Stimulating the unaffected side results in a normal ipsilateral R1 and R2, but a delayed contralateral R2. In this pattern, all potentials on the affected side are abnormal, regardless of which side is stimulated. **E:** Complete right facial lesion. Stimulating the affected side results in absent ipsilateral R1 and R2 potentials, but a normal contralateral R2. Stimulating the unaffected side results in a normal ipsilateral R1 and R2, but an absent contralateral R2. **F:** Right mid-pontine lesion (main sensory nucleus V and/or lesion of the pontine interneurons to the ipsilateral facial nerve nucleus). Stimulating the affected side results in an absent or delayed R1, but an intact ipsilateral and contralateral R2. Stimulating the unaffected side results in all normal potentials. **G:** Right medullary lesion (nucleus of the spinal tract of V, and/or lesion of the medullary interneurons to the ipsilateral facial nerve nucleus). Stimulating the affected side results in a normal R1 and contralateral R2, but an absent or delayed ipsilateral R2. Stimulating the unaffected side results in normal ipsilateral R1 and R2 potentials, but a delayed or absent contralateral R2. **H:** Demyelinating peripheral polyneuropathy. All potentials of the blink response may be markedly delayed or absent, reflecting slowing of either or both motor and sensory pathways.

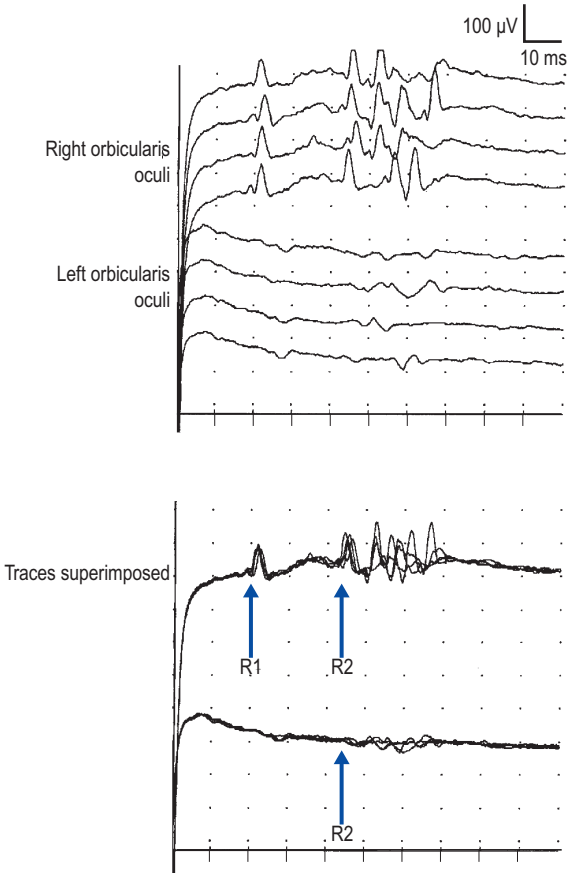

FIGURE 5–5 Blink reflex, demyelinating polyneuropathy. Patient with Guillain–Barré syndrome and moderately severe bifacial weakness (left greater than right). Stimulating the right side, recording both orbicularis oculi muscles resulted in the following pattern: the R1 is prolonged at 21 ms, as is the ipsilateral R2 at 43 ms. The contralateral R2 is barely present and also prolonged at 46 ms.

here, one can extrapolate the patterns of abnormalities for more complex lesions (e.g., bilateral pontine, bilateral medullary).

Suggested Readings

Aramideh, M., Ongerboer de Visser, B.W., 2002. Brainstem reflexes: electrodiagnostic techniques, physiology, normative data, and clinical applications. Muscle Nerve 26, 14–30.

Aramideh, M., Ongerboer de Visser, B.W., Koelman, J.H., et al, 1997. The late blink reflex response abnormality due to lesion of the lateral tegmental field. Brain 120, 1685–1692.

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6 Repetitive Nerve Stimulation

The use of repetitive nerve stimulation (RNS) dates back to the late 1800s, when Jolly made visual observations of muscle movement that occurred after nerve stimulation. Although his initial studies were done with submaximal stimuli and mechanical rather than electrical measurements were made, Jolly noted a decrementing response following RNS in patients with myasthenia gravis and correctly concluded that the disorder was peripheral.

Subsequently, RNS has been refined and validated as one of the most useful electrodiagnostic (EDX) tests in the evaluation of patients with suspected neuromuscular junction (NMJ) disorders. RNS should be performed whenever there is a possible diagnosis of myasthenia gravis, Lambert–Eaton myasthenic syndrome, or botulism. It also should be considered in any patient who presents with fatigability, proximal weakness, dysphagia, dysarthria, or ocular abnormalities, which are clinical symptoms and signs suggestive of a possible NMJ disorder.

In the EDX laboratory, the effects of RNS are studied on the compound muscle action potential (CMAP), with analysis of any decremental or incremental response forming the basis of the study. Understanding these responses requires knowledge of normal NMJ physiology and the effects of repetitive stimulation on a single NMJ and its associated muscle fiber. That knowledge can be used in the EDX laboratory to accurately predict the effect of RNS on the CMAP, both in normal subjects and in patients with NMJ disorders.

NORMAL NEUROMUSCULAR JUNCTION PHYSIOLOGY

The NMJ essentially forms an electrical–chemical–electrical link between nerve and muscle (Figure 6–1). The chemical neurotransmitter at the NMJ is acetylcholine (ACH). ACH molecules are packaged as vesicles in the presynaptic terminal in discrete units known as quanta; each quantum contains approximately 10,000 molecules of ACH. The quanta are located in three separate stores. The *primary, or immediately available store* consists of approximately 1000 quanta located just beneath the presynaptic nerve terminal membrane. This store is immediately available for release. The *secondary, or mobilization store* consists of approximately 10,000 quanta that can resupply the primary store after a few seconds. Finally, *a tertiary, or reserve* store of more than 100,000 quanta exists far from the NMJ in the axon and cell body.

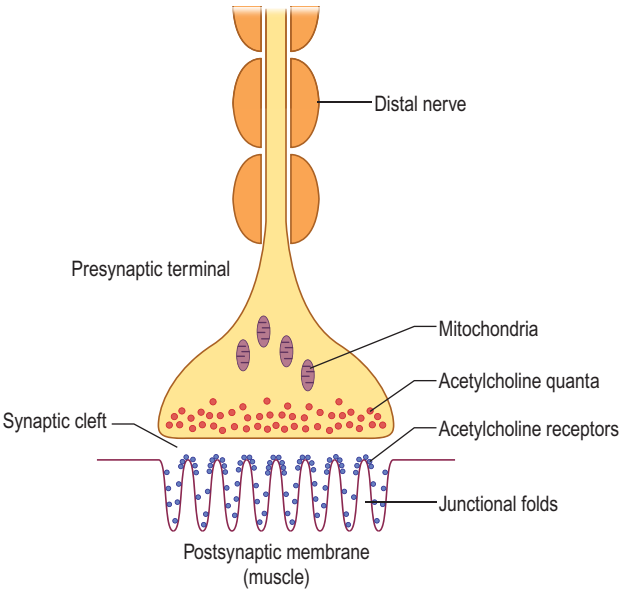

FIGURE 6–1 Normal neuromuscular junction anatomy.

When a nerve action potential invades and depolarizes the presynaptic junction, voltage-gated calcium channels (VGCCs) are activated, allowing an influx of calcium. The infusion of calcium starts a complicated interaction of many proteins that ends in the release of ACH from the presynaptic terminal. The greater the calcium concentration inside the presynaptic terminal, the more quanta are released. ACH then diffuses across the synaptic cleft and binds to ACH receptors (ACHRs) on the postsynaptic muscle membrane. The postsynaptic membrane is composed of numerous junctional folds, effectively increasing the surface area of the membrane, with ACHRs clustered on the crests of the folds. The binding of ACH to ACHRs opens sodium channels, resulting in a local depolarization, the endplate potential (EPP). The size of the EPP is proportional to the amount of ACH that binds to the ACHRs.

In a process similar to the generation of a nerve action potential, if the EPP depolarizes the muscle membrane above threshold, an all-or-none muscle fiber action

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potential is generated and propagated through the muscle fiber. Under normal circumstances, the EPP always rises above threshold, resulting in a muscle fiber action potential. The amplitude of the EPP above the threshold value needed to generate a muscle fiber action potential is called the *safety factor*. In the synaptic cleft, ACH is broken down by the enzyme acetylcholinesterase, and the choline subsequently is taken up into the presynaptic terminal to be repackaged into ACH.

During slow RNS (2–3 Hz) in normal subjects, ACH quanta are progressively depleted from the primary store, and fewer quanta are released with each successive stimulation. The corresponding EPP falls in amplitude, but because of the normal safety factor, it remains above threshold to ensure generation of a muscle fiber action potential with each stimulation. After the first few seconds, the secondary (mobilization) store begins to replace the depleted quanta with a subsequent rise in the EPP.

The physiology of rapid RNS (10–50 Hz) in normal subjects is more complex. Depletion of quanta from the presynaptic terminal is counterbalanced not only by the mobilization of quanta from the secondary store but also by the accumulation of calcium. Normally, it takes about 100 ms for calcium to be actively pumped out of the presynaptic terminal. If RNS is rapid enough so that new calcium influx occurs before the previously infused calcium has been fully pumped out, calcium accumulates in the presynaptic terminal, causing an increased release of quanta. Normally, this accumulation of calcium predominates over depletion, leading to an increased number of quanta being released and a correspondingly higher EPP. However, the result is the same as with any other EPP above threshold: an all-or-none muscle fiber action potential is generated.

Thus, the effects of slow and rapid RNS are very different at the molecular level, yet in normal subjects the result is the same: the consistent generation of a muscle fiber action potential. In pathologic conditions where the safety factor is reduced (i.e., baseline EPP is reduced but still above threshold), slow RNS will cause depletion of quanta and may drop the EPP below threshold, resulting in the absence of a muscle fiber action potential. In pathologic conditions where baseline EPP is below threshold and a muscle fiber action potential is not generated, rapid RNS may increase the number of quanta released, resulting in a larger EPP, so that threshold is reached. A muscle fiber action potential is then generated where one had not been present previously. These concepts form the basis of the decrements with slow RNS and increments with rapid RNS that are seen in NMJ disorders.

PHYSIOLOGIC MODELING OF REPETITIVE NERVE STIMULATION

RNS in normal subjects and patients with NMJ disorders can be modeled effectively by making the following three assumptions:

1. $m=pn$, where m represents the number of quanta released during each stimulation; p is the probability of release (effectively proportional to the concentration of calcium), typically approximately 0.2 in normal subjects; and n represents the number of quanta in the immediately available store (at baseline, approximately 1000 in normal subjects).
2. The mobilization store starts to replenish the immediately available store after 1 to 2 seconds.
3. Approximately 100 ms is required to pump calcium out of the presynaptic terminal. If stimulation occurs again sooner than 100 ms (i.e., stimulation rate >10 Hz), the calcium concentration increases, the probability of release of ACH quanta increases, and more quanta are released.

Modeling Slow Repetitive Nerve Stimulation

The effects of slow RNS on the EPP, the muscle fiber action potential (MFAP), and the CMAP can best be illustrated with the following three examples (Figure 6–2A–C):

3 Hz Repetitive Nerve Stimulation: Normal Subject

Stimulus	*n*	*m*	EPP	MFAP	CMAP
1	1000	200	40	+	Normal
2	800	160	32	+	No change
3	640	128	26	+	No change
4	512	102	20	+	No change
5	640	128	26	+	No change

In this first example, initially there are 1000 quanta in the immediately available store (n), and with each stimulation, 20% of the quanta are released. If the EPP is >15 mV (threshold in this example), a muscle fiber action potential is generated. Note the normal depletion of the immediately available store (n), the subsequent decline in the number of quanta released (m), and the corresponding fall in the EPP from the first to the fourth stimulation. During the second stimulation, only 160 quanta are released instead of the initial 200 because the number of quanta in the immediately available store has dropped to 800 (1000 minus the 200 released during the first stimulation), and subsequently 20% of the 800 is released. At the fifth stimulus, however, sufficient time has elapsed for the secondary or mobilization store to begin to resupply the primary store. The number of quanta in the immediately available store increases, with a corresponding increase in the number of ACH quanta released, resulting in a higher EPP. Note that at all times the EPP stays above threshold (15 mV), resulting in the consistent generation of a muscle fiber action potential (Figure 6–2A). In the EDX laboratory, these findings translate to normal baseline CMAPs with no change in amplitude, because action potentials are generated in all muscle fibers.

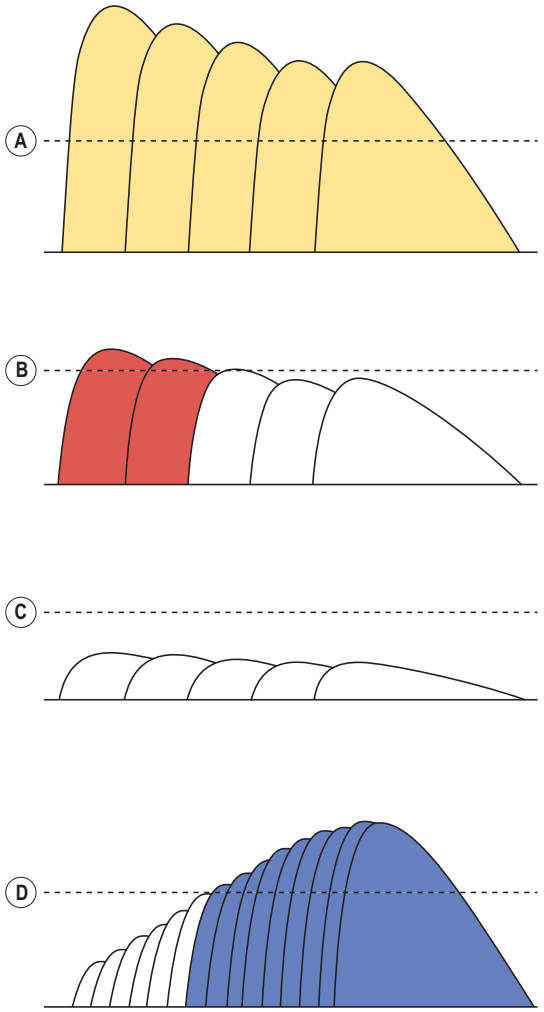

FIGURE 6–2 Endplate potentials (EPPs). Threshold is indicated by the dashed line. Shaded EPPs are those that rise above threshold and generate a muscle fiber action potential. **A:** Three-Hertz repetitive nerve stimulation (RNS), normal NMJ. Note that all potentials remain well above threshold despite the normal decline in EPP amplitude (safety factor). **B:** Three-Hertz RNS, postsynaptic NMJ disorder. Note the lower EPP amplitudes. With further acetylcholine depletion, the last three potentials fall below threshold, and a muscle fiber action potential is not generated. **C:** Three-Hertz RNS, presynaptic NMJ disorder. Note that all EPPs are below threshold, and no muscle fiber action potentials are generated. The EPP declines in amplitude but the decrement is not as marked as in normal subjects or patients with postsynaptic NMJ disorders. **D:** Fifty-Hertz RNS, presynaptic NMJ disorder. Note the progressive increment in the EPP amplitude to above threshold and the subsequent generation of muscle fiber action potentials.

3 Hz Repetitive Nerve Stimulation: Postsynaptic Disorder (e.g., Myasthenia Gravis)

Stimulus	*n*	*m*	EPP	MFAP	CMAP
1	1000	200	20	+	Normal
2	800	160	16	+	Normal
3	640	128	13	–	Decrement
4	512	102	10	–	Decrement
5	640	128	13	–	Decrement (repair)

In this next example, the number of quanta in the immediately available store (n), the number of quanta released (m), and the depletion of quanta with slow RNS all are normal. The response to the quanta (i.e., the EPP) is abnormal, however. Whereas in normal subjects the release of 200 quanta generated an EPP of 40 mV, in this case the same number of quanta generates an EPP of only 20 mV. Accordingly, the safety factor is reduced. In myasthenia gravis, this occurs as a result of fewer ACHRs and, accordingly, less binding of ACH. The reduced safety factor, in conjunction with normal depletion of quanta, results in subsequent EPPs falling below threshold and their corresponding muscle fiber action potentials not being generated (Figure 6–2B). As the number of individual MFAPs declines, a decrement of CMAP amplitude and area occurs. This decrement reflects fewer EPPs reaching threshold and fewer individual MFAPs contributing to the CMAP. Often, after the fifth or sixth stimulus, the secondary stores are mobilized and no further loss of MFAPs occurs. This results in stabilization or sometimes slight improvement or repair of the CMAP decrement after the fifth or sixth stimulus, giving the characteristic "U-shaped" decrement (see later).

3 Hz Repetitive Nerve Stimulation: Presynaptic Disorder (e.g., Lambert-Eaton Myasthenic Syndrome)

Stimulus	*n*	*m*	EPP	MFAP	CMAP
1	1000	20	4	–	Low
2	980	19.6	3.9	–	Decrement
3	960	19.2	3.8	–	Decrement
4	940	18.8	3.7	–	Decrement
5	920	19.2	3.8	–	Decrement (repair)

In this next example, the number of quanta in the immediately available store (n) is normal, and the EPP is normal for the number of quanta released (m). What is abnormal is the number of ACH quanta released (m) and the baseline EPP. In Lambert–Eaton myasthenic syndrome, the calcium concentration in the presynaptic terminal is reduced, due to an antibody attack on the voltage-gated calcium channels. Thus, the probability of release (p) falls dramatically, along with a decrease in the number of quanta released. There still is depletion, although it is not as marked as in normal or postsynaptic disorders. Simply because so few quanta are released, the subsequent amount of depletion cannot be as great. In this example, because the EPP is below threshold at baseline, a muscle fiber action potential is never generated (Figure 6–2C). Thus, the baseline CMAP is low in amplitude because many muscle fibers do not reach threshold due to inadequate release of quanta after a single stimulus. With slow RNS, there is also further decrement of the CMAP because subsequent stimuli result in further loss of MFAPs. Just as in postsynaptic disorders, after the fifth or sixth stimulus, the secondary stores are mobilized and no further loss of MFAPs occurs. This results in stabilization or sometimes slight improvement or repair

of the CMAP decrement after the fifth or sixth stimulus, giving the characteristic "U-shaped" decrement (see later). Note that in some presynaptic disorders, the baseline EPP may be low but still above threshold, resulting in a reduced safety factor. In this situation, a muscle fiber action potential initially may be generated but then fails to be generated as the EPP falls below threshold with slow RNS.

Modeling Rapid Repetitive Nerve Stimulation

The effects of rapid RNS can be deduced from the three basic assumptions (see section on Physiologic Modeling of Repetitive Nerve Stimulation). With rapid RNS, the depletion of quanta is counterbalanced by (1) increased mobilization of quanta from the secondary to the primary store, and (2) calcium accumulation in the presynaptic terminal, which increases *p*, the probability of release. The sum of these influences usually results in a greater number of quanta released and higher EPPs with rapid RNS.

In normal subjects, rapid RNS always results in the generation of a muscle fiber action potential, the same as with any EPP above threshold. In patients with postsynaptic NMJ disorders, the EPP also will increase, but because the EPP usually is above threshold at baseline, the result will still be the generation of a muscle fiber action potential. However, if the EPP has been lowered, such as after slow RNS, the decreased EPP may be repaired or improved with rapid RNS. If the EPP has dropped below threshold, subsequent rapid RNS may increase the EPP back to above threshold.

Presynaptic NMJ disorders are distinctly different. Because the EPP is abnormally low at baseline in those disorders – often below threshold – rapid RNS may increase the EPP above threshold so that a muscle fiber action potential is generated where one had not been present previously (Figure 6–2D).

Exercise Testing

When a subject is asked to voluntarily contract a muscle at maximum force, motor units fire at their maximal firing frequency, typically 30 to 50 Hz. Thus, maximal voluntary exercise can be used to demonstrate many of the same effects as rapid (30–50 Hz) RNS. Both result in higher-amplitude EPPs.

In normal subjects, maximal exercise results in the usual generation of a muscle fiber action potential. In postsynaptic NMJ disorders, exercise, just like rapid RNS, results in higher EPPs. Because the EPP is usually above threshold at baseline, the result is the same: the generation of a muscle fiber action potential. Exercise likewise may repair or improve a low EPP that has developed during slow RNS. If the EPP has dropped below threshold, subsequent exercise may increase the EPP back to above threshold. In presynaptic NMJ disorders, exercise, like rapid RNS, often can facilitate low EPPs. If the baseline EPP is below threshold, exercise may increase the EPP above threshold so that a muscle fiber action potential is generated where one had not been present previously.

The effects of rapid RNS or voluntary exercise just described occur with brief periods of exercise or rapid RNS, typically 10 seconds. This process is known as *post-exercise (or posttetanic) facilitation*. The phenomenon of *postexercise (or posttetanic) exhaustion* is less well understood. Immediately after a prolonged exercise or rapid RNS (usually 1 minute), EPPs typically increase initially, as described earlier, but then subsequently decline over the next several minutes, usually falling below baseline. In normal subjects with a normal safety factor, the EPP never falls below threshold. However, in patients with impaired NMJ transmission, slow RNS performed 2 to 4 minutes after a prolonged exercise may result in a greater decline of the EPP, such that the EPP does not reach threshold and its muscle fiber action potential is not generated.

REPETITIVE NERVE STIMULATION IN THE ELECTROMYOGRAPHY LABORATORY

RNS is easy to learn, easy to perform, and requires no special equipment. However, it is poorly tolerated in some patients and is prone to a number of important technical problems that, if not recognized and corrected, can influence its reliability, validity, and therefore its value. The earlier discussion above pertained to endplate and individual muscle fiber action potentials. During RNS in the electromyography (EMG) laboratory, all measurements are made on the CMAP, the sum of the individual muscle fiber action potentials generated in a muscle. Thus, it is assumed that the CMAP amplitude and area are proportional to the number of muscle fibers activated. In normal subjects, the EPP is affected by both slow and rapid RNS. However, in both cases, the EPP always stays above threshold, resulting in consistent generation of muscle fiber action potentials. Thus, in normal subjects, CMAPs generated following either slow or rapid RNS do not change significantly in amplitude or area.

In NMJ disorders, if the normal EPP safety factor is reduced, slow RNS will cause a depletion of quanta and reduce the amplitude of the EPP. If the EPP of some muscle fibers falls below threshold, those muscle fiber action potentials will not be generated, and the number of individual muscle fiber action potentials will decline. This provides the basis for the decremental CMAP response to slow RNS seen in the EMG laboratory (Figure 6–3A). As the number of individual muscle fiber action potentials declines, a decrement of the CMAP amplitude and area occurs. This decrement reflects fewer EPPs reaching threshold and fewer individual muscle fiber action potentials contributing to the CMAP.

In NMJ disorders in which some EPPs are below threshold at baseline (usually the presynaptic disorders), rapid RNS can be used to facilitate the EPP. If subthreshold EPPs can be brought above threshold, muscle fiber action

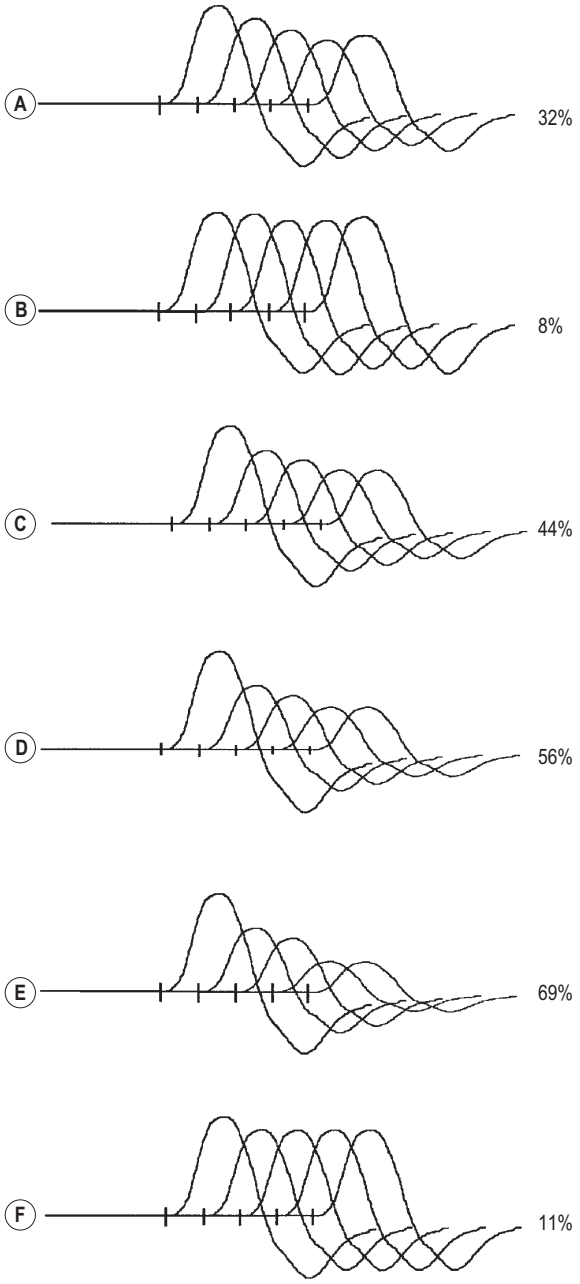

FIGURE 6–3 Postexercise facilitation and exhaustion. Three-Hertz repetitive nerve stimulation in a patient with myasthenia gravis. **A:** Decrement of compound muscle action potential (CMAP) amplitude at rest. **B:** Postexercise facilitation. Decrement of CMAP immediately following 10 seconds of maximal voluntary exercise has repaired toward normal. **C–E:** Postexercise exhaustion. Decrements of CMAP 1, 2, and 3 minutes after 1 minute of maximal voluntary exercise. Decrement becomes progressively more marked over the baseline decrement. **F:** Postexercise facilitation after a decrement. Immediately following another 10 seconds of maximal voluntary exercise, the decrement, which has worsened as a result of postexercise exhaustion, repairs toward normal.

potentials will be generated where they had not been present previously, and the number of individual muscle fiber action potentials will increase. This provides the basis for the incremental CMAP response to rapid RNS seen in the EMG laboratory. As the number of individual muscle fiber action potentials increases, an increment of CMAP amplitude and area occurs (Figure 6–4). This increment reflects more EPPs reaching threshold and more individual muscle fiber action potentials contributing to the CMAP. Incremental responses that are >100% (i.e., double in value) in response to rapid RNS are not unusual in presynaptic NMJ disorders.

Exercise Testing in the Electromyography Laboratory

Exercise testing plays an important role in the electrophysiologic evaluation of all patients with suspected NMJ disorders. *Brief maximal voluntary exercise can be used instead of rapid RNS in cooperative subjects*. Exercise testing has the distinct advantage of being painless, whereas rapid RNS is quite painful and often difficult to tolerate. If not convinced, the reader can perform an experiment. First, maximally contract your median-innervated abductor pollicis brevis muscle voluntarily for 10 seconds, and then contrast the experience with 10 seconds of 50 Hz supramaximal median nerve stimulation. The difference between the two is not subtle.

The effects of both postexercise facilitation and postexercise exhaustion can be demonstrated on the CMAP in patients with NMJ disorders (Figure 6–3). After 10 seconds of maximal voluntary contraction, increased mobilization of quanta and accumulation of calcium occur, resulting in greater numbers of quanta released and a higher EPP. This *postexercise facilitation* can be demonstrated in two situations. First, in presynaptic disorders such as Lambert–Eaton myasthenic syndrome that are associated with reduced release of quanta and subthreshold EPPs at baseline, brief exercise can facilitate EPPs above threshold, giving rise to muscle fiber action potentials that were not present previously. Accordingly, an increment of CMAP amplitude and area occurs. Second, brief exercise can repair EPPs that have been lowered by slow repetitive nerve stimulation. If the EPPs are facilitated above threshold, muscle fiber action potentials will be generated that were not present previously. Accordingly, a decrement of CMAP amplitude and area that has developed during slow RNS may be lessened or "repaired" (Figure 6–3A and B).

To demonstrate *postexercise exhaustion*, the muscle is maximally exercised for 1 minute. Then slow RNS is performed immediately after and 1, 2, 3, and 4 minutes later. In normal subjects with a normal safety factor, the EPP never falls below threshold, and the CMAP amplitude and area remain stable. In patients with impaired NMJ transmission, however, the decrement in CMAP amplitude and area in response to slow RNS becomes more marked 2 to 4 minutes after prolonged exercise (Figure 6–3C–E). If this

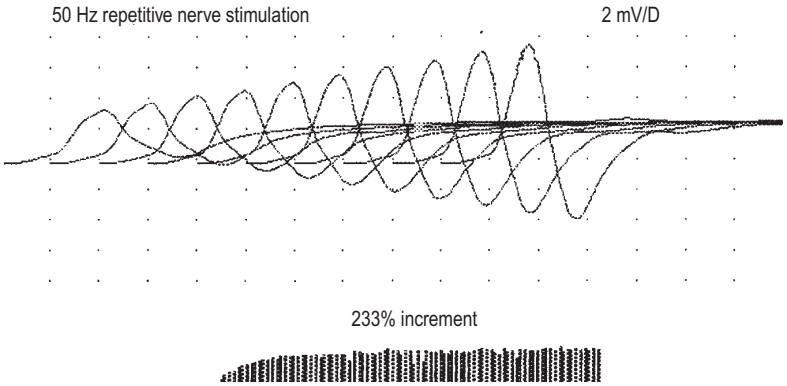

FIGURE 6–4 Increment during rapid repetitive nerve stimulation. Recording the hypothenar muscles, stimulating the ulnar nerve at 50 Hz in a patient with Lambert–Eaton myasthenic syndrome. **Top trace:** First ten responses. **Bottom trace:** Change in compound muscle action potential amplitude over 5 seconds. Note in this example the marked increment, typical of a presynaptic neuromuscular junction disorder.

occurs, 10 seconds of maximal voluntary exercise can be used to repair the decrement toward normal (Figure 6–3F).

In normal subjects, brief intense exercise may lead to a slight increase in CMAP amplitude by a process known as "pseudofacilitation." After brief exercise, EPPs are facilitated. Because they are above threshold at baseline, however, the same number of muscle fiber action potentials is generated. Although there is no increase in the actual number of muscle fiber action potentials that summate to create the CMAP, brief maximal exercise causes the muscle fibers to fire more synchronously. This likely occurs as a result of a faster rise time of all the EPPs, which then results in more muscle fiber action potentials firing at the same time. This pseudofacilitation results in an increase in CMAP amplitude, but usually with a decrease in CMAP duration and little change in the CMAP area (Figure 6–5). In general, postexercise increments of CMAP amplitude from pseudofacilitation do not exceed 40% in normal subjects (i.e., 40% higher than the baseline).

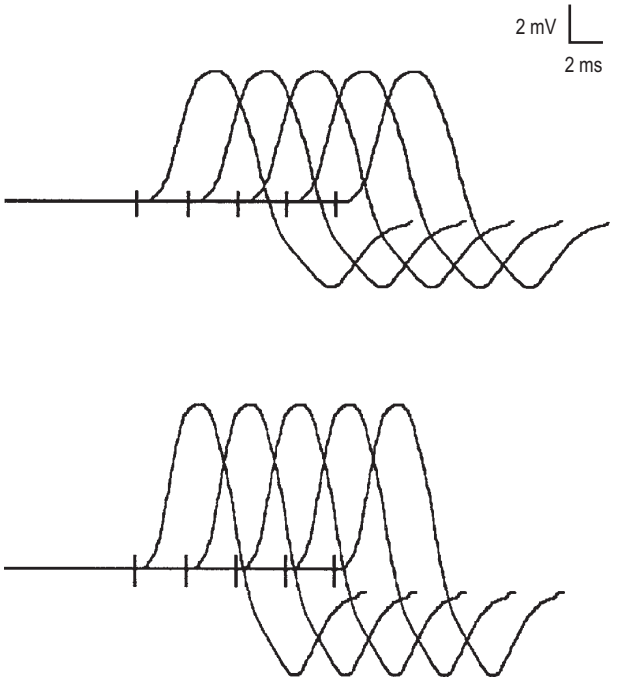

FIGURE 6–5 Pseudofacilitation. When performing repetitive nerve stimulation (RNS) following exercise testing, pseudofacilitation is often encountered. Pseudofacilitation is a normal phenomenon caused by more synchronous firing of muscle fiber action potentials immediately following brief intense exercise. In the figure above from a normal subject, 3 Hz RNS results in a 0% compound muscle action potential (CMAP) decrement at rest **(top trace).** Immediately following 10 seconds of maximal voluntary exercise, 3 Hz RNS is repeated **(bottom trace).** A similar 0% decrement is found. However, the CMAP amplitudes are higher, the durations shorter, and the areas unchanged, due to the normal effects of pseudofacilitation.

Technical Factors in Repetitive Nerve Stimulation

Close attention to technical factors is critical when performing RNS and exercise testing. If not appreciated and closely controlled, technical factors may result in either factitious decrements or increments and lead to the mistaken impression of an NMJ disorder.

Immobilization: Isometric Electrode Position is Essential

The greatest technical problem with RNS is failure to properly immobilize the recording electrode over the muscle. If the position of the recording electrode moves in relationship to the muscle during stimulation, CMAP configuration may change. The goal is to minimize any movement of the limb, stimulator, or recording electrodes during RNS. The recording electrodes should always be well secured with tape. If possible, the stimulator should be secured with tape or a Velcro© strap, while being held in place by the electromyographer, and the entire limb should be secured to a pad or board (Figure 6–6). Immobilization is more easily accomplished when stimulating distal nerves such as the median or ulnar. When stimulating proximal nerves, securing the stimulator and limb to prevent movement is more problematic.

Stimuli must be Supramaximal

Submaximal stimulation can create a host of problems, including both artifactual CMAP decrements and increments (Figure 6–7). Always check to ensure that the stimulus is supramaximal before beginning RNS.

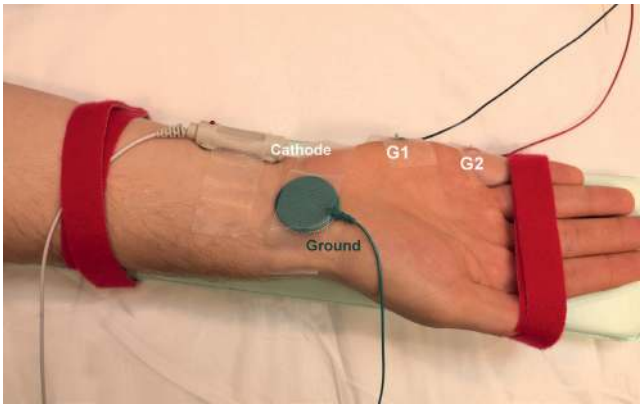

FIGURE 6–6 Immobilization during repetitive nerve stimulation of a limb muscle. Setup for ulnar nerve repetitive nerve stimulation. Recording electrodes secured with tape over the abductor digiti minimi, as usual. The stimulator is secured to the wrist with a Velcro© strap or tape. The entire forearm and hand are secured to an arm board with additional Velcro© straps, and the fingers are taped together.

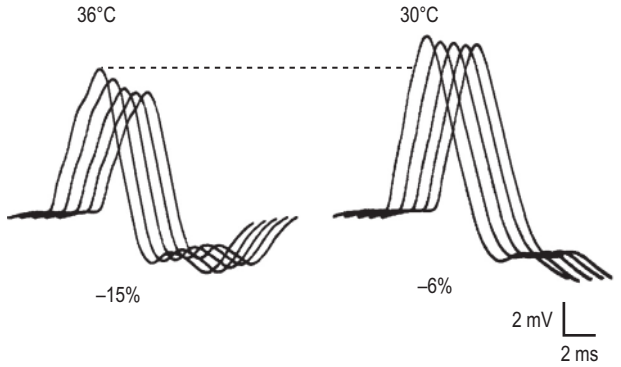

FIGURE 6–8 Temperature effect on repetitive nerve stimulation. Decremental response is diminished in a cool limb. Patient with myasthenia gravis, before and after limb cooling.
(From Denys EH. AAEM minimonograph #14: the influence of temperature in clinical neurophysiology. Muscle Nerve 1991;14:803. Reprinted by permission of John Wiley & Sons, Inc.)

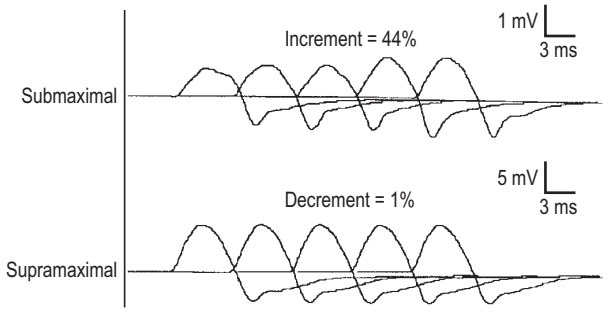

FIGURE 6–7 Artifactual increment with submaximal stimuli. Compound muscle action potential increment with 3 Hz repetitive nerve stimulation in a normal subject caused by submaximal stimulation. Note that there is no increment with supramaximal stimulation.

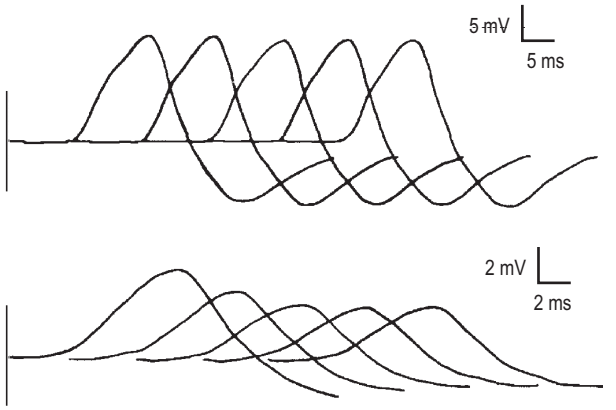

FIGURE 6–9 Three-Hertz repetitive nerve stimulation of proximal and distal nerves in patient with myasthenia gravis. **Top trace:** Normal decrement (4%) in the ulnar nerve. **Bottom trace:** Markedly abnormal decrement (42%) in the spinal accessory nerve. In myasthenia gravis, the yield of finding an abnormal decrement is greater with proximal nerves. Note the U-shaped decrement.

Temperature must be Controlled

In NMJ disorders, a CMAP decrement may be diminished if the limb is cold (Figure 6–8). The reason for this is not completely known but may be related to decreased functioning of the enzyme acetylcholinesterase when it is cold, effectively making more ACH available to bind at the ACHRs. Clinically, patients with myasthenia gravis note worsening of their symptoms in warm weather, perhaps because the acetylcholinesterase is more active. RNS in the EDX laboratory should always be done with the temperature at least 33°C at the recording site or there is a risk that a decrement will be missed.

Acetylcholinesterase Inhibitors should be Withheld Prior to the Study

It is best to advise patients to refrain from taking acetylcholinesterase inhibitors (e.g., pyridostigmine [Mestinon®]) for at least 3 to 4 hours before the study, unless medically contraindicated. These agents make more ACH available to bind at the ACHRs and may diminish a decrement, resulting in a normal study.

Nerve Selection

RNS can be performed using any motor nerve. The nerves most commonly used are the ulnar, median, musculocutaneous, axillary, spinal accessory, and facial.

In patients with postsynaptic NMJ disorders (e.g., myasthenia gravis), clinical weakness predominantly affects ocular, bulbar, and proximal muscles. Thus, it is not surprising that the yield of abnormalities increases with the use of more proximal nerves (Figure 6–9). Unfortunately, however, more technical difficulties are associated with stimulation of proximal nerves. Of the proximal nerves, we favor stimulation of the spinal accessory nerve and recording of the upper trapezius (Figure 6–10). The spinal accessory nerve is quite superficial, just posterior to the

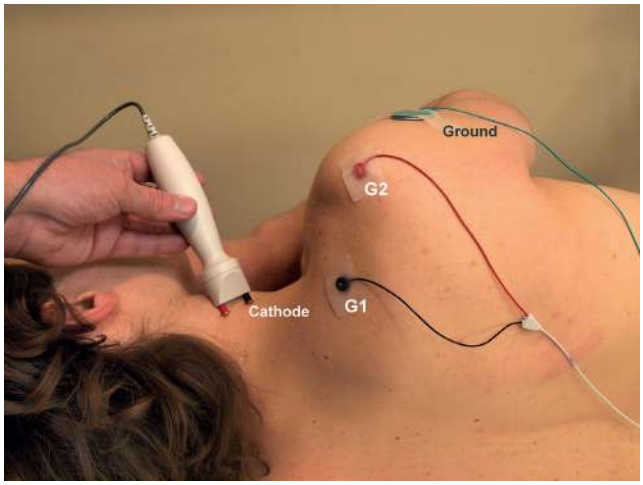

FIGURE 6–10 Spinal accessory nerve stimulation. The nerve is easily stimulated posterior to the sternocleidomastoid muscle with recording electrodes over the upper trapezius (G1) and shoulder (G2).

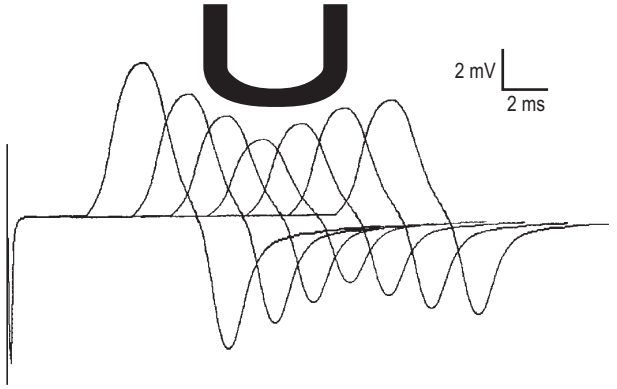

FIGURE 6–11 "U-shaped" decrement. Three-Hertz repetitive nerve stimulation of the ulnar nerve recording the hypothenar muscles in a patient with myasthenia gravis. Note the large decrement between the first and fourth potentials. However, after the fourth potential, the decrement is not as marked and forms a "U shape." The decrement begins to improve when the mobilization store begins to resupply the immediately available store. This normally requires 1 to 2 seconds and is highly characteristic of a true neuromuscular junction disorder.

sternocleidomastoid muscle, and it can usually be supramaximally stimulated with 15 to 25 mA of current. Shoulder movement can be reduced by gentle but firm downward pressure on the shoulder or arm.

The facial nerve can be used for RNS, recording the nasalis, orbicularis oculi, or other facial muscle. However, two basic problems are often encountered with facial RNS: CMAP amplitudes are small at baseline, and the muscle cannot be immobilized so as to prevent possible electrode movement. Consider the following. If a facial muscle has a baseline CMAP amplitude of 1 mV at rest, a drop of 0.1 mV will result in a 10% decrement. In contrast, the ulnar nerve may have a baseline CMAP amplitude of 10 mV, which would require a drop of 1 mV to yield a 10% decrement. It is easy to see that small changes from the baseline CMAP (e.g., from electrode movement or failure to perform supramaximal stimulation) would be much more likely to confound facial RNS, possibly creating false-positive results.

Stimulation Frequency

The optimal frequency for slow RNS is 2 or 3 Hz. The frequency for slow RNS must be kept low enough to prevent calcium accumulation but high enough to deplete the quanta in the immediately available store before the mobilization store starts to replenish it. For rapid RNS, the optimal frequency is 30 to 50 Hz, but, as noted earlier, having the patient perform brief intense exercise is always preferable to rapid RNS. Only in the event of an uncooperative patient (e.g., an infant or a patient in coma) or a patient who is too weak to perform brief intense exercise should rapid RNS be used.

Number of Stimulations

A train of 5 to 10 pulses is preferable for slow RNS. The number should be kept to a minimum for patient comfort, but that concern is counterbalanced by the need to have enough pulses to detect a decrement. When the mobilization store begins to resupply the immediately available store, the decrement begins to improve. The result is a so-called *U-shaped* decrement, which is highly characteristic of true NMJ disorders (Figure 6–11). For rapid RNS, which should be done only in patients who cannot perform brief maximal voluntary exercise, a stimulus train of 5 to 10 seconds should be given (i.e., 250 to 500 stimulations). This is the length of time often required to see the maximal incremental response from increased mobilization of quanta and calcium accumulation.

Decrement and Increment Calculation

The decrement usually is calculated by comparing the lowest CMAP amplitude or area to the baseline CMAP. The CMAP decrement is expressed as a percentage and calculated as follows:

$$\%\ \text{Decrement} = \frac{\text{Amplitude (baseline CMAP)} - \text{Amplitude (lowest CMAP)}}{\text{Amplitude (baseline CMAP)}} \times 100$$

With 3 Hz RNS, the lowest CMAP usually is the third or fourth. By the fifth or sixth stimulation, the decrement begins to improve because the mobilization store has begun resupplying the immediately available store (i.e., the U-shaped decrement). Any decrement of >10% is defined as abnormal. Normal subjects should have no decrement. The 10% cutoff allows for inherent technical factors that are often encountered. However, any reproducible decrement probably is abnormal.

Increments are calculated by comparing the highest CMAP amplitude or area with the baseline CMAP. With 10 seconds of maximal voluntary contraction, the calculation is simple and consists of comparing the CMAP obtained

after brief exercise with the baseline CMAP. With rapid RNS, the highest CMAP usually is the last one obtained after 5 to 10 seconds, which then is compared with the baseline CMAP. The CMAP increment is expressed as a percentage and calculated as follows:

$$\%\ \text{Increment} = \frac{\text{Amplitude (highest CMAP)} - \text{Amplitude (baseline CMAP)}}{\text{Amplitude (baseline CMAP)}} \times 100$$

In normal subjects, pseudofacilitation may cause an increment of up to 40%. Increments of >100% are often encountered in presynaptic NMJ disorders. Increments between 40 and 100% are best considered equivocal. What is meant by a percentage increment often is confusing. For example, does a 200% increment mean that the potential increases by an extra 200% above baseline, or does it mean that the increment is 200% of baseline? The former is correct. If the baseline CMAP is 1 mV, which increments to 3 mV after 10 seconds of exercise, this is a 200% increment.

Other Disorders that may Show a Decrement on RNS

A decremental response with RNS occurs predominantly in primary disorders of the NMJ. However, a decrement also may be seen in other disorders, especially in severe denervating disorders (e.g., motor neuron disease). In any condition in which there is prominent denervation and reinnervation, newly formed NMJs, which occur as denervated fibers are reinnervated, are immature and unstable. These immature and unstable NMJs may show a decrement in response to RNS. In addition to denervating disorders, some myopathic conditions, including the myotonic disorders and the metabolic myopathies (e.g., McArdle's disease), may show a decrement in response to RNS. *This underscores that RNS should not be performed in isolation.* For every patient, a clinical history and directed neurologic examination, as well as routine nerve conduction studies and needle EMG, must be performed so that any decremental response during RNS can be interpreted correctly.

Repetitive Nerve Stimulation Protocol

The recommended RNS protocol is outlined in Box 6–1. Because technical factors commonly complicate RNS, one must constantly ask, "Does the decrement make sense in terms of NMJ physiology?" The following questions should be kept in mind.

1. Is the baseline CMAP stable?
2. If there is a CMAP decrement or increment, is it reproducible? Any data that are not reproducible are of questionable value.
3. If there is a CMAP decrement, does it repair with 10 seconds of maximal voluntary exercise (i.e., postexercise facilitation)?
4. Does the CMAP decrement worsen several minutes after a prolonged (1-minute) exercise (postexercise exhaustion)? If the decrement worsens several minutes after prolonged exercise, can the decrement then be repaired after 10 seconds of maximal voluntary exercise (postexercise facilitation again)?
5. Is there a U-shaped decrement (i.e., does the CMAP amplitude decrement up to the third, fourth or fifth stimulation, stabilize, and then slightly improve (as the result of the secondary or mobilization store resupplying the immediately available store with a resultant increase in ACH release)?

If all of these questions can be answered affirmatively, the decrement or increment probably is secondary to a true NMJ disorder.

Box 6–1. Protocol for Evaluating Disorders of the Neuromuscular Junction

1. Warm the extremity (33°C).
2. Immobilize the muscle as best as possible.
3. Perform routine motor nerve conduction studies first to ensure that the nerve is normal.
4. Perform RNS at rest. After making sure that the stimulus is supramaximal, perform 3 Hz RNS at rest for 5–10 impulses, repeated three times, 1 minute apart. Normally, there is <10% decrement between the first and fourth responses.
5. If >10% decrement occurs and is consistently reproducible:
   A. Have the patient perform maximal voluntary exercise for 10 seconds.
   B. Immediately repeat 3 Hz RNS postexercise to demonstrate postexercise facilitation and repair of the decrement.
6. If <10% decrement or no decrement occurs:
   A. Have the patient perform maximal voluntary exercise for 1 minute, then perform 3 Hz RNS immediately and 1, 2, 3 and 4 minutes after exercise to demonstrate postexercise exhaustion.
   B. If a significant decrement occurs, have the patient perform maximal voluntary exercise again for 10 seconds and immediately repeat 3 Hz RNS to demonstrate repair of the decrement.
7. Perform RNS on one distal and one proximal motor nerve. Always try to study weak muscles. If no decrement is found with a proximal limb muscle, a facial muscle can be tested, keeping in mind technical considerations.
8. If the compound muscle action potential amplitude is low at baseline, have the patient perform 10 seconds of maximal voluntary exercise, then stimulate the nerve supramaximally immediately postexercise, looking for an abnormal increment (>40% above the baseline is abnormal, >100% is highly suggestive of a presynaptic NMJ disorder). If the patient exercises for >10 seconds or the nerve is not stimulated immediately postexercise, a potential increment may be missed.
9. Always perform concentric needle EMG of proximal and distal muscles, especially of clinically weak muscles. Any muscle with denervation or myotonia on needle EMG may demonstrate a decrement on RNS. In these situations, a decrement on RNS does not signify a primary disorder of the neuromuscular junction.

EMG, electromyography; RNS, repetitive nerve stimulation.

Suggested Readings

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7 Anomalous Innervations

Although peripheral nerve anatomy is more or less similar among individuals, in a sizable minority, there are some significant anatomic variations. These are known as anomalous innervations. Several of these anomalous innervations of peripheral nerve are commonly seen in the EMG laboratory. It is critical that every electromyographer be able to identify them during routine nerve conduction studies. If these anomalies are not recognized, they may easily be mistaken for technical abnormalities or, in some cases, for actual pathology.

MARTIN–GRUBER ANASTOMOSIS

The most commonly encountered anomaly in the upper extremity is a cross-over of median-to-ulnar fibers, the Martin–Gruber anastomosis (MGA). The anastomosis involves only motor fibers; sensory fibers are spared. The cross-over usually occurs in the mid-forearm originating from the branches of the median nerve supplying the superficial forearm flexor muscles, the anterior interosseous nerve, or directly from the main median nerve. The median fibers that have crossed over then run with the distal ulnar nerve to innervate any of the following ulnar muscles: (1) the hypothenar muscles (abductor digiti minimi), (2) the first dorsal interosseous muscle (FDI), (3) the thenar muscles (adductor pollicis, deep head of flexor pollicis brevis), or (4) a combination of these. The most common by far is for the anastomosis to innervate the FDI.

This particular anomaly is quite common and has been reported to occur in 15 to 30% of patients. When present, it may be unilateral or bilateral. During routine nerve conduction studies, the MGA may be recognized under the following circumstances.

Routine Ulnar Conduction Study: Pseudo-Conduction Block between the Wrist and Below-Elbow Sites

The MGA may be recognized during routine ulnar motor studies, recording the abductor digiti minimi, stimulating at the wrist and below-elbow sites (Figure 7–1). If the anastomotic fibers innervate the abductor digiti minimi, a characteristic pattern results: a drop in the ulnar compound muscle action potential (CMAP) amplitude is seen between the wrist and the below-elbow stimulation sites (Figure 7–2). With stimulation at the wrist, the CMAP reflects all motor fibers innervating the hypothenar muscles, including those that have crossed over more proximally from the median nerve. Stimulation at the below-elbow site activates fewer fibers, however, as this stimulation site is above the cross-over. Thus, the portion of fibers innervating the abductor digiti minimi that originate from the median nerve have already crossed over in the forearm and, therefore, do not contribute to the CMAP. The differential diagnosis of this pattern (i.e., higher amplitude distally than proximally) includes the following:

- Excessive stimulation of the ulnar nerve at the wrist resulting in co-stimulation of the median nerve
- Submaximal stimulation of the ulnar nerve at the below-elbow site
- Conduction block of the ulnar nerve between the wrist and below-elbow sites
- An MGA with crossing fibers innervating the hypothenar muscles

If a reduced ulnar CMAP is found at the below-elbow stimulation site compared with the wrist, it is essential first to check that co-stimulation has not occurred at the wrist and that submaximal stimulation has not occurred at the below-elbow site. Note that up to a 10% drop in the ulnar CMAP amplitude at the below-elbow (compared with wrist) site is considered normal secondary to normal temporal dispersion. *The major danger in not recognizing an MGA in this situation is that of mistakenly interpreting the findings as a conduction block in the forearm, an unequivocal sign of demyelination.* This error is especially serious in that the presence of a conduction block at a nonentrapment site usually signifies an acquired demyelinating peripheral neuropathy, which often is treated with immunosuppressive or immunomodulating therapy.

Whenever there is a >10% drop in amplitude between the wrist and below-elbow sites on routine ulnar motor studies, median nerve stimulation should always be

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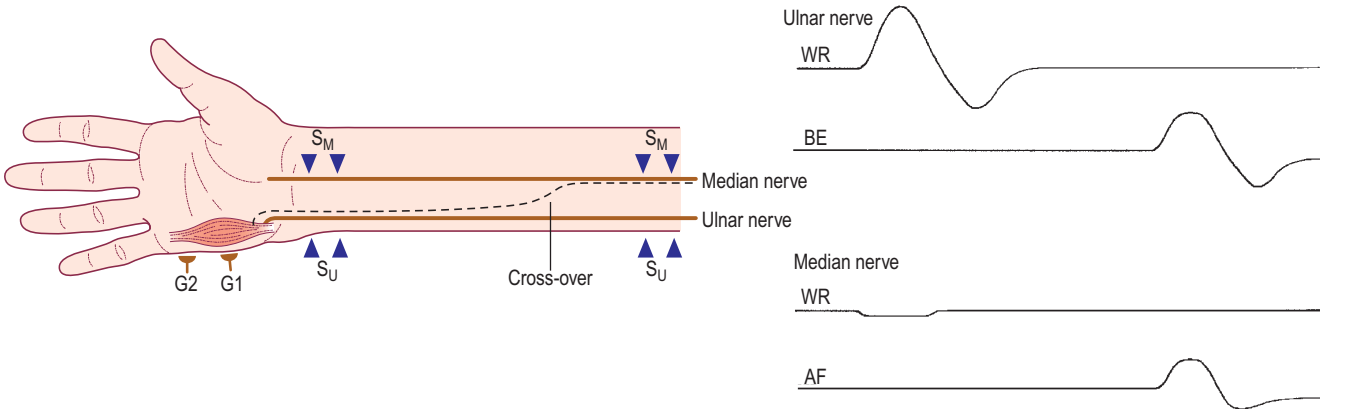

FIGURE 7–1 Martin–Gruber anastomosis (MGA). Cross-over of median-to-ulnar fibers supplying the hypothenar muscles may occur in MGA. During routine ulnar motor studies, recording the abductor digiti minimi and stimulating the ulnar nerve (S_U) at the wrist (WR) and below-elbow (BE) sites, the ulnar compound muscle action potential (CMAP) amplitude with BE stimulation is lower than with WR stimulation. If an MGA is not recognized, a mistaken impression of a conduction block may occur. To demonstrate an MGA in this situation, the median nerve is stimulated (S_M) at the WR and antecubital fossa (AF) while recording the hypothenar muscles, looking for a CMAP stimulating at the AF that is not present stimulating at the WR.

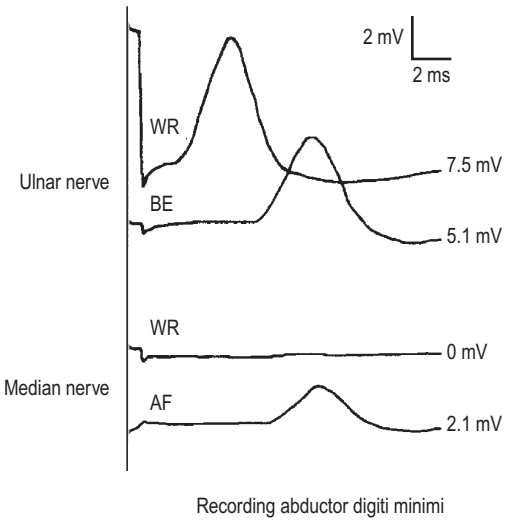

FIGURE 7–2 Martin–Gruber anastomosis and pseudo-conduction block of the ulnar nerve in the forearm. Recording hypothenar muscles (abductor digiti minimi), stimulating ulnar nerve at the wrist (WR) and below-elbow (BE) sites results in a drop in amplitude at the BE site. The anastomosis is demonstrated by stimulating the median nerve at the wrist and antecubital fossa (AF), recording hypothenar muscles. There is no potential with WR stimulation, whereas one is present with AF stimulation. The compound muscle action potential amplitude evoked with median nerve stimulation at the AF is approximately equal to the drop in amplitude on the ulnar studies.

performed at the wrist and at the antecubital fossa while recording the hypothenar muscles to check for an MGA. If no MGA is present, a small positive deflection usually is recorded with both the wrist and antecubital fossa stimulation sites, reflecting a volume-conducted potential from median muscles (see Chapter 2). If an MGA is present, a small positive volume-conducted potential will be present with median nerve stimulation at the wrist; however, median stimulation at the antecubital fossa will evoke a small CMAP over the abductor digiti minimi. The amplitude of the CMAP evoked by stimulating the median nerve at the antecubital fossa (recording the hypothenar muscles) will approximately equal the difference between the CMAP amplitudes evoked with ulnar nerve stimulation at the wrist and below-elbow sites (recording the hypothenar muscles). However, it is important not to overstimulate the median nerve at the antecubital fossa, resulting in co-stimulation of the ulnar nerve at the elbow, and thereby giving the appearance of an MGA when none truly exists. This can be avoided by slowly moving the stimulator from the median nerve at the antecubital fossa to the ulnar nerve at the elbow, stimulating at several points. In a true MGA, the CMAP that is evoked with median nerve stimulation at the antecubital fossa will briefly disappear as the stimulator is moved toward, but not over, the ulnar nerve at the elbow. It will then reappear with ulnar nerve stimulation at the elbow.

Ulnar Conduction Study: Proximal Martin–Gruber Anastomosis and Pseudo-Conduction Block between the Below-Elbow and Above-Elbow Sites

In patients with ulnar neuropathy at the elbow, one of the classic electrophysiologic findings is conduction block across the elbow, whereby a drop in the CMAP amplitude is seen between the below-elbow and above-elbow sites during routine ulnar motor studies (see Chapter 19). This pattern is not typically confused with an MGA, because the drop in CMAP amplitude in a typical MGA occurs between

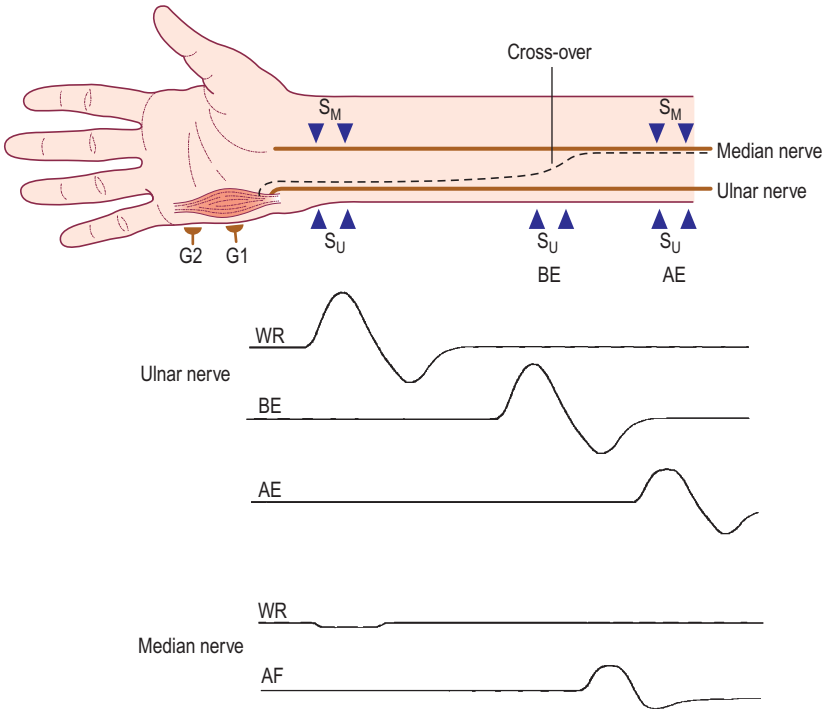

FIGURE 7–3 Proximal Martin–Gruber anastomosis (MGA) mimicking ulnar neuropathy at the elbow. An MGA may rarely result in the mistaken diagnosis of ulnar neuropathy at the elbow if the anastomosis is very proximal, the below-elbow (BE) stimulation site is too distal, or a combination of both. In this example, routine ulnar motor studies are performed, recording the abductor digiti minimi and stimulating the ulnar nerve (S_U) at the wrist (WR), below-elbow (BE), and above-elbow (AE) sites. The ulnar amplitude at the AE stimulation site is lower than at the WR and BE stimulation sites. If the MGA is not recognized, a mistaken impression of a conduction block across the elbow may occur. To demonstrate an MGA in this situation, the median nerve is stimulated (S_M) at the WR and antecubital fossa (AF) while recording the ulnar muscles, looking for a compound muscle action potential that is either present or higher in amplitude at the AF than when stimulating at the WR. This error is avoided if the BE stimulation site of the ulnar nerve is maintained at 3 cm distal to the medial epicondyle. In addition, one should always look for an MGA in a patient with an apparent ulnar neuropathy at the elbow that is diagnosed solely by a conduction block across the elbow without any other abnormalities or clinical symptoms to suggest an ulnar neuropathy.

the wrist and below-elbow sites, mimicking a conduction block in the forearm, not across the elbow. However, very rarely, the cross-over fibers of the MGA are very proximal, and if stimulated, will contribute to the CMAP amplitude at the below-elbow site. In contrast stimulation above the elbow will not excite these cross-over fibers, thereby giving the impression of a conduction block across the elbow. It is in these cases, where the below-elbow stimulation might occur below the MGA, that an MGA may result in the mistaken diagnosis of ulnar neuropathy with conduction block at the elbow (Figure 7–3). This is especially apt to occur when the below-elbow stimulation site is too distal, making it more likely that the below-elbow stimulation occurs below the MGA, thereby exciting the cross-over fibers.

In one anatomic study of cadavers found to have an MGA, the anastomosis joined the ulnar nerve an average of 8.4 cm (range 5–12) distal to the medial epicondyle, whereas electrophysiologic studies have suggested the possibility of an MGA even more proximal, as close as 3 cm distal to the medial epicondyle. Thus, if the below-elbow site is stimulated 3 cm or further distal to the medial epicondyle (especially >5 cm), there is a possible risk of a proximal MGA mimicking the pattern of an ulnar neuropathy with conduction block at the elbow. As ulnar neuropathies across the elbow typically occur either at the elbow or at the cubital tunnel (under the aponeurosis of the flexor carpi ulnaris), the below-elbow stimulation site needs to be at least 2 cm distal to the medial epicondyle, which is the most distal location of the cubital tunnel. This underscores the need to stimulate the below-elbow site of the ulnar nerve at the proper location, 3 cm distal to the medial epicondyle (see Chapter 10), and not more distally. In addition, one should always look for an MGA in any patient with a conduction block of the ulnar nerve at the elbow without any other supporting abnormalities to suggest an ulnar neuropathy at the elbow.

Ulnar Conduction Study Recording the First Dorsal Interosseous: Pseudo-Conduction Block between the Wrist and Below-Elbow Sites

The most common MGA (Figure 7–4) occurs with crossing over of median-to-ulnar fibers supplying the FDI. Nevertheless, this anastomosis is not often recognized during routine ulnar motor nerve conduction studies because the abductor digiti minimi is the muscle most often recorded for routine ulnar motor studies. However, it is not an uncommon finding when ulnar motor studies are performed recording the FDI. The FDI is commonly recorded in two situations: (1) looking for a lesion of the deep palmar motor branch of the ulnar nerve (i.e., ulnar neuropathy at the wrist), and (2) when evaluating a suspected ulnar neuropathy at the elbow (see Chapter 19).

The pattern that suggests an MGA to the FDI is similar to that seen in routine ulnar motor studies recording the hypothenar muscles with an anastomosis to the abductor digiti minimi: there is a drop in the CMAP amplitude between the wrist and below-elbow sites. However, it is more complicated to prove an MGA to the FDI than to the abductor digiti minimi because a CMAP is normally

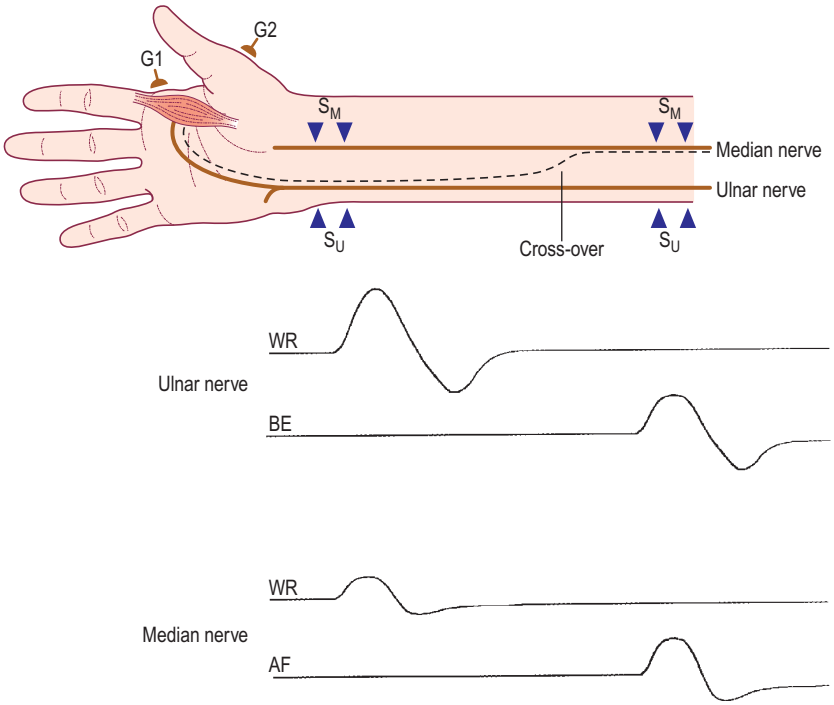

FIGURE 7–4 Martin–Gruber anastomosis (MGA). Cross-over of median-to-ulnar fibers supplying the first dorsal interosseous is the most common type of MGA. However, this anastomosis frequently is not recognized unless ulnar motor studies are performed recording the first dorsal interosseous muscle (FDI). This type of MGA manifests as a drop in amplitude between the wrist (WR) and below-elbow (BE) stimulation sites (S_U), when ulnar motor studies are performed recording the FDI. If the MGA is not recognized, a mistaken impression of a conduction block may occur. To demonstrate an MGA in this situation, the median nerve is stimulated (S_M) at the WR and antecubital fossa (AF) while recording the FDI, looking for a higher amplitude proximally than distally. Normally, there is a compound muscle action potential provoked by median nerve stimulation recording the FDI as a result of volume conduction of nearby median innervated muscles. The higher amplitude occurs stimulating the AF due to the added contribution of the cross-over fibers as well as the normal contribution from the co-recording of nearby median-innervated muscles.

provoked when stimulating the median nerve at the wrist or at the antecubital fossa, recording the FDI. This is a normal finding due to volume conduction from nearby median-innervated muscles, specifically the abductor pollicis brevis, opponens pollicis, and superficial head of the flexor pollicis brevis. Thus, to prove an MGA to the FDI, the median nerve is stimulated at the wrist and antecubital fossa while recording the FDI, looking for a higher-amplitude CMAP with antecubital fossa stimulation than with wrist stimulation (Figure 7–5). Antecubital fossa stimulation produces a higher-amplitude CMAP than wrist stimulation because of the added contribution of the cross-over fibers in addition to the contribution from the co-recorded nearby median-innervated muscles. Typically, the difference between the wrist and antecubital fossa stimulations approximates the drop in amplitude between the wrist and below-elbow sites when stimulating the ulnar nerve. The same caveat regarding overstimulating at the antecubital fossa applies here, as noted above. It is important to not overstimulate the median nerve at the antecubital fossa, resulting in co-stimulation of the ulnar nerve at the elbow, and thereby giving the appearance of an MGA when none truly exists.

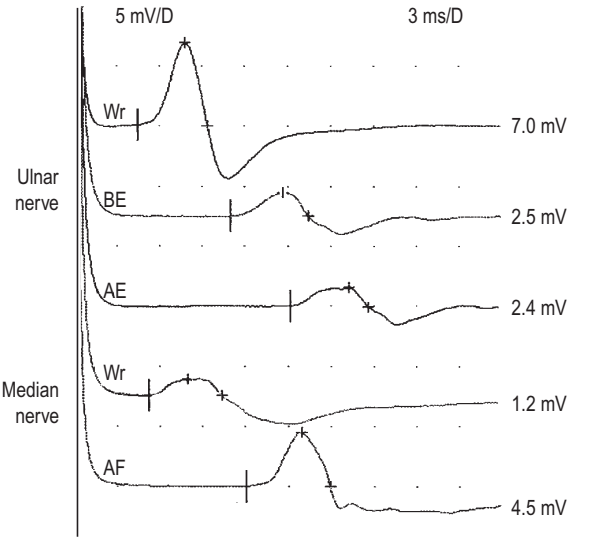

FIGURE 7–5 Martin–Gruber anastomosis during routine ulnar motor studies recording the first dorsal interosseous muscle (FDI). Recording the FDI, stimulating the ulnar nerve at the wrist (WR), below-elbow (BE), and above-elbow (AE) sites, results in a drop in amplitude between the WR and BE sites. The anastomosis is demonstrated by stimulating the median nerve at the WR and the antecubital fossa (AF), showing a larger amplitude potential at the AF site than at the WR. Normally when stimulating the median nerve at the wrist, recording the FDI, there is a potential evoked. This occurs as a normal finding from volume conduction of nearby median-innervated muscles.

Routine Median Motor Study: Increased Compound Muscle Action Potential Amplitude Proximally

The third instance in which an MGA should be suspected is during routine median motor studies, when the median-to-ulnar cross-over innervates one of the ulnar-innervated thenar muscles (i.e., adductor pollicis or deep head of the

flexor pollicis brevis) (Figure 7–6). With this type of MGA, routine ulnar motor studies, recording the abductor digiti minimi, are normal. However, during routine median motor studies, recording the thenar muscles, a characteristic pattern is seen: the CMAP amplitude is higher stimulating the median nerve at the antecubital fossa than stimulating at the wrist (Figure 7–7), unlike the usual pattern of a higher-amplitude CMAP with distal stimulation. The differential diagnosis of this pattern is:

- Submaximal stimulation of the median nerve at the wrist
- Excessive stimulation of the median nerve at the antecubital fossa resulting in co-stimulation of the ulnar nerve
- An MGA with cross-over fibers innervating the thenar muscles

To demonstrate that an MGA is present, the examiner must then stimulate the ulnar nerve at the wrist and below-elbow sites while recording the thenar muscles. Normally, ulnar stimulation at the wrist, recording thenar muscles, evokes a thenar CMAP, usually with an initial positive deflection. This CMAP reflects the normal ulnar-innervated muscles in the thenar eminence. If no MGA is present, subsequent stimulation of the ulnar nerve at the below-elbow site will evoke a CMAP potential with the same amplitude. If an MGA is present, the CMAP amplitude will be substantially lower stimulating the ulnar nerve at the below-elbow site than at the wrist. This is because stimulation at the below-elbow site is above the cross-over, and, therefore, the cross-over fibers do not contribute to the CMAP. The difference in amplitude between these two potentials approximates the contribution of the cross-over fibers.

Martin–Gruber Anastomosis and Carpal Tunnel Syndrome: Positive Proximal Deflection ("Dip") and Factitiously Fast Conduction Velocity

The last situation in which an MGA should be recognized occurs when there is a coexistent carpal tunnel syndrome (median neuropathy at the wrist). Because MGA and carpal tunnel syndrome both are quite common, this situation is not infrequent and thus can be seen during routine median motor studies. The clues to an MGA with carpal tunnel syndrome are (1) a positive deflection with median nerve stimulation at the antecubital fossa recording the thenar muscles (note: the positive deflection does not occur stimulating the median nerve at the wrist), and often (2) a surprisingly fast conduction velocity of the median nerve in the forearm (Figure 7–8).

In this situation, the distal median motor latency is prolonged when stimulating at the wrist. All median nerve fibers stimulated at the wrist must travel through the carpal tunnel and therefore are delayed. However, when the median nerve is stimulated at the antecubital fossa, most fibers travel down the arm and through the carpal tunnel as usual, but some median nerve fibers bypass the carpal tunnel by traveling through the anastomosis and innervating ulnar muscles. Because these fibers bypass the carpal tunnel, they arrive in the hand much sooner than the median fibers that are delayed through the carpal tunnel. When they depolarize their ulnar-innervated muscles, a

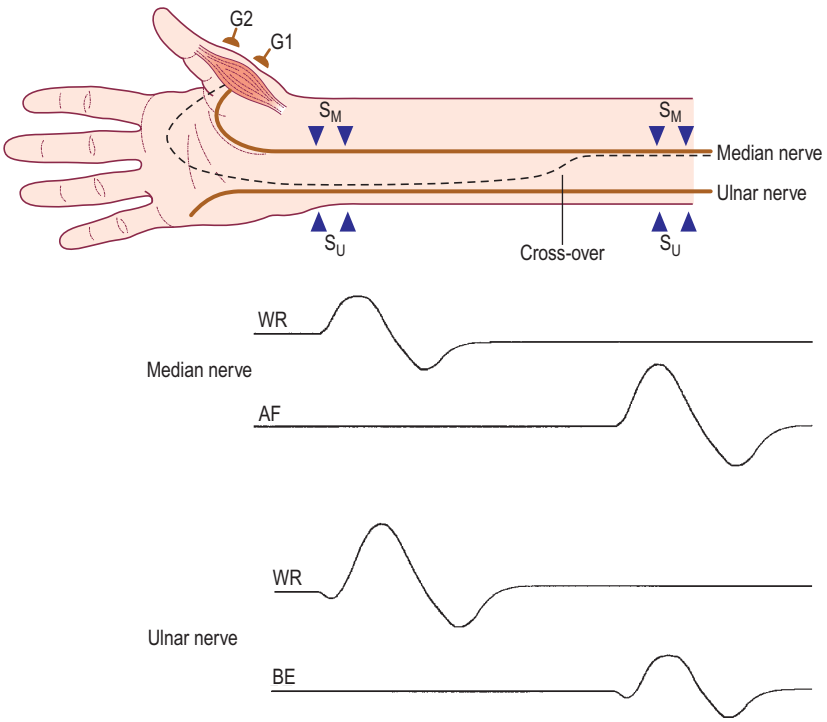

FIGURE 7–6 Martin–Gruber anastomosis (MGA). Cross-over of median-to-ulnar fibers supplying the thenar muscles may occur in MGA. During routine median motor studies, recording the abductor pollicis brevis and stimulating the median nerve (S_M) at the wrist (WR) and the antecubital fossa (AF), the median compound muscle action potential (CMAP) amplitude stimulating the AF is higher than that obtained with WR stimulation. Routine ulnar studies, recording the hypothenar muscles, are normal. To demonstrate an MGA in this situation, the ulnar nerve is stimulated (S_U) at the WR and below-elbow (BE) sites while recording the thenar muscles, looking for a drop in CMAP amplitude between WR and BE sites.

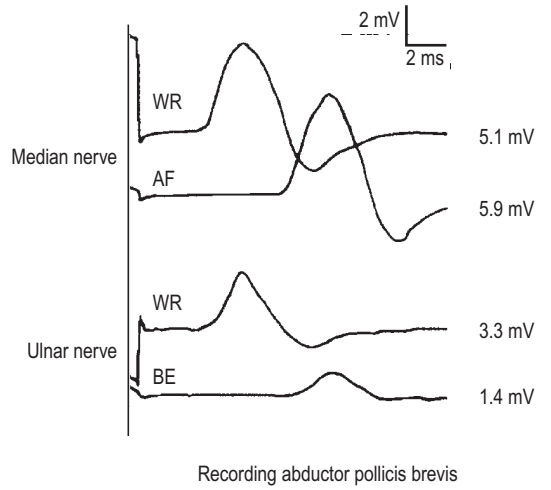

FIGURE 7–7 Martin–Gruber anastomosis during routine median motor studies. Recording thenar muscles (abductor pollicis brevis), stimulating the median nerve at the wrist (WR) and antecubital fossa (AF), results in an increase in amplitude at the AF site. The anastomosis is demonstrated by stimulating the ulnar nerve at the wrist (WR) and below-elbow (BE) sites, recording thenar muscles. There is a larger potential stimulating at the WR than at the BE site.

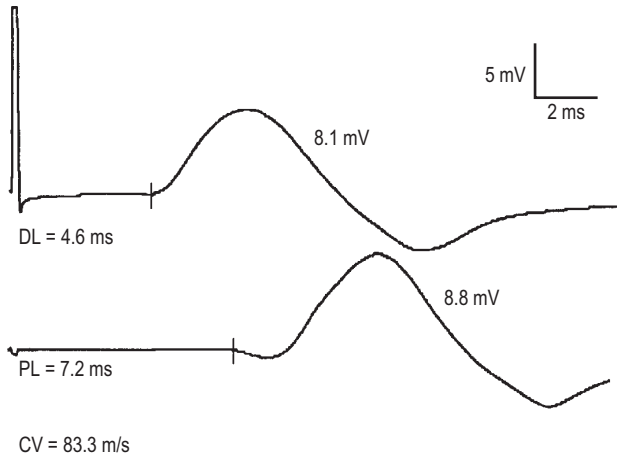

FIGURE 7–8 Martin–Gruber anastomosis and carpal tunnel syndrome. Routine median motor study, recording the abductor pollicis brevis, stimulating wrist (top trace) and antecubital fossa (bottom trace). There is a prolonged distal latency (DL) at the wrist stimulation site. At the antecubital fossa site, there is a positive dip and a factitiously fast conduction velocity (CV) due to some median fibers stimulated at the antecubital fossa bypassing the carpal tunnel via the anastomosis. Note also the slightly higher amplitude at the proximal stimulation site. PL, proximal latency.

positive deflection is seen at the thenar electrodes, indicating that a depolarization has occurred at a distance from the recording electrode (see Chapter 2). Furthermore, because the median fibers from the distal stimulation are delayed due to slowing in the carpal tunnel, whereas the anastomotic fibers from proximal median stimulation arrive much sooner than expected, the time difference is artificially shortened, and the calculated conduction velocity in the forearm often is surprisingly fast. With rare exception, the normal median conduction velocity in the forearm never exceeds 70 to 75 m/s. Any velocity faster

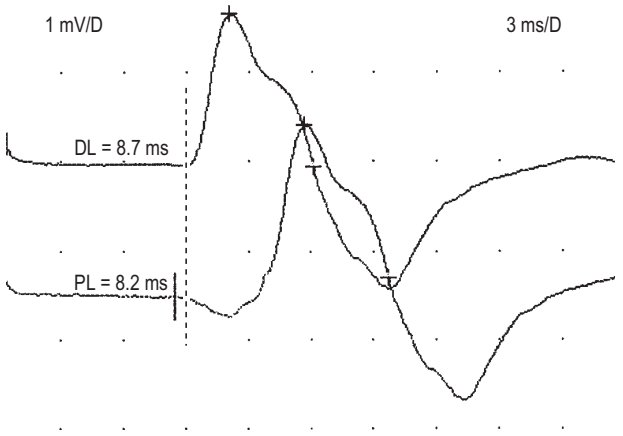

FIGURE 7–9 Reversal of proximal and distal latency in Martin–Gruber anastomosis (MGA) and severe carpal tunnel syndrome. In some cases of severe carpal tunnel syndrome, in which a marked delay occurs with wrist stimulation, the median fibers traveling through the MGA with proximal stimulation may actually arrive at the thenar eminence before fibers stimulated at the wrist. In such a case, a very unusual situation arises: the proximal median latency (PL) actually is shorter than the distal median latency (DL).

than that, especially with a positive dip on proximal stimulation, suggests the possibility of an MGA with carpal tunnel syndrome. In some cases of severe carpal tunnel syndrome, the median fibers traveling through the MGA with antecubital fossa stimulation actually arrive at the thenar eminence before the fibers stimulated at the wrist, because of the marked delay that occurs with wrist stimulation. In such cases, a very unusual situation arises: the proximal median latency is actually shorter than the distal median latency (Figure 7–9).

The positive dip on proximal median stimulation is seen only with the combination of an MGA and carpal tunnel syndrome. If there is no delay of the signal that travels through the carpal tunnel, it will arrive in the hand at the same time as the signal that travels through the anastomotic fibers. In that case, the small positive deflection (from the anastomotic fibers) is obscured by the normal median CMAP that occurs at the same time. In some cases, the median motor study will be completely normal with the exception of the small positive dip on proximal stimulation which is not present on distal stimulation. When this occurs, and there is no technical error (i.e., no overstimulating the median nerve at the antecubital fossa), it almost always means there is a combination of a median neuropathy at the wrist and an MGA. Thus, in this situation, the presence of an MGA can help support the electrical diagnosis of a median neuropathy at the wrist.

Needle Electromyography and Martin–Gruber Anastomosis

When performing routine needle electromyography (EMG), the examiner determines the anatomic localization of the lesion from the pattern of muscles involved and those spared. A patient with an MGA, however, may show

a different pattern than what is expected. For instance, a proximal lesion of the median nerve at or above the antecubital fossa may cause abnormalities in median-innervated muscles, as expected. However, in a patient with a proximal lesion of the median nerve and a coexistent MGA, EMG abnormalities may also be seen in ulnar-innervated hand muscles (especially the FDI and abductor digiti minimi, which are commonly sampled during routine EMG). The opposite may occur with lesions of the ulnar nerve at or above the elbow. In this situation, there may be paradoxical sparing of ulnar-innervated hand muscles if they receive a substantial portion of their innervation from the median-to-ulnar cross-over fibers. This underscores that nerve conduction studies are needed to properly interpret any findings on needle EMG. This additionally underscores why nerve conduction studies are done first and then followed by the needle EMG.

ACCESSORY PERONEAL NERVE

The most common anomalous innervation in the lower extremity is the accessory peroneal nerve (APN) in the lateral calf. This anomaly involves innervation of the extensor digitorum brevis muscle (EDB). The EDB is the muscle usually recorded during routine peroneal motor conduction studies and normally is innervated exclusively by the deep peroneal nerve. Patients with an APN have an anomalous innervation to the EDB; the medial portion of the EDB is supplied by the deep peroneal nerve as usual, but the lateral portion is supplied by an anomalous motor branch originating from the superficial peroneal nerve, the APN (Figure 7–10).

This anomaly is recognized during routine peroneal motor studies. If the anastomosis is present, the peroneal CMAP amplitude recording the EDB is higher stimulating at the below-fibular neck and lateral popliteal fossa sites than at the ankle (Figure 7–11). This pattern could be caused by (1) submaximal stimulation of the peroneal nerve at the ankle site, (2) excessive stimulation of the peroneal nerve at the below-fibular neck and lateral popliteal fossa sites, causing co-stimulation of the tibial motor fibers, or (3) an APN.

It is simple and straightforward to demonstrate an APN. If present, an APN originates from the distal superficial peroneal nerve and travels down the lateral calf, posterior to the lateral malleolus. If stimulation is performed posterior to the lateral malleolus while recording the EDB, a small CMAP will be evoked if an APN is present; otherwise, no potential will be seen. Commonly, the amplitude of the CMAP evoked by stimulating the APN posterior to the lateral malleolus will approximate the difference between the CMAP amplitudes evoked with ankle and below-fibular neck or lateral popliteal fossa stimulation sites of the peroneal nerve, recording the EDB.

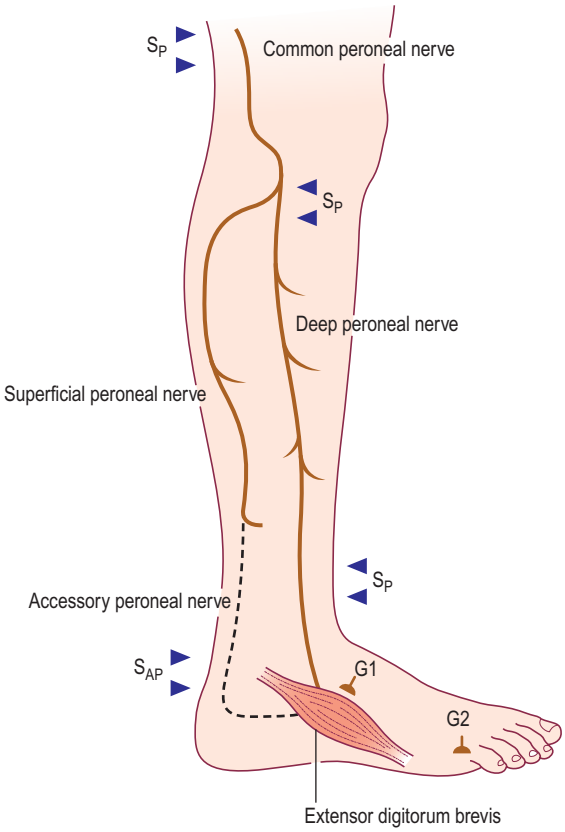

FIGURE 7–10 Accessory peroneal nerve (APN). The APN is derived from the distal superficial peroneal nerve and runs posterior to the lateral malleolus to supply the lateral portion of the extensor digitorum brevis muscle. During routine peroneal motor studies, recording the extensor digitorum brevis, the peroneal nerve is stimulated (S_P) at the ankle, below the fibular neck, and at the lateral popliteal fossa. If an APN is present, the compound muscle action potential (CMAP) amplitude will be higher on stimulation below the fibular neck and at the lateral popliteal fossa than on stimulation at the ankle. To demonstrate an APN, stimulation is performed posterior to the lateral malleolus (S_{AP}) while recording from the extensor digitorum brevis muscle, looking for a CMAP.

Miscellaneous Anatomic Variations

Although the MGA and APN are the most common anomalous innervations encountered in the EMG lab, other rare anomalous innervations have been described. Among these rare conditions, probably the most frequently mentioned is a connection between the median and ulnar nerves in the palm, known as the *Riche–Cannieu anastomosis*. This anastomosis involves communications between the deep palmar branch of the ulnar nerve and either the main motor branch or the recurrent thenar branch of the median nerve in the palm. Although most commonly reported as involving only motor fibers, some reports include sensory and mixed fibers as well. Further complicating the issue is the question of whether fibers go from the median nerve to ulnar muscles, from the ulnar nerve to median muscles, or both ways. Depending on how detailed the anatomic studies are, some of these connections can be demonstrated in the majority of individuals. However, whether they have any clinical or electrodiagnostic importance remains the subject of debate. Nevertheless, they do explain one common finding: that the flexor pollicis brevis (which has a superficial and a deep head) can be supplied completely by the median nerve,

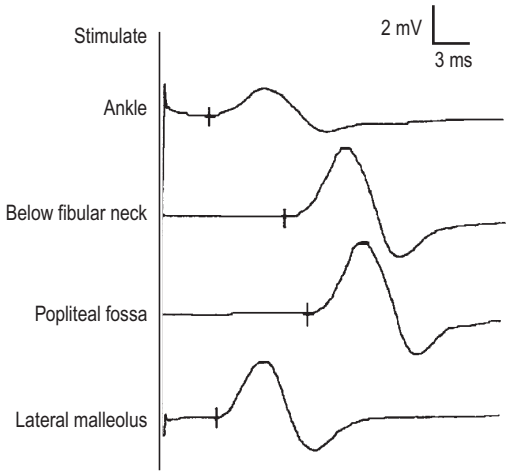

FIGURE 7–11 Accessory peroneal nerve (APN). Routine peroneal motor study, recording the extensor digitorum brevis (EDB), stimulating at the ankle (top trace), below the fibular neck (second trace), and at the lateral popliteal fossa (third trace). The compound muscle action potential amplitude is higher with stimulation below the fibular neck and at the popliteal fossa sites compared with stimulation at the ankle site. An APN is confirmed by stimulating posterior to the lateral malleolus and recording the EDB (bottom trace).

completely by the ulnar nerve, or have a dual innervation with the superficial head supplied by the median and the deep by the ulnar. In addition, these connections probably explain the exceptional reports of the "all-ulnar hand." In these very rare cases, stimulation of the median nerve while recording the thenar muscles results in no response, despite normal bulk and strength of the thenar muscles. On EMG testing, this could lead to a confusing picture wherein the routine median motor study shows an absent response, yet the needle EMG of thenar muscles is normal. In these cases, stimulation of the ulnar nerve while recording the thenar muscles results in a normal appearing CMAP, since the median motor fibers are running with the ulnar nerve, and innervating the thenar muscles.

Additionally, one can imagine a situation that if such a person had a median neuropathy at the wrist, the median motor fibers (which actually travel with the ulnar nerve) would be spared, since they would not travel through the carpal tunnel. However, the median sensory fibers, which do travel through the carpal tunnel, would be involved. On nerve conduction studies, the routine median motor study would show an absent response, since they are traveling with the ulnar nerve. In addition, the median sensory response might be present, though with a prolonged latency and low amplitude. This combination is very unusual in median neuropathy at the wrist: an absent median motor response in the setting of a present, albeit abnormal, median sensory response. Furthermore, needle EMG of the thenar muscles could be paradoxically normal or the degree of abnormality could be much milder than what would be expected from an absent median motor response in the nerve conduction studies. Such a finding should alert the electromyographer to the rare possibility of a

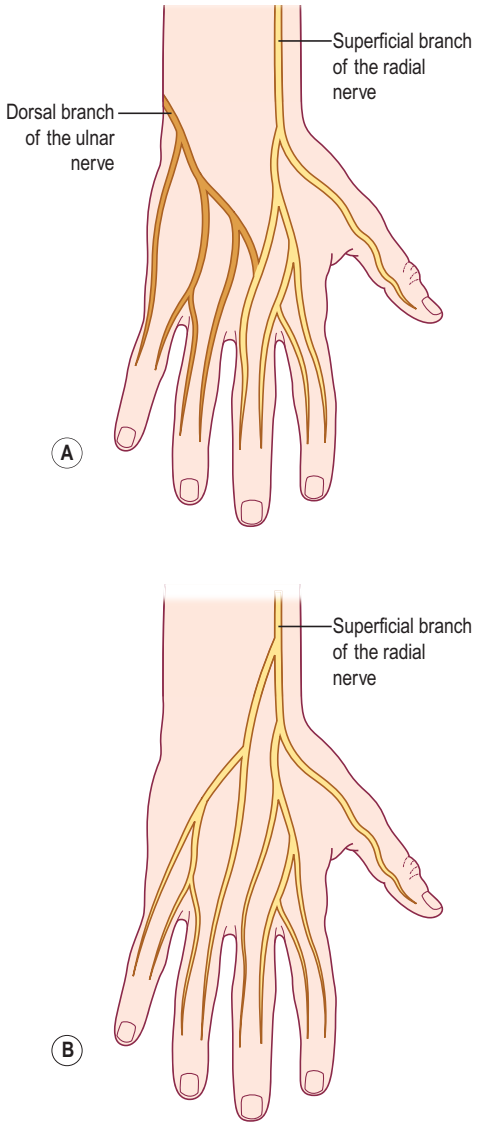

FIGURE 7–12 Anomalous cutaneous innervation of the dorsum of the hand. **A:** The typical innervation of the dorsum of the hand. The superficial branch of the radial nerve innervates the dorsolateral aspect of the hand including digits 1–3, and the dorsal branch of the ulnar nerve supplies the dorsomedial hand and digits 4–5. **B:** Anomalous cutaneous innervation of the dorsum of the hand, with almost the entire dorsum of the hand supplied by the superficial branch of the radial nerve.
(Adapted with permission from Kuruvilla, A., Laaksonen, S., Falck, B., 2002. Anomalous superficial radial nerve: a patient with probable autosomal dominant inheritance of the anomaly. Muscle Nerve 26, 716–719.)

Riche–Cannieu anastomosis. While a superimposed C8–T1 radiculopathy or lower trunk brachial plexopathy might be considered, given the absent median motor response, the fact that the needle EMG of the thenar muscles is normal would argue against this.

In addition, if such an individual had a severe ulnar neuropathy (e.g., at the elbow), this could result in severe weakness and atrophy of all of the intrinsic hand muscles, including all the thenar muscles. Such a pattern of

weakness would more normally imply a combined lesion of the median and ulnar nerves, a lower brachial plexopathy, or a C8–T1 radiculopathy.

Other rare anomalies have also been described. In the upper extremity, an anomalous innervation between the superficial radial and the dorsal ulnar cutaneous sensory nerves can occur. Normally, sensation to the dorsum of the hand is mediated by both nerves: the little and ring fingers and medial hand by the dorsal ulnar cutaneous nerve, and the remainder by the superficial radial nerve. In rare individuals, the superficial radial nerve innervates the entire territory (Figure 7–12). During nerve conductions, this situation may present as an apparently absent response recording the dorsal ulnar cutaneous sensory nerve. The anomaly can be demonstrated by stimulating the superficial radial nerve over the radius in the lateral forearm, with recording electrodes placed over the dorsal ulnar cutaneous nerve territory.

Also in the upper extremity, there have been reports of the lateral antebrachial cutaneous sensory nerve (the terminal branch of the musculocutaneous nerve) supplying some of the median forearm muscles. In other cases, it continues down the forearm to supply some of the thenar muscles as well as sensation to the base of the thumb (i.e., the distribution of the palmar cutaneous branch of the median nerve).

From a practical point of view, however, it is the MGA and the APN that one will encounter in the EMG laboratory on a routine basis. All the other anomalies, including the ones discussed above, have been the subject of cases reports or very small series. However, these rare cases do emphasize that if an unusual or unexpected nerve conduction pattern is seen, one should always consider not only technical factors but also the possibility of an anomalous innervation.

Suggested Readings

Gutmann, L., 1993. AAEM minimonograph #2: important anomalous innervations of the extremities. Muscle Nerve 16, 339.

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Artifacts and Technical Factors 8

Understanding and recognizing artifacts and technical factors play a central role in every nerve conduction and electromyography (EMG) study (Box 8–1). The value of the information gained during an electrodiagnostic (EDX) study relies on two important and complementary processes: (1) collecting the data correctly and (2) interpreting the data correctly. If the collected data are not technically accurate, then correct interpretation of the data can never occur, either at the time of the study or later by the referring physician.

EDX studies rely upon acquiring and amplifying very small bioelectric signals in the microvolt and millivolt range. This process is technically demanding, because a large number of physiologic and non-physiologic factors can significantly interfere with the accuracy of the data. Physiologic factors, such as limb temperature and age, as well as non-physiologic factors, such as electrode impedance and electrical noise, are equally important. Failure to recognize these technical factors that influence the EDX study can result in type I errors: diagnosing an abnormality when none is present (i.e., convicting an innocent man), and type II errors: failing to recognize an abnormality when one is present (i.e., letting a guilty man go free). Although both are important, type I errors are potentially more serious. For example, "abnormalities" on EDX testing due to unrecognized technical errors can result in a patient being misdiagnosed with a condition they do not have. Such faulty diagnoses can lead to further inappropriate testing and treatment. Recognizing technical factors and other potential sources of error in the EDX laboratory is essential in improving the efficiency and validity of the EDX study and reducing patient discomfort.

Box 8–1. Important Technical Factors Influencing Nerve Conduction Studies and Electromyography

Physiologic Factors
- Temperature
- Age
- Height
- Proximal versus distal nerve segments
- Anomalous innervations (see Chapter 7)

Non-physiologic Factors
- Electrode impedance mismatch and 60 Hz interference
- Filters
- Electronic averaging
- Stimulus artifact
- Cathode position: reversing stimulator polarity
- Supramaximal stimulation
- Co-stimulation of adjacent nerves
- Electrode placement for motor studies
- Antidromic versus orthodromic recording
- Distance between recording electrodes and nerve
- Distance between active and reference recording electrodes
- Limb position and distance measurements
- Limb position and waveform morphology
- Sweep speed and sensitivity

PHYSIOLOGIC FACTORS

Temperature

Temperature is the most important of all the physiologic factors. It affects nearly every parameter measured in a nerve conduction study, including conduction velocity, distal latency, and waveform morphology. Temperature also can affect motor unit action potential (MUAP) morphology during the needle EMG examination. Physiologically, cooler temperatures result in delayed inactivation of sodium channels and subsequently prolong the time of depolarization (see Chapter 2). For myelinated fibers, conduction velocity is primarily determined by the time delay of depolarization that occurs at the nodes of Ranvier. Hence, prolonged depolarization times result in slowed conduction velocities for the nerve being studied. Conduction velocity slows in a fairly linear manner within the normal physiologic range of limb temperature (approximately 21–34°C). *For motor and sensory conduction velocities, conduction velocity slows between 1.5 and 2.5 m/s for every 1°C drop in temperature, and distal latency prolongs by approximately 0.2 ms per degree.*

In addition, longer channel opening time results in a larger influx of sodium. Subsequently, each nerve fiber depolarization is larger and longer. For both compound muscle action potentials (CMAPs) and sensory nerve action potentials (SNAPs), cooling results in a higher amplitude and longer duration as a consequence of larger and longer individual muscle and sensory fiber action potentials, respectively (Figure 8–1). This effect is more pronounced

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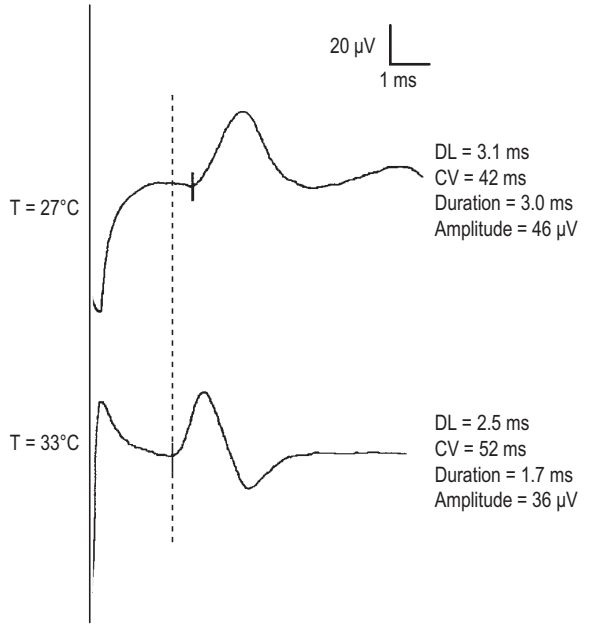


FIGURE 8–1 Temperature effect on nerve conduction studies. Median antidromic sensory studies, stimulating wrist, recording second digit. Same patient at different limb temperatures. Note that with cooler limb temperature (top), distal latency and conduction velocity slow, while duration and amplitude increase.

in sensory fibers, because the duration of individual sensory nerve fiber action potentials normally is shorter than that of individual muscle fibers. The normal process of phase cancellation is more prominent when individual fiber action potential durations are shorter (see Chapter 3). Thus, when cooling occurs, individual sensory nerve fiber action potentials prolong, resulting in less phase cancellation and a higher compound nerve action potential. Accordingly, any sensory study that yields a high-amplitude, long-duration potential along with a slow conduction velocity should alert the electromyographer to a possible cooling effect.

Lowering the temperature has a similar though less marked effect on MUAPs measured during needle EMG. MUAP duration and amplitude increase with cooler temperatures; correspondingly, the number of phases also may increase.

There may be significant variation in limb temperature among individuals, even when ample time is allowed for temperature to equilibrate in a warm laboratory. Moreover, there is marked variation of temperature over the course of a given nerve, with a trend toward cooler temperatures as the nerve travels distally and superficially within the respective limb. Furthermore, in a warm limb, skin surface temperature typically is 1 to 2°C warmer compared to the near nerve temperature. The opposite often is true in a cool limb, where the skin surface temperature typically is cooler compared to the near nerve temperature.

It is easy to see how an electromyographer might mistakenly interpret a nerve conduction or needle EMG study as abnormal if a cool limb temperature is not appreciated and corrected. For example, a common mistake is to make a diagnosis of a polyneuropathy based on findings of slowed conduction velocities, prolonged distal latencies, and slightly large, polyphasic MUAPs that actually are due to cold limb temperatures. Another common misdiagnosis is that of a distal entrapment neuropathy. For example, prolonged distal median motor and sensory latencies in a cool limb may create the false impression of a median neuropathy at the wrist (i.e., carpal tunnel syndrome). Lastly, in patients with axonal peripheral neuropathies, cooling may slow nerve conduction velocity into the range associated with demyelination, which then could profoundly alter the electrodiagnostic impression and subsequent evaluation and treatment.

There are several ways to reduce the influence of cooling on the EDX study. First, the electromyographer must recognize the importance of temperature in every nerve conduction and EMG study (Box 8–2). Distal limb temperatures should be routinely recorded and monitored in all patients and ideally maintained between 32 and 34°C. A normal temperature at the beginning of a study does not ensure that the limb will not cool down as the study progresses; in fact, it often does cool down.

Limbs can be heated with heating lamps, warming packs or hydrocollators. The ideal way to warm and maintain proper limb temperature is to use a heating lamp device that has a feedback control mechanism from a temperature sensor placed on the distal hand or foot. Unfortunately, these devices are now very difficult to obtain because most manufacturers have stopped producing them due to concerns over litigation; there were incidents wherein patients were burned when they grabbed the heating element and did not realize it was a heating device. It is important to be aware, however, that regardless of the method used to warm the limb, there may be a significant delay between

Box 8–2. Temperature and Nerve Conduction Studies and Electromyography

Effects of Cool Temperature

- Slowed nerve conduction velocity
- Prolonged distal latency
- Increased amplitude and duration of potentials on nerve conductions (SNAP>CMAP)
- Increased duration, amplitude, and phases of MUAPs

Maintenance of Temperature

- Measure distal limb temperature in all patients
- Maintain temperature at 32–34°C with heating lamp, warm packs, or hydrocollator
- Remember there may be a delay when heating between when the skin and the underlying nerve reach the desired temperature
- If limb is profoundly cool (>10°C cooler than desired), immerse the limb in warm water and then maintain temperature with a heating lamp
- If limb cannot be warmed, use conversion factors of 1.5–2.5 m/s/°C for conduction velocity and 0.2 m/s/°C for distal latency

CMAP, compound muscle action potential; MUAP, motor unit action potential; SNAP, sensory nerve action potential.

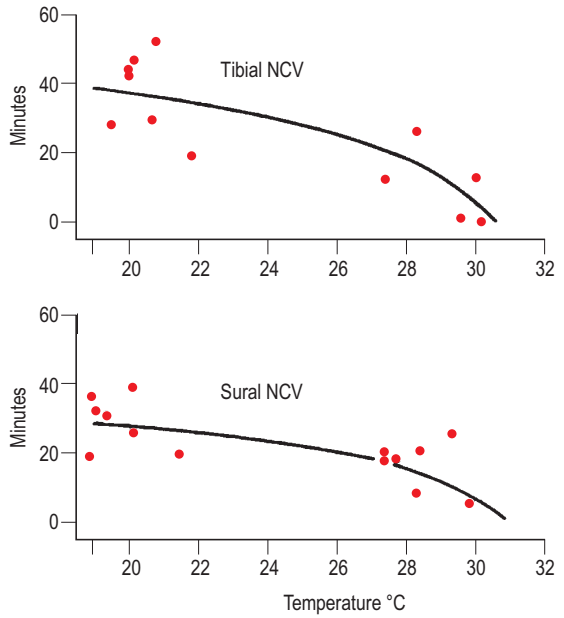


FIGURE 8–2 Warming time and conduction velocity. The time required for conduction velocity of the tibial **(upper)** or sural **(lower)** nerve to reach 95% of its limit value is plotted against the skin temperature prior to warming. Note that even at a skin temperature of 28°C, 15 to 20 minutes may be required for nerve temperature to reach a steady state.
(From Franssen, H., Wieneke, G.H., 1994. Nerve conduction and temperature: necessary warming time. Muscle Nerve 17, 336–344. Reprinted by permission of Wiley.)

the time that the skin reaches the desired temperature and when the underlying nerve and muscle warm up. When a limb is warmed, skin temperature usually reaches the desired temperature several minutes before the underlying nerve and muscle do so. For limbs that are profoundly cool, it may require 20 to 40 minutes for the underlying nerve temperature to equilibrate (Figure 8–2). If this fact is not recognized, the conduction velocity may increase through the EDX study as more time passes and the nerve warms up, despite a constant skin temperature. Nerves studied earlier in the examination will conduct more slowly than those studied later in the examination, after the underlying nerve has warmed up. This can result in confusing and difficult to interpret results.

If a limb is profoundly cool (e.g., more than 10°C cooler than desired), surface heating usually is inadequate or requires too much time to heat the limb adequately. In such situations, it is useful to immerse the limb in warm water and allow it to heat up over several minutes. Once the target temperature is reached, the proper temperature should be maintained; otherwise, the limb usually will cool down again during the course of the study.

The electromyographer must always keep in mind that a mildly to moderately slowed conduction velocity or a slightly to moderately prolonged latency could be the result of an initially cool limb or inadequate heating. If limb warming is not possible or is difficult to achieve (e.g., portable studies in the intensive care unit), then a correction factor should be used, most commonly 1.5 to 2.5 m/s/°C for conduction velocity and 0.2 m/s/°C for distal latency.

Several modern EMG machines can monitor limb temperature, and can be set to automatically report corrected values for conduction velocity and latency based on temperature. However, one should keep in mind that these correction factors are derived primarily from individuals with normal nerves, and as such they may not hold true for all diseased nerves. *Hence, it always is preferable to warm or rewarm a limb than to use a correction factor*. On needle EMG, there is no correction factor for MUAP duration, amplitude, or phases.

Age

Age most prominently affects nerve conduction velocity and waveform morphology at the extremes of age. One of the most important determinants of nerve conduction velocity is the presence and amount of myelin. The process of myelination is age dependent and begins in utero, with nerve conduction velocities in full-term infants approximately half those of adult normal values. Accordingly, nerve conduction velocities of 25 to 30 m/s are considered normal at birth but would be in the demyelinating range for an adult. Conduction velocity rapidly increases after birth, reaching approximately 75% of adult normal values by age 1 year and the adult range by age 3 to 5 years, when myelination is complete.

Conduction velocities decrease slightly with age in adults, most likely as a consequence of the normal loss of motor and sensory neurons that occur with aging. This is more prominent for individuals older than 60 years, in whom conduction velocity decreases approximately 0.5 to 4.0 m/s/decade. The effect is slightly more pronounced for sensory than for motor fibers.

For adults, one can use normal values based on age for nerve conduction velocities, which take into account these small age-related changes in conduction velocity. However, it is difficult to remember values from tables based on both the age range and the nerve being studied. More commonly, tables of normal control values provide a range of nerve conduction velocities, usually for subjects between ages 10 and 60, which take into account the normal variability within that age range. Generally, the lower limits of normal are provided. Additional correction factors of 0.5 to 4.0 m/s/decade can then be used for older patients. For example, a normal median motor conduction velocity in the adult population is 49 m/s. However, in a 90-year-old patient, a median motor conduction velocity of 46 m/s would be considered normal, within the expected range for advanced age.

Age also has an effect on CMAP and SNAP amplitudes. Again, most tables of normal control values provide a range of amplitudes that take into account normal variability for subjects between the ages of 10 and 60. Assessment of distal lower extremity sensory responses in an elderly individual, especially the commonly recorded sural sensory response, can be difficult. The sural sensory response in particular is often a small potential, and it may be hard to

elicit in some older individuals. SNAP amplitudes are known to decrease substantially with advanced age. Some have estimated that the SNAP amplitude drops by up to 50% by age 70. Thus, very low amplitude or absent lower extremity sensory responses in patients of advanced age must always be interpreted with caution and not necessarily considered abnormal without other confirmatory data.

Age also affects many parameters on the needle EMG study. The most prominent effect is on MUAP duration. It is well known that as an individual ages, MUAP duration increases. In the years from birth through childhood, the duration increases due to the physiologic increase of muscle fiber and motor unit size as an individual grows. In later life, the normal aging process results in a slow dropout of motor units. Some normal reinnervation occurs to compensate, which results in slight prolongation of motor unit duration as the individual ages. For these reasons, it is important to compare MUAP durations on needle EMG with normal values based on age (see Chapter 15).

Height

Along with temperature and age, height also affects nerve conduction velocity. Taller individuals commonly have slower conduction velocities than do shorter individuals. This effect of nerve length also is reflected in the well-recognized finding that normal conduction velocities are slower in the lower extremities, where the limbs are longer, than in the upper extremities. For example, on average, the normal sural sensory conduction velocity typically is 5 m/s slower than the median sensory conduction velocity, and the peroneal and tibial motor velocities typically are 6 to 9 m/s slower than the median and ulnar motor conduction velocities.

Two separate factors likely account for the effect of height or limb length on conduction velocity. First, nerves taper as they proceed distally. In general, the taller the individual, the longer the limb and the more tapered the distal nerve. Because conduction velocity is directly proportional to nerve diameter, the more distally tapered nerves in taller individuals conduct more slowly. By the same reasoning, nerves in the leg conduct more slowly than those in the arm because of longer limb length and more distal tapering. Second, and not as well appreciated, is that limbs are cooler distally than proximally and the legs generally are cooler than the arms. Thus, conduction velocity slowing due to cooling usually is more prominent in the legs than in the arms.

Tables of normal nerve conduction values usually take into account the range of normal height. However, modifications must be made for individuals of extreme height, just as they are needed for extremes of age. In practice, the adjustment usually is no more than 2 to 4 m/s below the lower limit of normal. For example, for an individual who is 6 feet 10 inches tall, a tibial conduction velocity of 38 m/s (the normal lower limit of normal is 41 m/s) should be considered within the normal range because of the effect of height.

The effect of height is especially relevant to the interpretation of late responses (F responses and H reflexes). The circuitry of these responses extends twice the length of the limb for the F response and twice the length of the proximal lower limb for the H reflex. Normal values of absolute latency for these potentials must be based on limb length or height (see Chapter 4). Failure to do so will result in erroneously labeling of taller individuals as having "abnormal" late responses. In some situations, however, the effect of height is not relevant, as when latencies are compared between a symptomatic and a contralateral asymptomatic limb.

Proximal versus Distal Nerve Segments

Nerve conduction velocities vary between the distal and proximal segments of a limb, just as they vary with height, because of changes in nerve diameter and temperature. Proximal nerve segments tend to conduct slightly faster than distal segments in a normal individual. For example, the normal conduction velocity of the median nerve between the axilla and elbow is slightly faster than between the elbow and wrist. This is true for the same reasons that conduction velocity is faster in the arms than in the legs: (1) distal nerve segments are tapered and therefore conduct more slowly than proximal segments, and (2) distal limb segments are cooler than proximal segments and therefore conduct more slowly.

NONPHYSIOLOGIC FACTORS

Electrode Impedance and Noise

Electrical noise is present in every EDX laboratory. The most common cause of electrical noise is 60 Hz interference generated by other electrical devices (e.g., lights, fans, heaters, computers). Outside of the EDX laboratory, particularly in the intensive care unit, there may be many other sources of electrical noise such as ventilators, monitors, and other electrical devices. This noise can create a host of problems, especially when recording very small potentials such as SNAPs or fibrillation potentials (Figure 8–3). However, the examiner usually can reduce electrical noise to an acceptable level by paying close attention to technical details.

All signals recorded during the nerve conduction study and needle EMG are the result of differential amplification (Figure 8–4). With differential amplification, the difference between the signals at the active (G1) and reference (G2) electrodes is amplified and then displayed. Thus, if the *same* electrical noise is present at both the active and reference electrodes, it will be subtracted out, and only the signal of interest will be amplified (this is known as common mode rejection).

The best way to achieve identical electrical noise at each electrode is to ensure that the impedance at each electrode is the same (i.e., to prevent electrode impedance mismatch). Impedance is an electrical term that combines the

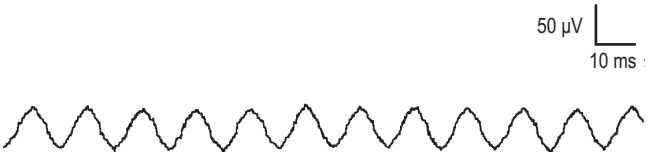


FIGURE 8–3 Electrode impedance mismatch and electrical noise. Ambient 60 Hz electrical noise in the environment often can obscure small amplitude potentials (e.g., sensory nerve action potentials, fibrillation potentials). Electrical noise is recognized in the electromyography trace as a sinusoidal 60 Hz waveform. Note in the trace, the sweep speed of 10 ms allows one to appreciate the sinusoidal waveform. However, if the sweep speed is set at 1 or 2 ms and the sensitivity increased to 10 µV, as is done for sensory nerve conduction studies, the 60 Hz waveform can saturate the amplifier. The 60 Hz interference usually results from electrode impedance mismatch. If the impedances of the active and reference electrodes are similar, the same electrical noise is seen at the G1 and G2 inputs and subsequently is removed by differential amplification (common mode rejection). Electrode impedance mismatch can be reduced by proper skin cleaning and use of conducting electrode jelly.

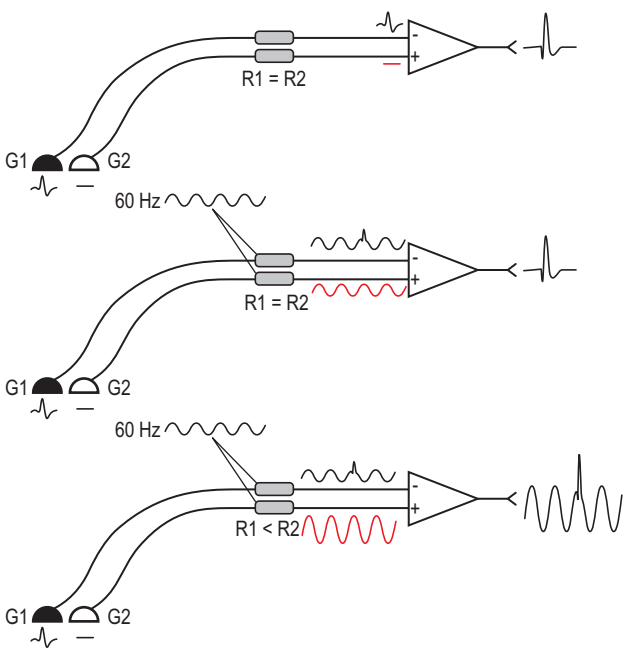


FIGURE 8–4 Differential amplification and electrode impedance mismatch. All signals recorded in nerve conduction studies and electromyography result from differential amplification. **Top:** The signal present at the reference electrode (G2) is subtracted from the signal seen at the active electrode (G1) and amplified. Each recording electrode has its own impedance or resistance, modeled as R1 and R2, for the active and reference electrodes, respectively. **Middle:** If R1 and R2 are identical, any 60 Hz interference will induce a similar electrical noise at both inputs. The noise will then be subtracted out, and only the signal of interest will be amplified. **Bottom:** If electrode impedances are mismatched (R1 < R2), the amount of electrical noise will be different at the two inputs. Some of the electrical noise will then be amplified, often obliterating or obscuring the signal of interest.

Box 8–3. Methods to Reduce Electrode Impedance Mismatch and 60 Hz Interference

- Active and reference recording electrodes should be the same type.
- Ensure all contacts are intact without any frayed or broken connections.
- Clean all dirt and oil from the skin using alcohol or acetone.
- Apply conducting electrode jelly between the skin and electrodes.
- Secure electrodes firmly to the skin with tape or Velcro straps.
- Place ground between stimulator and recording electrodes.
- Use coaxial recording cables.

effects of resistance to flow for a direct current (DC), and capacitance and inductance for an alternating current (AC). One will recall from Ohm's law that $E=IR$. The voltage (E), in this case the voltage from electrical noise, equals the current (I) induced from the electrical noise multiplied by the resistance (R), or impedance. If the resistance, or impedance, is different at the two electrodes, the same electrical noise will induce a different voltage at each electrode input. This difference will then be amplified and displayed, often obscuring the signal of interest.

The best way to eliminate 60 Hz interference is to ensure that each electrode appears identical to the amplifier (Box 8–3). This can be accomplished by several steps. First, ensure that the electrodes are intact, without any frayed or broken connections. Next, the skin preparation should be thorough, using either alcohol or acetone to remove dirt and oil. Conducting electrode jelly is then applied to the electrode before it is attached to the skin. The recording electrodes should be held firmly against the skin with tape or a Velcro band. Finally, the closer the electrodes are to each other, the more likely any associated electrical noise will appear identical to a differential amplifier.

Filters

Every potential recorded during nerve conduction studies and needle EMG passes through both a low- and a high-frequency filter before being displayed. The role of the filters is to faithfully reproduce the signal of interest while trying to exclude both low- and high-frequency electrical noise. Low-frequency (high-pass) filters exclude signals below a set frequency while allowing higher-frequency signals to pass through. High-frequency (low-pass) filters exclude signals above a certain frequency while allowing lower-frequency signals to pass through. Low-frequency noise (<10 Hz) results in wandering of the baseline (close to DC), whereas high-frequency noise (>10 kHz) commonly obscures high-frequency potentials (e.g., sensory nerve action potentials or fibrillation potentials).

By allowing the signal to pass through a certain "pass band," some unwanted electrical noise can be excluded. The pass band varies for different EDX studies. For motor conduction studies, the low- and high-frequency filters

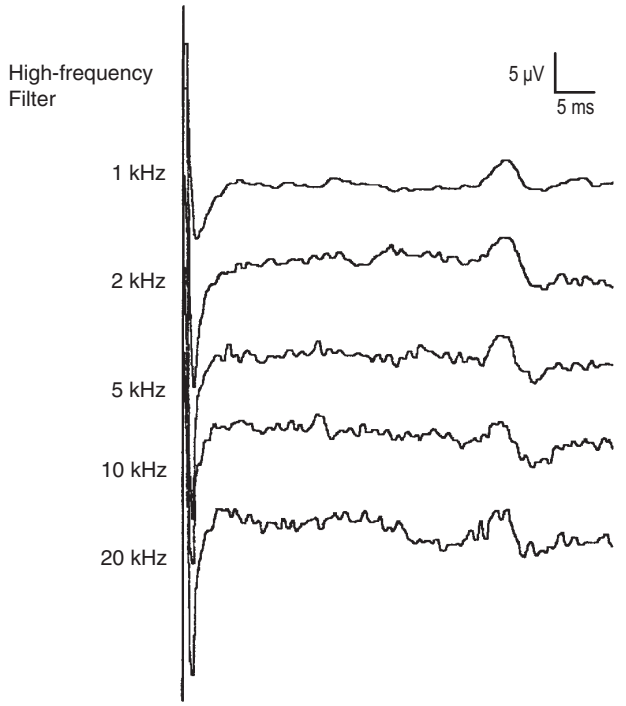


FIGURE 8–5 High-frequency filter and sensory nerve action potentials. Ulnar sensory study, stimulating elbow, recording digit 5, with varying high-frequency filters. As the high-frequency filter is reduced from 20 KHz to 1 kHz, high-frequency noise is reduced and the sensory nerve action potential (SNAP) is better visualized. Note that the SNAP amplitude also decreases slightly.

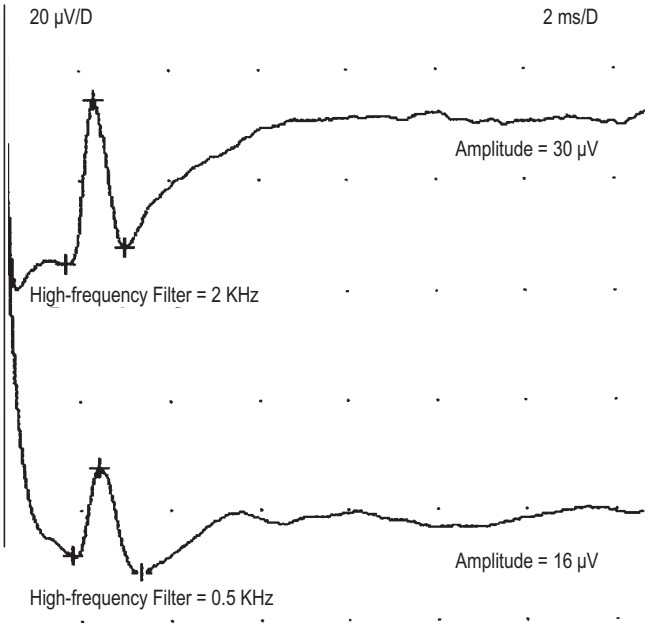


FIGURE 8–6 High-frequency filter and sensory nerve action potentials. Median sensory study, stimulating the wrist, recording digit 2. **Top trace:** High-frequency filter is set at 2 kHz. **Bottom trace:** High-frequency filter is set at 0.5 kHz. Note that as the higher frequencies are filtered out (bottom trace), the amplitude of the sensory potential markedly decreases.

typically are set at 10 and 10 kHz, respectively. For sensory conduction studies, the low- and high-frequency filters typically are set at 20 and 2 kHz, respectively. Note that the high-frequency filter is set lower for sensory than for motor nerve conduction studies. This is done in order to reduce high-frequency noise, which more easily interferes with the recording of sensory nerve action potentials, which contain higher-frequency components compared with motor potentials (Figure 8–5).

The use of filters always involves some tradeoff. No filter, whether analog or digital, results in a sharp cutoff with complete exclusion of all signals above the high-frequency settings or below the low-frequency settings. It is essential to recognize that filtering also results in some loss or alteration of the signal of interest. For instance, as the low-frequency filter is reduced, more low-frequency signals pass through. This results in the duration of the recorded potential increasing slightly because the duration is primarily a lower frequency response. Likewise, as the high-frequency filter is lowered, more high-frequency signals are excluded. This results in the amplitude of the recorded potential usually decreasing because amplitude is primarily a higher frequency response (Figure 8–6). Accordingly, all potentials should be obtained with standardized filter settings and should be compared only with normal values based on studies using the same filter settings.

Electronic Averaging

Electrical noise occasionally may contaminate a potential despite filtering and one's best efforts to eliminate electrode impedance mismatch. Most often this occurs when recording small potentials in the microvolt range, typically during sensory and mixed nerve studies. In this situation, the electrical noise can be reduced or eliminated by using electronic averaging. With electronic averaging, serial stimulations are digitized and then mathematically averaged. Because electrical noise is random, positive and negative phases of electrical noise will cancel each other out as a greater number of stimulations are averaged, thereby leaving the potential of interest. Electronic averaging is especially helpful in clarifying the electrical baseline so that onset latency and amplitude can be correctly measured (Figure 8–7).

Stimulus Artifact

During routine nerve conduction studies, the current from the stimulator depolarizes the underlying nerve, but it also spreads via volume conduction through the tissues within the limb and is seen at the recording electrodes. This stimulus artifact occurs in every nerve conduction study and serves a useful purpose by indicating when the shock occurred and from which point latencies should be measured. The stimulus artifact becomes problematic, however, if its trailing edge overlaps with the potential being recorded. This occurs most commonly when

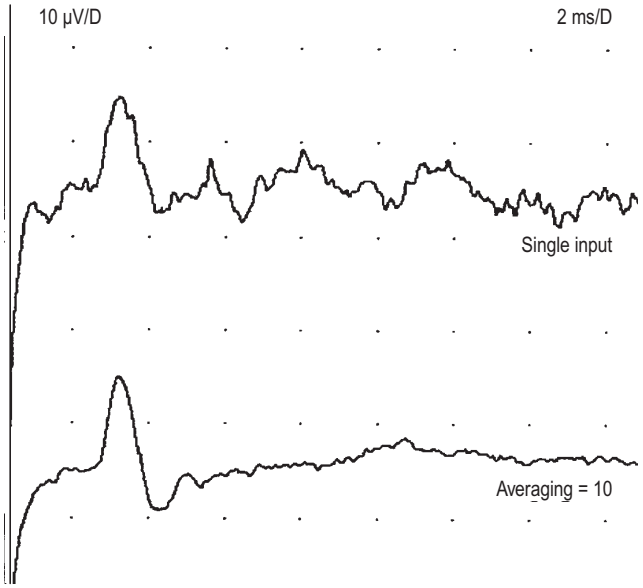


FIGURE 8–7 Electronic averaging. Median sensory study, recording digit 2, stimulating the wrist. **Top trace:** Single stimulation. Note that the potential is present but that there is significant baseline noise. **Bottom trace:** Electronic averaging of ten stimulations. With the averaged trace, the noise is much improved, and the signal of the sensory response is more clearly seen, allowing the onset latency and amplitude to be more accurately measured.

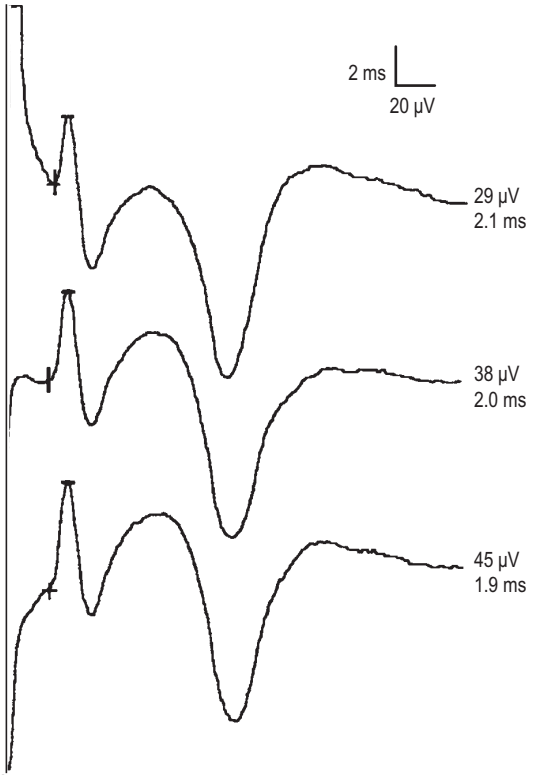


FIGURE 8–8 Stimulus artifact and measurement error. Median antidromic sensory study, stimulating wrist, recording second digit. Stimulus artifact can be influenced by rotating the anode while maintaining the cathode in place. Large negative stimulus artifacts (top trace) may result in artifactually low amplitudes and prolonged onset latencies. Conversely, large positive stimulus artifacts (bottom trace) may result in artifactually large amplitudes and short onset latencies.

recording small potentials (i.e., sensory potentials) or when stimulating at very short distances. In those situations, the onset of the recorded potential may be obscured, possibly leading to inaccurate measurements of both amplitude and latency (Figure 8–8).

There are several ways to reduce the trailing edge of the stimulus artifact (Box 8–4). First, the ground electrode should always be placed between the stimulator and the recording electrodes to reduce stimulus artifact. Next, reducing electrode impedance mismatch between the recording electrodes will help to reduce any electrical interference, including stimulus artifact. Coaxial recording cables are especially useful in this regard (Figure 8–9). Lowering the stimulus intensity also helps to diminish the effects of the stimulus artifact. Another very useful way to reduce the effect of the stimulus artifact is to slightly rotate the anode of the stimulator one way or another while maintaining the position of the cathode. The effect of the stimulus artifact also can be reduced by increasing the distance between the stimulus and the recording electrodes. Finally, ensuring that the stimulator and recording electrode cables do not overlap and are kept as far apart as possible will help to reduce the influence of the stimulus artifact.

Box 8–4. Methods to Reduce Stimulus Artifact

- Place ground between stimulator and recording electrodes.
- Reduce electrode impedance mismatch between the recording electrodes.
- Use coaxial recording cables.
- Ensure stimulator position is optimized directly over the nerve.
- Lower the stimulus intensity.
- Rotate anode of the stimulator while maintaining the cathode.
- Increase the distance between the stimulator and recording electrodes.
- Ensure that the stimulator and recording electrode cables do not overlap.

Cathode Position: Reversing Stimulator Polarity

When a nerve is stimulated, depolarization first occurs beneath the cathode. Accordingly, distance measurements should always be made between the cathode of the stimulator, where depolarization first occurs, and the active recording electrode (Figure 8–10). For nerve conduction studies, the proper position of the stimulating cathode is facing the active recording electrode. If the cathode and anode of the stimulator are inadvertently reversed, two effects are possible. First, although depolarization occurs under the cathode, hyperpolarization theoretically occurs at the anode (Figure 8–11). This hyperpolarization may create a block,

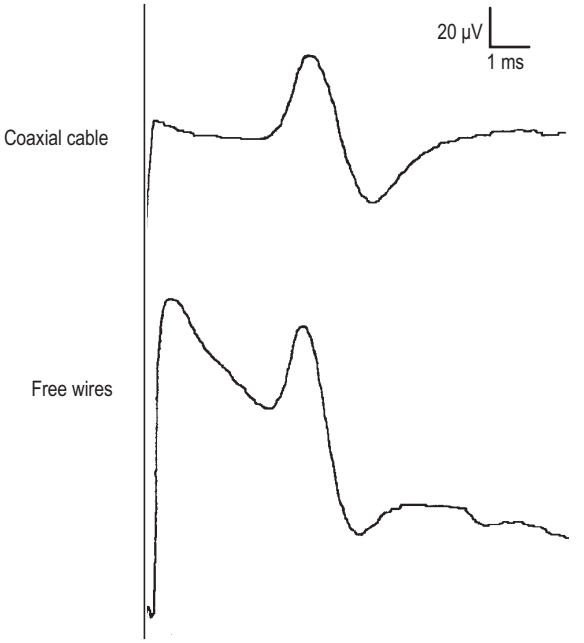


FIGURE 8–9 Electrical noise and recording cables. Median antidromic sensory study, stimulating wrist, recording digit 2 with ring electrodes, using different recording cables. Coaxial cable **(top trace)** and separate free wires **(bottom trace).** The closer the active and reference recording leads are to each other (coaxial cable closer than free wires), the less the chance that the stimulus artifact or any other electrical noise will be induced in the recorded trace.

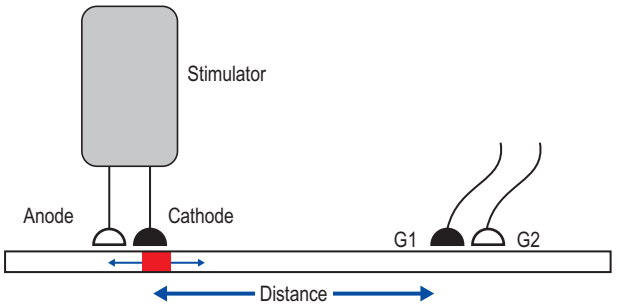


FIGURE 8–10 Positions of the stimulator cathode and active recording electrode. With nerve stimulation, depolarization first occurs beneath the cathode and travels in both directions. The cathode should always face the active recording electrode (G1) (remember: black to black). To calculate a conduction velocity, distance is measured between the cathode and the active recording electrode.

preventing the depolarization that occurs under the cathode from proceeding past the anode to the recording electrode (i.e., anodal block). The resultant sensory or motor potential may then be reduced or absent. The issue of anodal block is more of a theoretic concern and is rarely seen in practice.

Second, and more common than a reduced or absent potential, is a predictable error in latency measurement when the cathode and anode are inadvertently reversed (Figure 8–12). In such cases, the distal latency will prolong

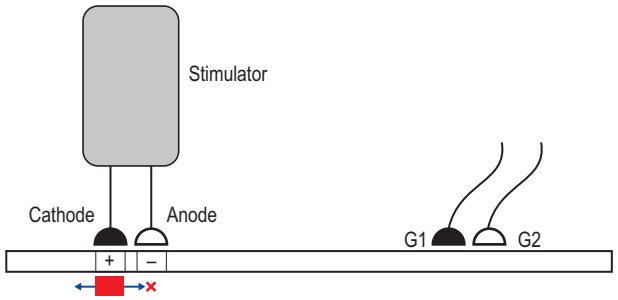
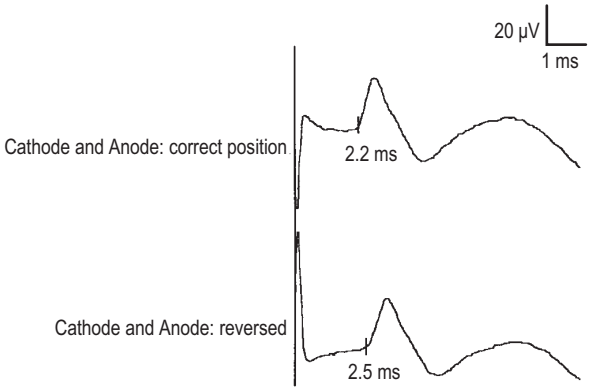


FIGURE 8–11 Anodal block. If the cathode and anode are reversed, anodal block may occur. With stimulation, the nerve depolarizes beneath the cathode and travels in both directions, and the segment under the anode may hyperpolarize. This hyperpolarization may block the action potential that originates at the cathode and prevent it from proceeding past the anode.



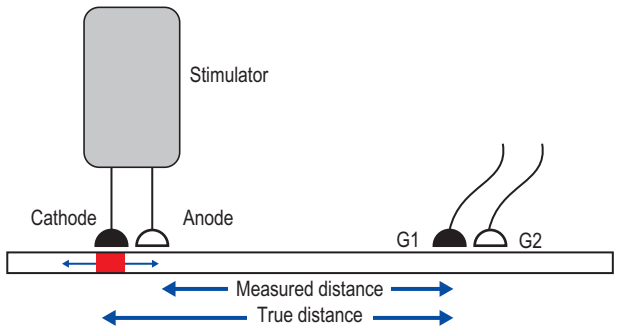


FIGURE 8–12 Stimulator cathode and anode reversed. **Top:** Median sensory study, stimulating wrist, recording digit 2. Top trace reflects the correct position, with the cathode facing the active recording electrode. Bottom trace reflects the cathode and anode reversed, with the cathode facing away from the active recording electrode. **Bottom:** If the cathode and anode are inadvertently reversed, artifactual slowing of latency and conduction velocity occurs. This error usually prolongs the latency by 0.3 to 0.4 ms and slows the sensory conduction velocity by approximately 10 m/s. The slowed conduction velocity is a result of the measured distance being shorter than the true distance traveled. The true distance is the measured distance plus the distance between the cathode and anode.

by approximately 0.3 to 0.4 ms. This represents the approximate time it takes for a normal nerve to traverse 2.5 to 3.0 cm, the typical distance between the cathode and anode of a stimulator. Failure to recognize this error results in an unusual set of findings. First, all of the distal sensory nerve latencies will be prolonged by 0.3 to 0.4 ms, resulting in a slowing in sensory conduction velocities of about 10 m/s. Second, distal motor latencies will be similarly prolonged, but motor conduction velocities, which are calculated between a distal and a proximal site, will remain unchanged. The motor conduction velocities do not change because the distal latencies are subtracted out in the calculations. If the electromyographer does not recognize that the stimulating cathode and anode have been inadvertently reversed, these findings on the nerve conduction studies may easily be interpreted as consistent with a polyneuropathy or a distal entrapment neuropathy.

Supramaximal Stimulation

Supramaximal stimulation is one of the most important concepts to understand when performing nerve conduction studies. All measurements made in nerve conduction studies are based on the assumption that all of the axons of the nerve have been depolarized. Different degrees of current intensity are required in different anatomic locations and in different individuals in order to depolarize all nerve fibers. For example, the current intensity needed to stimulate the median nerve at the wrist is much less than the current needed to stimulate the tibial nerve at the popliteal fossa.

To ensure that all axons have been depolarized, supramaximal stimulation must be performed. To achieve supramaximal stimulation, one must slowly increase current intensity until a point is reached where the amplitude of the recorded potential no longer increases. At that point, one increases the current an additional 25% to ensure that the potential will not change further. If it does not, then it can be assumed that supramaximal stimulation has been achieved (Figure 8–13). Note that the latency decreases as supramaximal stimulation is approached.

If a nerve is not supramaximally stimulated at a distal site, a mistaken impression of axonal loss may result. If supramaximal stimulation is not achieved at a proximal stimulation site where it had been achieved with a distal stimulation site, the mistaken impression of a conduction block may occur (Figure 8–14). In either case, depending on the nerve being stimulated, one might also mistakenly conclude that there is an anomalous innervation (see Chapter 7). Finally, a true conduction velocity cannot be obtained unless supramaximal stimulation is achieved at all stimulation sites. Conduction velocity measurements assume that the same fibers (i.e., the fastest) are stimulated at distal and proximal sites. Without supramaximal stimulation, one may be measuring different fibers at different sites, resulting in invalid measurements of nerve conduction velocity. One of the most common pitfalls made in the EDX laboratory is to stop increasing the current once the amplitude of the potential falls within the "normal range." In this case, the potential may be within the normal range, but because it is not achieved with supramaximal stimulation, it may not be normal for the particular patient being studied.

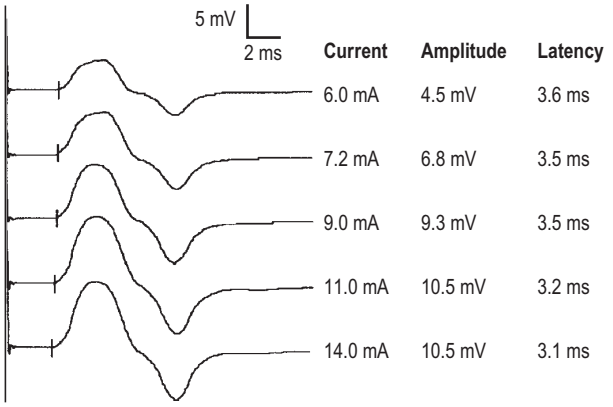


FIGURE 8–13 Supramaximal stimulation. Median motor study, stimulating wrist, recording the abductor pollicis brevis, with increasing stimulator currents. To ensure that all axons are stimulated, supramaximal stimulation is required for all nerve conduction studies. Supramaximal stimulation is achieved by increasing the stimulator current until the recorded potential has reached maximal amplitude. To ensure supramaximal stimulation, the current should then be increased by an additional 25% to ensure that the amplitude does not increase further (bottom trace). Note that the latency also decreases as supramaximal stimulation is approached.

Note that if one does not go through the meticulous process of incrementally increasing the stimulus current, one can never be certain that supramaximal stimulation has been achieved, no matter how high the stimulus current intensity! Thus, the electromyographer should never assume that the maximum stimulus machine output is the same as supramaximal stimulation, without going through this process.

Co-stimulation of Adjacent Nerves

Although it is imperative to ensure that supramaximal stimulation has been achieved at all stimulation sites, preventing co-stimulation of adjacent nerves is equally important. In individuals with normal nerves and normal stimulation thresholds, co-stimulation is not a common problem. In pathologic situations, however, nerves often require higher currents to achieve supramaximal stimulation. As the stimulus current is increased, the current may spread to excite nearby nerves. As nearby nerves are excited, spuriously large amplitude potentials may result, caused by the inadvertent co-recording of additional nerve or muscle potentials beyond the potential of interest. Co-stimulation occurs most commonly in motor studies of the upper extremity when the median and ulnar nerves are stimulated at the wrist, elbow, and axilla. In the lower extremity, co-stimulation of the peroneal and tibial nerves may occur at the knee.

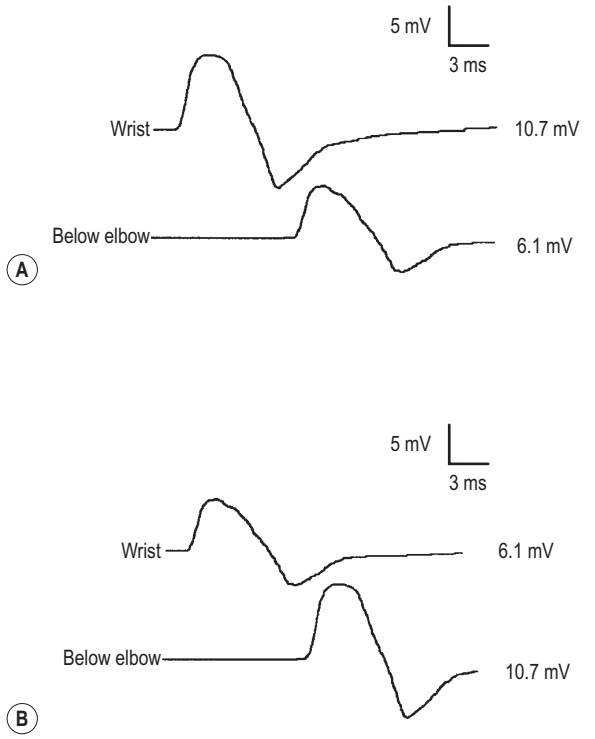


FIGURE 8–14 Difference in compound muscle action potential (CMAP) amplitude between proximal and distal stimulations. Ulnar motor study, stimulating wrist and below-elbow sites, recording hypothenar muscles. **A:** CMAP amplitude is lower at the below-elbow site than at the wrist. This pattern may be seen with the following: (1) conduction block, (2) co-stimulation of the median and ulnar nerves at the wrist, (3) submaximal stimulation of the ulnar nerve at the below-elbow site, or (4) anomalous innervation (see Chapter 7). **B:** CMAP amplitude is higher at the below-elbow site than at the wrist. This pattern may be seen with the following: (1) submaximal stimulation of the ulnar nerve at the wrist, or (2) co-stimulation of the median and ulnar nerves at the below-elbow site. If this was a median motor study recording the abductor pollicis brevis, this pattern also could represent an anomalous innervation.

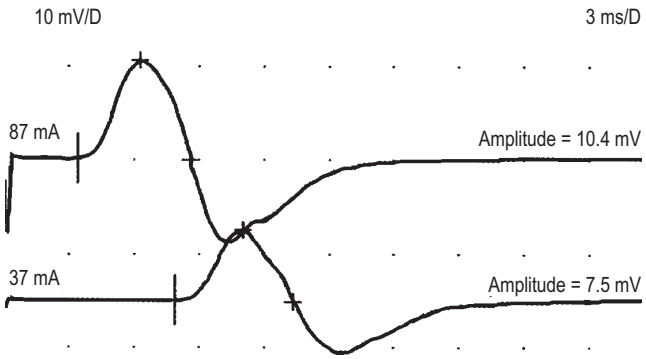


FIGURE 8–15 Co-stimulation. Ulnar motor study, stimulating wrist **(top trace)** and below-elbow **(bottom trace)** sites, recording the first dorsal interosseous muscle. Stimulus current intensities noted at the beginning of each trace. Note that the amplitude at the wrist site is significantly higher than at the below-elbow site. In this case, an error is caused by excessive current at the wrist that stimulates the ulnar nerve as well as the adjacent median nerve (i.e., co-stimulation). In general, for normal individuals, currents exceeding 50 mA with a duration of 0.2 ms often will result in co-stimulation of adjacent nerves. If not recognized and corrected, co-stimulation at a distal site may result in the mistaken impression of a partial conduction block at the proximal site or, in the case of the ulnar nerve, may mimic a Martin–Gruber anastomosis.

Co-stimulation of adjacent nerves is unavoidable when stimulating very proximal nerves and nerve roots. In the upper extremity, stimulation at Erb's point or at the C8–T1 nerve roots always results in co-stimulation of both the ulnar and median nerves. In this situation, the effects of co-stimulation can only be eliminated by the use of collision studies (see Chapter 30).

Inadvertent co-stimulation of adjacent nerves can create a host of problems, even in routine nerve conduction studies (see Figures 8–14 and 8–15). First, a low-amplitude potential, due to axonal loss, may reach the normal range if an adjacent nerve is co-stimulated. Next, if co-stimulation occurs distally but not proximally, there may be the mistaken impression of a conduction block proximally (see Figure 8–16, top). In some nerves, such as the ulnar motor nerve, this pattern can mimic an anomalous innervation. On the other hand, if co-stimulation occurs proximally but not distally, this pattern also can mimic an anomalous innervation in certain nerves, such as the peroneal motor nerve (see Chapter 7). Finally, if there is a true conduction block between distal and proximal stimulation sites, co-stimulation at the proximal site will result in an inappropriately high amplitude proximally, which may obscure a true conduction block (see Figure 8–16, bottom).

There are several ways to prevent co-stimulation of adjacent nerves (Box 8–5). First, co-stimulation often can be prevented by ensuring that the stimulator is placed directly over the nerve. By doing so, much less current is required to achieve supramaximal stimulation, and co-stimulation is easily prevented. The stimulator is placed over a site where the nerve is expected to run, based on anatomic landmarks. The stimulus intensity is slowly increased until the first small submaximal potential is recorded. At this point, the stimulus current is held constant, and the stimulator is moved parallel to the initial stimulation site, both slightly laterally and then slightly medially. The position that yields the highest-amplitude response is the position closest to the nerve. Once the optimal position is determined, the current is increased to supramaximal. It is often surprising how little current is required to obtain supramaximal stimulation using this technique, which also improves efficiency and patient tolerance of the procedure. Second, while watching the amplitude of the waveform increase as the stimulus intensity is increased, the shape of the waveform will often change abruptly when co-stimulation occurs. For instance, the normal dome shape of the median motor response may abruptly develop a bifid morphology, signifying that the ulnar nerve now is being co-stimulated. Third, co-stimulation often can be

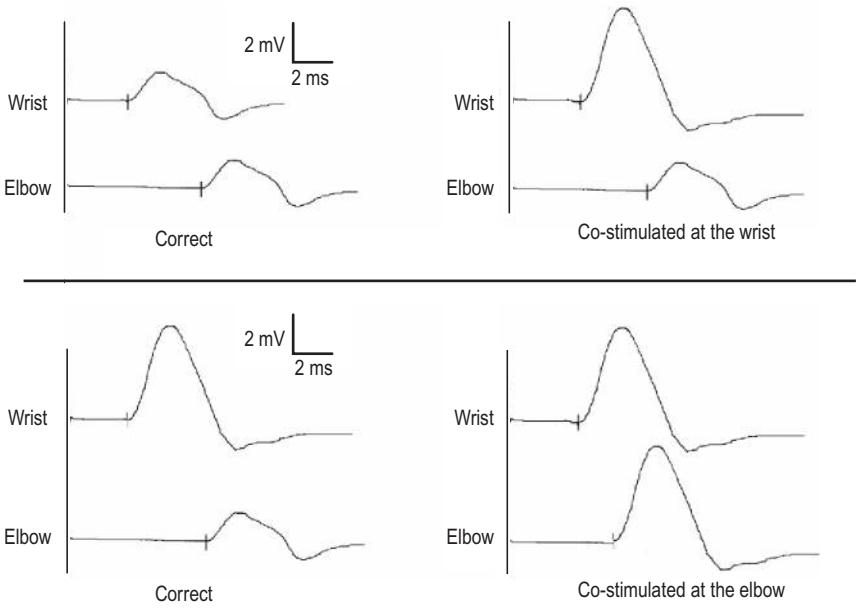


FIGURE 8–16 Co-stimulation and interpretation of conduction block. During motor nerve conduction studies, conduction block is recognized by a marked drop of amplitude or area on proximal stimulation as compared to distal stimulation. However, if the nerve is co-stimulated at the distal or proximal sites, different problems occur. **Top:** (Left) If the amplitude is truly reduced at the distal (wrist) and proximal (elbow) stimulation sites, the pattern is one of axonal loss. However, if the distal site is inadvertently co-stimulated (and not the proximal site) (Right), then a spuriously higher amplitude response will be present distally, and one will erroneously make the electrical diagnosis of conduction block. **Bottom:** (Left) If there is a true conduction block between distal and proximal stimulation sites, there will be a tendency to overstimulate the proximal site in order to get the amplitude "normal." However, if the nerve is inadvertently co-stimulated at the proximal site (and not at the distal site) (Right), the true conduction block pattern will be obscured, and the mistaken electrical diagnosis of a normal nerve conduction will be made.

Box 8–5. Methods to Avoid Co-Stimulation of Adjacent Nerves

- Ensure stimulator position is optimized directly over the nerve.
- Watch for abrupt change in waveform morphology.
- Watch for a change in the resultant muscle twitch.
- Avoid excessive stimulation currents.
- If necessary, co-record muscles simultaneously from adjacent nerves.
- Always consider possible distal co-stimulation when a conduction block is seen.

prevented if attention is paid to the muscle twitch during stimulation. For example, stimulation of the median nerve at the wrist results in contraction of the thenar eminence and first two lumbricals. In contrast, ulnar nerve stimulation results in a more widespread flexion contraction of the hand as the ulnar nerve innervates most of the intrinsic hand muscles. Thus, as the current intensity increases and co-stimulation of median and ulnar innervated muscles begins, the observer will witness a change in the muscle twitch. At this point, the stimulus intensity should be decreased until the point that only the median innervated muscles contract. This also applies to the lower extremities, especially at the popliteal fossa where the tibial nerve is in close proximity to the peroneal nerve. Stimulation of the peroneal nerve results in ankle dorsiflexion and eversion, whereas stimulation of the tibial nerve results in ankle plantar flexion and inversion. Thus, when stimulating the peroneal nerve at the knee, the normal twitch of ankle dorsiflexion will change to plantar flexion and inversion when the tibial nerve is co-stimulated. Finally, for most normal individuals, co-stimulation of the median and ulnar nerves at the wrist and elbow, and of the peroneal nerve at the lateral popliteal fossa, often occurs at stimulus intensities >50 mA (0.2 ms pulse duration). Thus, once stimulus intensities are increased beyond this point, the electromyographer needs to appreciate the increased possibility of co-stimulation.

If there is still a question of co-stimulation after taking into account the above suggestions, one should simultaneously record muscles innervated by adjacent nerves, watching for a potential from the unintended muscle. If such a potential occurs, the stimulus intensity should be lowered until the unintended potential is no longer seen. For instance, when stimulating the median nerve at the wrist, if there is a question of ulnar co-stimulation, the abductor pollicis brevis (median innervated) and abductor digiti minimi (ulnar innervated) should be simultaneously recorded. If median nerve stimulation is done correctly, no potential should be recorded from the abductor digiti minimi.

Electrode Placement for Motor Studies

The preferred montage for recording motor conduction studies is the belly–tendon method. The active electrode (G1) is placed over the motor point, typically located in the center of the muscle belly, while the reference electrode (G2) is placed over the muscle's distal tendon. When this montage is used, the muscle tendon site presumably represents an electrically inert point, and only the signal at G1 is amplified.

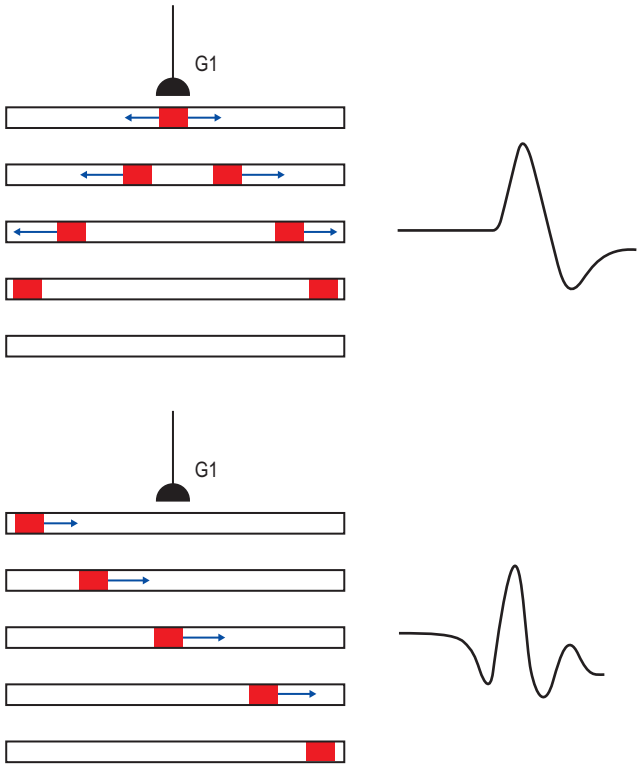


FIGURE 8–17 Compound muscle action potential (CMAP) morphology and site of depolarization. Depolarization occurs first at the motor endplate (motor point), with the depolarization subsequently spreading away from that site. With the active recording electrode (G1) placed over the motor point, the corresponding waveform has an initial negative deflection without any initial positivity **(top).** If the active recording electrode is not placed over the motor point, depolarization begins at a distance from and then travels beneath and past the active electrode, resulting in an initial positive deflection **(bottom).**

Muscle depolarization occurs first at the motor endplate zone (motor point). If the active recording electrode is not placed over the motor point, the volume-conducted depolarization potential first occurs at a distance from the recording electrode and is seen as an initial positive deflection. When the depolarization subsequently travels under the electrode, the potential then becomes negative (Figure 8–17). Two problems may occur with such an incorrect placement. First, the CMAP may not be maximized, giving the mistaken impression of a reduced amplitude (Figure 8–18). Second, if an initial positive deflection occurs, the latency is difficult to measure (Figure 8–19). Whenever an initial positive deflection is seen on a motor conduction study, the active electrode has most likely been placed off the motor point and should be moved until the positive deflection is no longer seen.

Not as well appreciated is the possibility of technical errors if the G2 electrode is misplaced. In the belly–tendon montage, it is generally assumed that the tendon is electrically inactive. Although this is true for most nerves, it is not so for all nerves, especially the ulnar and tibial nerves, where the reference electrode placed over the tendon is usually electrically active. Because there is no muscle over the tendon, this "tendon potential" is likely a volume-conducted far-field potential from nearby or proximal depolarizing muscles (Figure 8–20). In some cases, much of the CMAP amplitude is actually generated from the tendon potential. These tendon potentials are predominantly positive. Thus, the depolarization from G1 (which is negative) minus the tendon potential from G2 (which is positive) creates a larger negative potential. The key to avoiding errors from different G2 locations is consistency. For instance, if the right ulnar nerve is studied with G2 placed at the base of the fifth digit but the left ulnar nerve is studied with G2 placed distally on the fifth digit, then different, asymmetric amplitudes may result, based solely on the difference in the position of G2.

Antidromic versus Orthodromic Recording

For sensory conduction studies, either antidromic or orthodromic methods can be used. When a nerve is stimulated, conduction occurs equally well in both directions. Latencies and conduction velocities are identical using either method. However, each method has its advantages and disadvantages (Figure 8–21). First, amplitude is higher with antidromic than with orthodromic recordings. SNAP amplitude is directly proportional to the distance between the recording electrodes and the nerve. For most antidromic potentials, the active recording electrodes are closer to the nerve. For example, consider the antidromic median sensory study stimulating the wrist and recording the second digit. Using the antidromic method, recording ring electrodes are placed over the second digit. The ring electrodes are very close to the underlying digital nerves, which lie just beneath the skin. When the montage is reversed for orthodromic recording, the recording bar or disk electrodes are placed over the wrist. The thick transverse carpal ligament and other supporting connective tissue lie between the nerve and the recording electrodes. The recorded sensory response consequently is attenuated by the intervening tissue and results in a much lower amplitude. The major advantage of antidromic recording is the higher amplitude potentials obtained with this method. Not only is it easier to find the potential, but also larger amplitude potentials can be especially helpful in making side-to-side comparisons, following nerve injuries over time, or recording potentials from pathologic nerves, which can be quite small.

The antidromic method, however, does have its disadvantages. Although only sensory fibers are recorded, both motor and sensory fibers are stimulated. This often results in a volume-conducted motor potential following the SNAP (Figures 8–21, and 3–9). Because the SNAP usually occurs before the volume-conducted motor potential, it is not difficult to differentiate the two. However, if the two potentials have a similar latency or, more importantly, if the sensory potential is absent, one might mistake the first component of the volume-conducted motor potential for the SNAP where none truly exists.

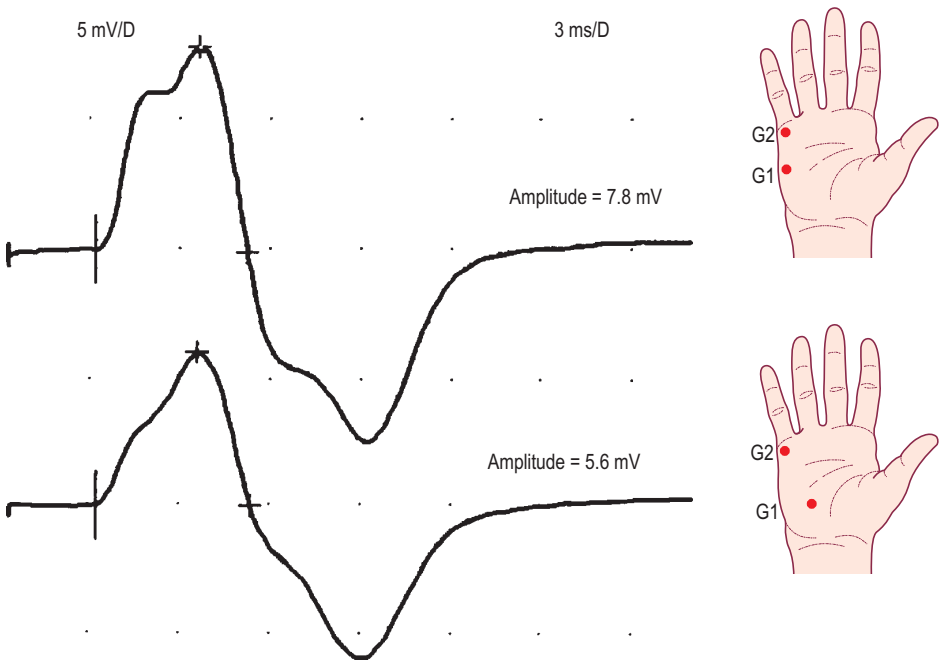


FIGURE 8–18 Effect of active recording electrode position on amplitude in motor studies. Ulnar motor study recording the hypothenar muscles, stimulating the wrist. The optimal position to evoke the maximal amplitude is over the motor point **(top trace).** When the active recording electrode (G1) is off the motor point, a positive initial deflection often is noted, alerting the examiner to the incorrect placement. However, this may not occur, especially when nearby muscles also are depolarized **(bottom trace).** Repositioning the active recording electrode often may result in a higher amplitude. This is especially important when comparing potentials from side to side.

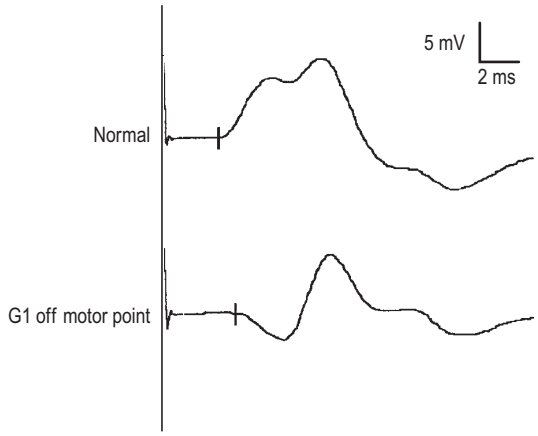


FIGURE 8–19 Active recording electrode placement and motor studies. Ulnar motor study, recording the abductor digiti minimi, stimulating wrist. The active recording electrode (G1) is properly placed over the motor point of the muscle, and the reference electrode (G2) is placed over the distal tendon **(top trace).** If G1 is placed off the motor point, the morphology of the compound muscle action potential changes, usually to show an initial positive deflection and a lower amplitude potential **(bottom trace).**

Distance between Recording Electrodes and Nerve

In sensory or mixed nerve studies, the amount of intervening tissue and the distance separating the recording electrodes and the underlying nerve can markedly influence the amplitude of the recorded potential. As a potential is recorded at an increasing distance from the nerve, the amplitude decreases dramatically (Figure 8–22). This accounts for the lower amplitude potentials seen with orthodromic sensory studies. In most orthodromic studies, the nerve lies deeper to the recording electrodes than it does in the corresponding antidromic study.

This situation is often encountered when performing lower extremity sensory studies (especially the sural and superficial peroneal sensory nerve studies) in a patient who has edema (Figure 8–23). Regardless of the cause of edema (venous insufficiency and congestive heart failure being the most common), the edema results in a greater distance between the surface recording electrodes and the nerves than is normally seen. This then results in an attenuation of the amplitude. Thus, in this situation, caution must be exercised before interpreting any low or absent response, especially a sensory response, as abnormal. Indeed, in such a situation, it is only the presence of a normal response that is helpful. An absent or reduced response, in the presence of marked edema, should be noted in the report as possibly due to technical factors from the edema, and should be appropriately incorporated into the final impression.

Lower amplitude potentials may be seen not only when the nerve lies deep but also when the recording electrodes are inadvertently placed lateral or medial to, and not directly over, the nerve. Because most nerves cannot be seen or palpated, recording electrodes for sensory and mixed nerve studies generally are placed based on anatomic landmarks and initially may not be placed in the optimal position directly over the nerve of interest. This situation occurs most frequently with sensory studies in which the position of the underlying nerve is slightly variable (e.g., palmar mixed studies, lateral antebrachial, medial antebrachial, superficial radial, sural, saphenous, and superficial peroneal sensory nerves). To avoid this pitfall, it is important to move the recording electrodes from the initial position slightly medially and then slightly laterally, with the stimulus current held constant, to determine which

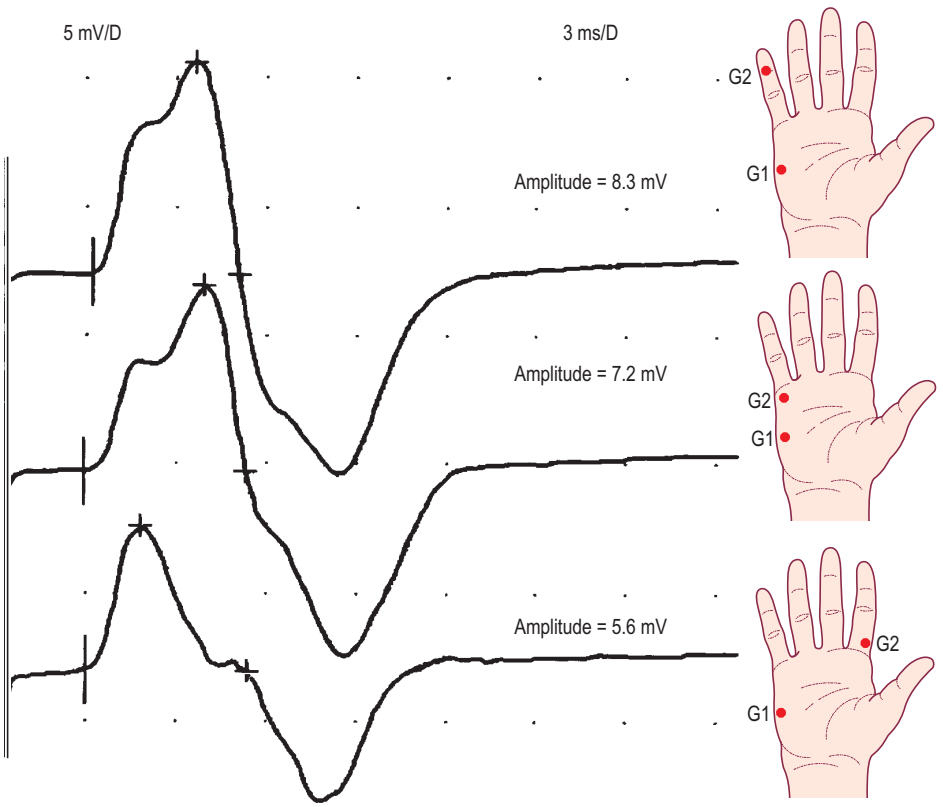


FIGURE 8–20 Effect of reference electrode position on amplitude in motor studies. Recording electrodes for motor studies are placed in the "belly–tendon" montage. The depolarization occurs under the muscle belly, where the active electrode (G1) is placed. The reference electrode (G2) is placed over the tendon which in theory is electrically neutral. However, the tendon may be electrically active, especially when studying the ulnar and tibial nerves. This tendon potential occurs as the result of volume conduction of proximal potentials. In the case of the ulnar nerve, this gives the motor response its characteristic bifid morphology. Note in the three traces how the morphology and amplitude of the motor response change as the placement of the reference electrode is changed. This underscores the need for consistency in placing both the reference and active recording electrodes when performing motor studies.

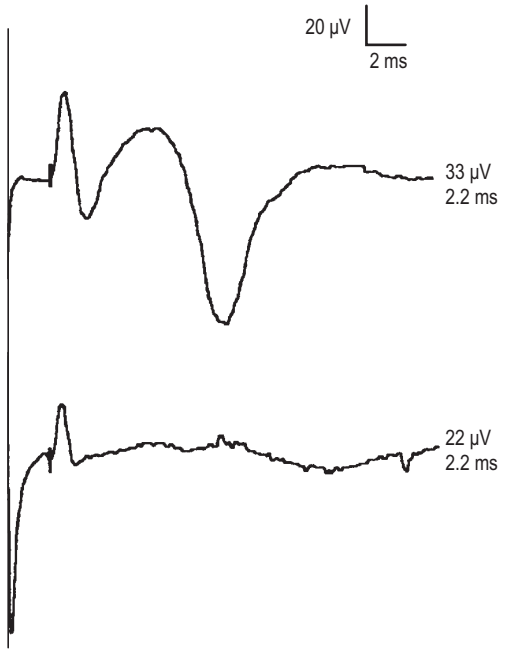


FIGURE 8–21 Comparison of antidromic and orthodromic median sensory studies. **Top trace:** Antidromic study, stimulating wrist, recording digit 2. **Bottom trace:** Orthodromic study, stimulating digit 2, recording wrist, same distance. Latencies and conduction velocities are identical. The antidromic method has the advantage of a higher amplitude, but the sensory nerve action potential (SNAP) may be followed by a large volume-conducted motor potential. If the SNAP is absent in an antidromic study, one must be careful not to mistake the volume-conducted motor potential for a sensory potential.

position yields the largest amplitude response. It often is surprising how minimal movement of the recording electrodes can greatly affect the amplitude of the response (Figure 8–24). Failure to do so often can result in technical errors, especially when comparing amplitudes from side to side. The median and ulnar antidromic studies are an exception, as the recording electrodes are placed over the digits and one can always be assured that the recording electrodes are placed as close to the nerve as possible (i.e., directly over the digital nerves).

In addition to its effect on amplitude, the placement of the recording electrodes also affects the latency measurements. If the recording electrodes are placed lateral or medial to the nerve, the onset latency shortens while the peak latency remains relatively unchanged. Although not intuitively obvious, these changes are due to the effects of volume conduction through tissue. The end result of the placement of recording electrodes at a distance from the nerve (because of intervening tissue, inaccurate placement of the electrodes, or both) is that the recorded electrical potential will be lower in amplitude and possibly spuriously fast (Figure 8–24). The closer the recording electrodes are to the nerve, the higher the amplitude and the more accurate the onset latency.

Distance between Active and Reference Recording Electrodes

Every potential recorded in a nerve conduction study is the result of the difference in electrical activity between the active and reference recording electrodes. For sensory and

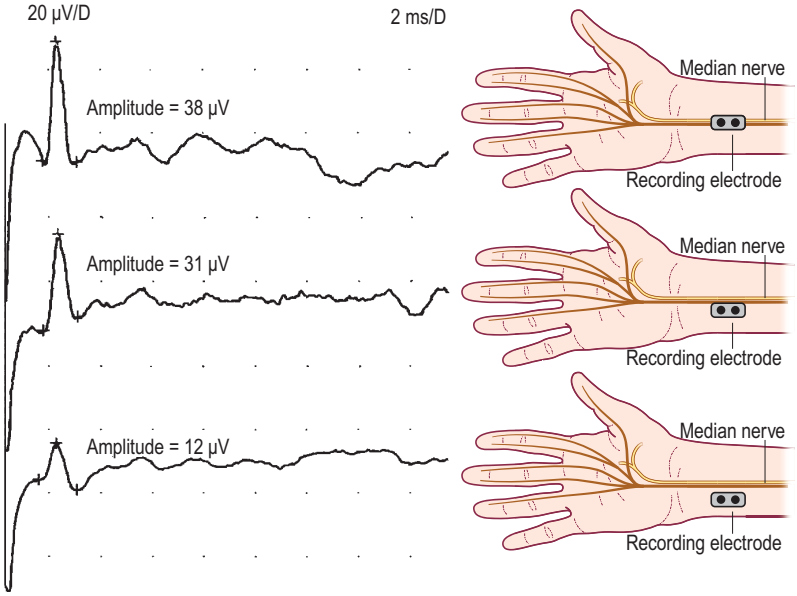


FIGURE 8–22 Effect of distance between recording electrodes and nerve on amplitude. Median mixed nerve study, stimulating the palm, recording over the wrist. **Top trace:** Recording electrodes placed directly over the median nerve. **Middle trace:** Recording electrodes placed 0.5 cm laterally. **Bottom trace:** Recording electrodes placed 1.0 cm laterally. If the recording electrodes are moved off the nerve (middle and bottom traces), maintaining the same distance and stimulus current, the amplitude drops markedly. In nerve conduction studies, side-to-side comparisons between amplitudes are often made, looking for asymmetry. One can easily appreciate that if the recording electrodes are placed lateral or medial to the nerve on one side and directly over the nerve on the other side, one might be left with the mistaken impression of a significant asymmetry in amplitude. When the location of the underlying nerve is not certain, it is important to try several recording electrode positions to ensure that the maximal amplitude is obtained.

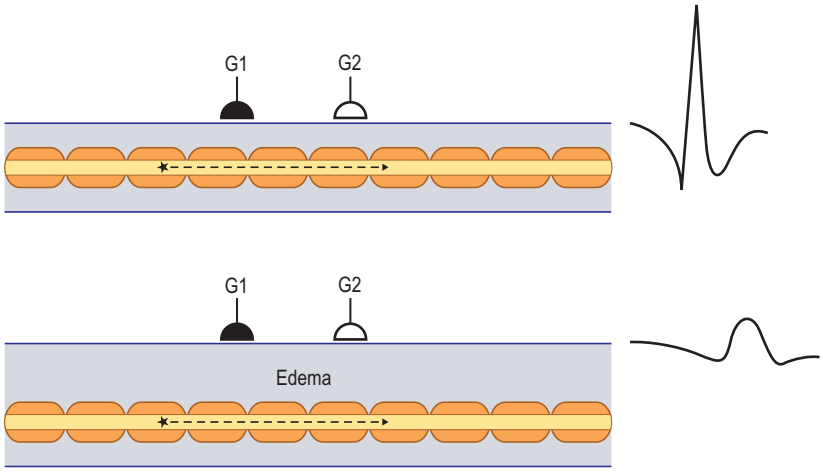


FIGURE 8–23 Effect of increased distance between recording electrodes and nerve on amplitude. When performing sensory and mixed nerve conduction studies, the nerve is assumed to lie just under the skin **(top).** However, if edema is present, there will be a greater distance between the surface recording electrodes and the nerve **(bottom).** This results in a marked attenuation of the amplitude of the potential, and if the distance is great enough, the response can even be absent. In addition, the potential is dispersed in duration, the onset latency may be slightly shortened and the peak latency slightly prolonged. This occurs because tissue acts as a high-frequency filter, attenuating the amplitude, which is predominantly a high-frequency response. The other changes occur from effects of volume conduction over a longer distance. Thus, caution must be exercised before interpreting any low or absent response as abnormal in the setting of marked edema, especially a sensory response.

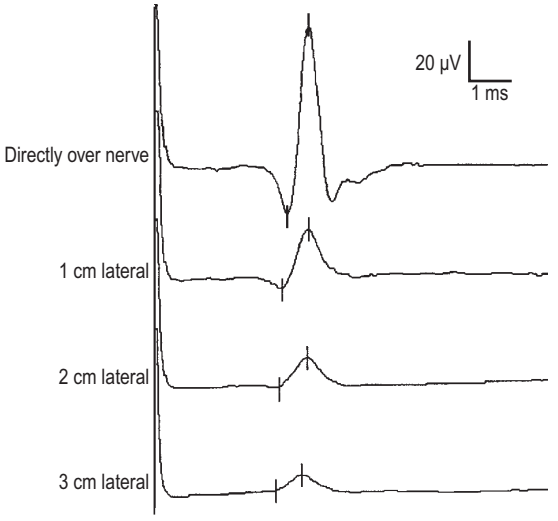


FIGURE 8–24 Effect of distance between recording electrodes and nerve on latency. Median mixed nerve study, stimulating wrist, recording antecubital fossa. In addition to the effect on amplitude, if the recording electrodes are moved off the nerve while maintaining the same distance and stimulus current, the onset latency shifts to the left. This results in a spuriously fast conduction velocity. (From Raynor, E.M., Preston, D.C., Logigian, E.L., 1997. Influence of surface recording electrode placement on nerve action potentials. Muscle Nerve 20, 361. Reprinted by permission of Wiley.)

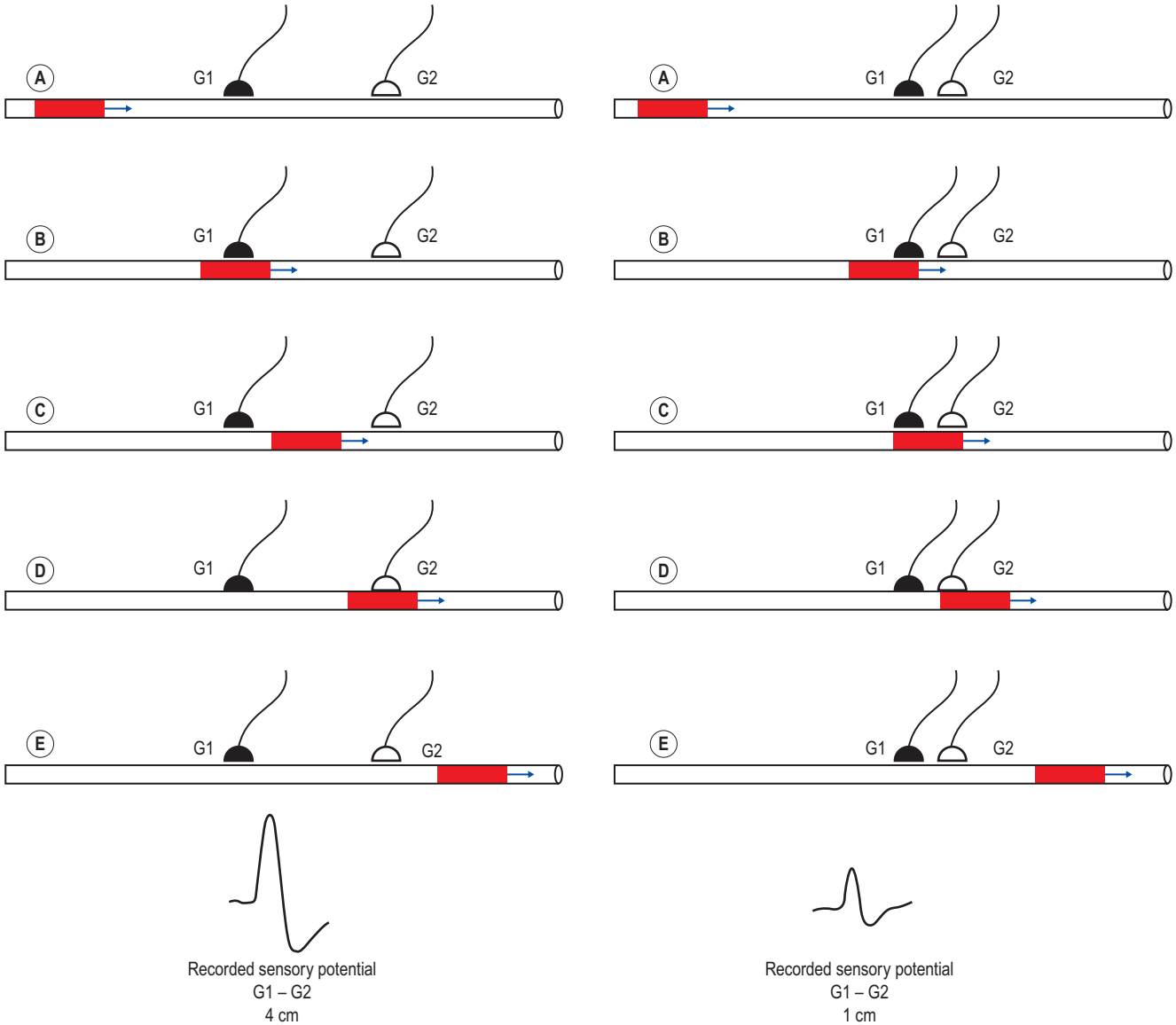


FIGURE 8–25 Influence of distance between active and reference recording electrodes on sensory studies. The distance between the active (G1) and reference (G2) recording electrodes influences the morphology of the sensory nerve action potential (SNAP). The SNAP is the result of the difference in electrical activity between the active and reference recording electrodes. The segment of depolarized nerve proceeds first under the active electrode and then travels distally beneath the reference electrode (left side, inter-electrode distance of 4 cm). If the active and reference electrodes are too close (e.g., inter-electrode distance of 1 cm), they may briefly become electrically active at the same time, resulting in a lower-amplitude potential (right side, third trace). For the usual range of nerve conduction velocities in sensory and mixed nerve studies, separating the active and reference recording electrodes by 3 to 4 cm will ensure that depolarization does not occur under both electrodes simultaneously.

mixed nerve studies, the active and reference electrodes typically are placed in a straight line over the nerve to be recorded. Accordingly, the segment of nerve that is depolarized proceeds first under the active electrode and then passes distally to travel under the reference electrode. If the active and reference electrodes are too close together, they may briefly become electrically active at the same time, resulting in a lower amplitude potential due to a cancellation effect (Figures 8–25 and 8–26). For this reason, the preferred inter-electrode distance between the active and reference recording electrodes for sensory and mixed nerve recordings is 3 to 4 cm. For the usual range of nerve conduction velocities, this distance ensures that depolarization will not occur under both electrodes simultaneously.

Limb Position and Distance Measurements

To compute a conduction velocity accurately, one must correctly measure the distance along the nerve. It usually is assumed that the surface distance accurately represents

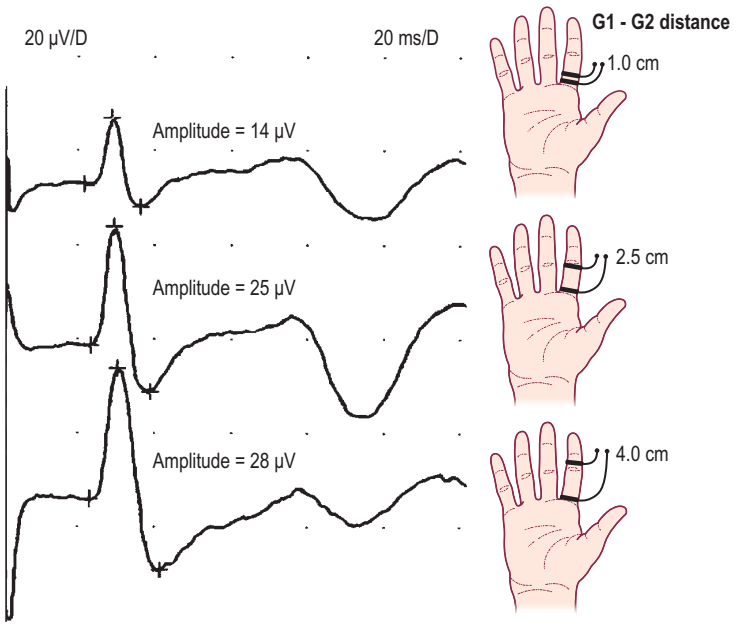


FIGURE 8–26 Influence of distance between active and reference recording electrodes on sensory studies. Median sensory studies, stimulating the wrist, recording digit 2. The distance between the active (G1) and reference (G2) recording electrodes is 1.0 cm **(top),** 2.5 cm **(middle),** and 4.0 cm **(bottom).** Note the much smaller-amplitude potential when the recording electrodes are 1.0 cm apart. In this case, the active and reference electrodes are so close that the segment of depolarized nerve may occur simultaneously at both electrodes, resulting in a lower-amplitude potential.

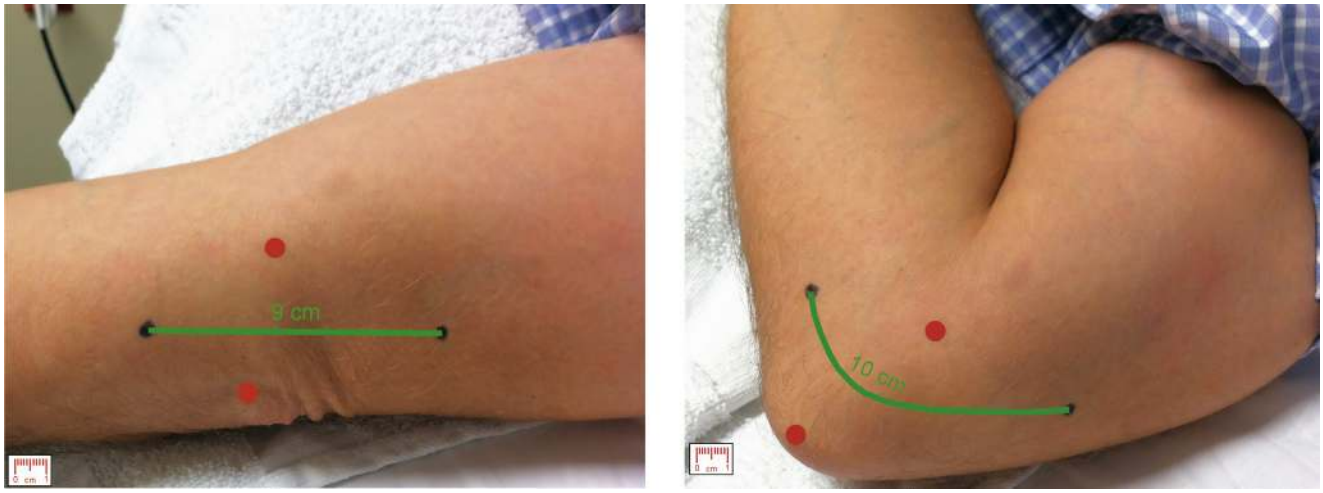


FIGURE 8–27 Limb position and nerve length of the ulnar nerve. At the elbow, the ulnar nerve is slack and redundant when the arm is in the extended position. If surface distance measurements of the ulnar nerve are made with the arm in this position, the true length of the underlying nerve is underestimated. **Left:** With the elbow in extension, a surface distance of 9 cm is measured between the below- and above-elbow sites (note: the ulnar nerve runs between the medial epicondyle and olecranon marked by the red circles on the photos). **Right:** With the elbow in flexion, the same two marks now measure 10 cm apart, which more accurately reflects the true length of the ulnar nerve. If ulnar conduction studies are performed with the elbow extended, artifactual slowing of conduction velocity occurs across the elbow segment. When the elbow assumes a flexed position, the measured surface distance of the nerve across the elbow better reflects the true underlying length of the nerve, and a more valid measurement of nerve conduction velocity can be made.

the true underlying length of the nerve, and in most circumstances that assumption is correct. There are several notable exceptions, however, the most important being that of the ulnar nerve across the elbow (Figure 8–27). Surgical and cadaver dissection studies have shown that the ulnar nerve is slack and redundant when the arm is in the extended position. If surface distance measurements of the ulnar nerve are made with the arm extended, the true length of the underlying nerve is underestimated. Thus, ulnar nerve conduction studies performed with the elbow extended often result in artifactual slowing of conduction velocity across the elbow segment. When the elbow assumes a flexed position, the measured surface distance of the nerve across the elbow better reflects the true underlying length of the nerve, and a more valid measurement of nerve conduction velocity is made.

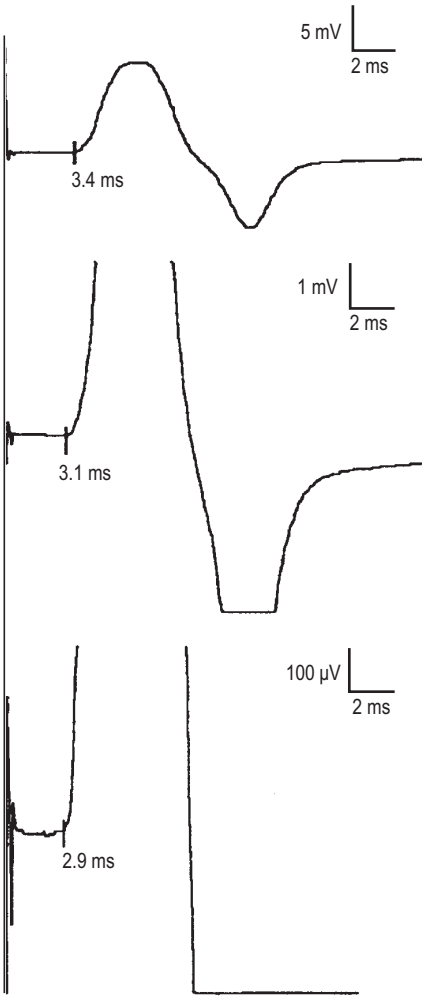


FIGURE 8–28 Latency measurement and sensitivity. Median motor study, stimulating wrist, recording the abductor pollicis brevis, using varying sensitivities, with sweep speed held constant. Latency measurements should always be made using the same sensitivity. Note that as sensitivity is increased, latency measurement usually decreases.

Surface distance measurements of several other nerves often are inaccurate. These include the radial nerve as it spirals around the humerus, and the median and ulnar nerves between the axilla and Erb's point. In these situations, obstetric calipers can be used to more accurately approximate the true length of the underlying nerve.

Limb Position and Waveform Morphology

During any nerve conduction study where more than one site is stimulated (typically motor studies), it is essential that the limb remains in the same position for all stimulation sites. If this is not done, slightly different responses may result with different limb postures. This may occur due to slight movement of the skin (and recording electrodes) in relation to the underlying muscle or nerve. In addition, there is the complicated issue of the "tendon potential" as discussed above. In the belly–tendon montage, it is generally assumed that the tendon is electrically

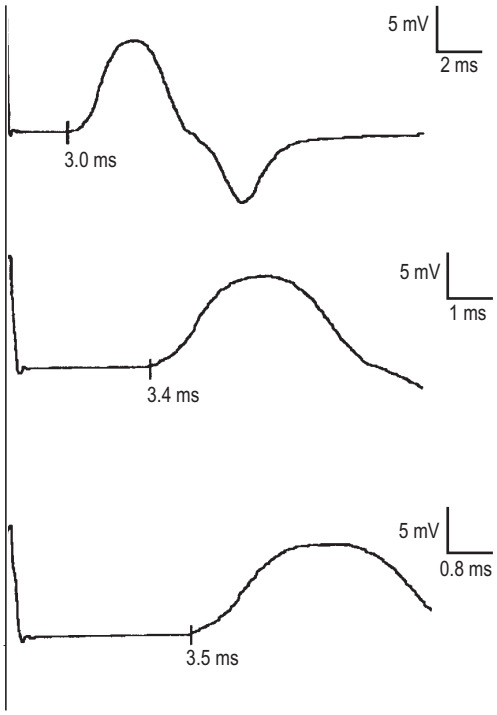


FIGURE 8–29 Latency measurement and sweep speed. Median motor study, stimulating wrist, recording the abductor pollicis brevis, using varying sweep speeds, with sensitivity held constant. Latency measurements should always be made using the same sweep speed. Note that as sweep speed decreases, latency measurement usually increases.

inactive. However, this is not so for all nerves, especially the ulnar and tibial nerves, where the reference electrode placed over the tendon is often electrically active. Because there is no muscle over the tendon, this "tendon potential" is a volume-conducted far-field potential from proximal depolarizing muscles. These volume conduction potentials can change in shape and latency as the limb position changes. Thus, take this example:

- The ulnar nerve motor study is performed, stimulating the wrist, below-elbow, and above-elbow sites, with the arm in the bent (i.e., flexed) position for all three stimulation sites

vs.

- The ulnar nerve motor study is performed, stimulating the wrist, below-elbow, and above-elbow sites. However, the ulnar nerve is stimulated at the wrist with the arm straight; then the elbow is flexed and the stimulations are done at the below-elbow and above-elbow sites

In this example, one would obtain slightly different amplitudes (especially at the below-elbow and above-elbow sites) and slightly different conduction velocities in the second scenario versus the first.

Although the physiology of volume conduction is complex and not intuitive, the bottom line is the following: *if at all possible, during a nerve conduction study, stimulate all sites with the limb in the same position.*

Latency Measurements: Sweep Speed and Sensitivity

Both the sweep speed and sensitivity can markedly influence the recorded latency of both sensory and motor potentials. As the sensitivity is increased, the onset latency measurement successively decreases (Figure 8–28). Conversely, as the sweep speed is decreased, latency measurements usually increase (Figure 8–29). *For this reason, all latency measurements for each nerve conduction study should be made using the same sensitivity and the same sweep speed*. This is especially true within nerves, where potentials obtained with different sweep speeds or sensitivities at distal and proximal stimulation sites along the nerve can easily result in the calculation of a faulty conduction velocity. This is one potential advantage of using peak latency as opposed to onset latency in sensory and mixed nerve studies, because peak latency is not affected by changes in either sweep speed or sensitivity (n.b., one cannot obtain a conduction velocity using peak latencies).

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9 Basic Statistics for Electrodiagnostic Studies

For every electrodiagnostic (EDX) test performed, one needs to decide if the study is normal or abnormal. That determination often needs to be made in real time as the testing progresses, so that the study can be modified based on new information obtained as the testing proceeds. However, interpreting a test as normal or abnormal is not always straightforward, and requires some understanding of basic statistics. A full discussion of statistics is beyond the scope and purpose of this text, but there are some basic statistical concepts that every electromyographer needs to know in order to properly interpret a study.

No two normal individuals have precisely the same findings on any biologic measurement, regardless of whether it is a serum sodium level, a hematocrit level, or a distal median motor latency. Most populations can be modeled as a *normal distribution*, wherein there is a variation of values above and below the mean. This normal distribution results in the commonly described *bell-shaped curve* (Figure 9–1). The center of the bell-shaped curve is the mean or average value of a test. It is defined as follows:

$$\text{Mean} = \frac{\sum(x_1, x_2, \ldots x_N)}{N}$$

where x=an individual test result, and N=total number of individuals tested.

The *standard deviation* (SD) is a statistic used as a measure of the dispersion or variation in a distribution. In general, it is a measure of the extent to which numbers are spread around their average. It is defined as follows:

$$\text{SD} = \sqrt{\frac{\sum[(x_1 - Mean)^2, (x_2 - Mean)^2 \ldots (x_N - Mean)^2]}{N-1}}$$

The reasons that the SD is such a useful measure of the scatter of the population in a normal distribution are as follows (Figure 9–1):

- The range covered between 1 SD above and below the mean is about 68% of the observations.
- The range covered between 2 SD above and below the mean is about 95% of the observations.
- The range covered between 3 SD above and below the mean is about 99.7% of the observations.

In EDX studies, one usually uses a lower or upper cutoff value, not both. For instance, a normal serum sodium may be 130 to 145 mmol/L (lower and upper cutoffs); however, a normal median distal motor latency is less than 4.4 ms (i.e., there is no lower cutoff because there is no median distal motor latency that is too good). Thus, for tests where the abnormal values are limited to one tail of the bell-shaped curve, instead of two:

- All observations up to 2 SD beyond the mean include approximately 97.5% of the population.
- All observations up to 2.5 SD beyond the mean include approximately 99.4% of the population.

These facts are important because cutoff values for most EDX studies often are set at 2 or 2.5 SD above or below the mean for upper and lower cutoff limits, respectively. After cutoff limits are established, one must next appreciate the important concepts of *specificity* and *sensitivity* of a test.

The *specificity* of a test is the percentage of all patients without the condition (i.e., normals) who have a negative test. Thus, when a test is applied to a population of patients

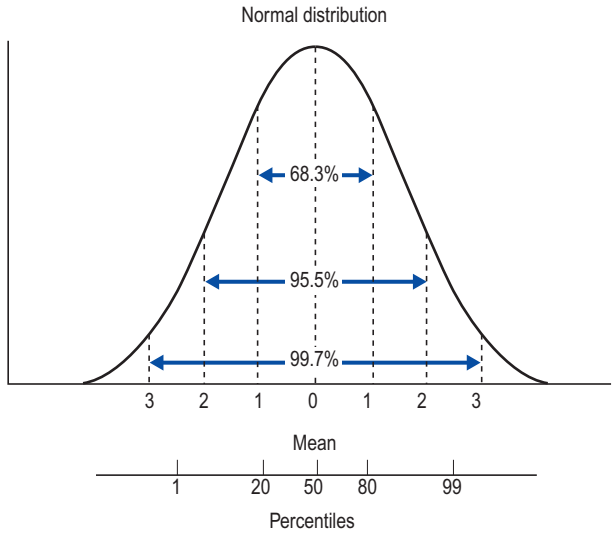

FIGURE 9–1 Normal distribution. Many biologic variables can be modeled as a normal distribution wherein there is a variation of values above and below the mean. This normal distribution results in a bell-shaped curve. The center of the bell-shaped curve is the mean or average value of a test. The numbers on the *x*-axis represent the number of standard deviations above and below the mean. The standard deviation is a measure of the dispersion or variation in a distribution. The number of standard deviations above and below the mean define a certain portion of the population.

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who are normal, the test will correctly identify all patients as normal who do not exceed the cutoff value (*true negative*); however, it will misidentify a small number of normal patients as abnormal (*false positive*) (Figure 9–2, left). It is important to remember that every positive test is not necessarily a true positive; there will always be a small percentage of patients (approximately 1–2%) who will be misidentified.

The *sensitivity* of a test is the percentage of all patients with the condition who have a positive test. When a test is applied to a disease population, the test will correctly identify all abnormal patients who exceed the cutoff value (*true positive*); however, it will misidentify a small number of abnormal patients as normal (*false negative*) (Figure 9–2, right). Thus, it is equally important to remember that every negative test is not necessarily a true negative; there will always be a small percentage of abnormal patients (approximately 1–2%) who will be misidentified as normal. Thus, the specificity and sensitivity can be calculated as follows:

$$\text{Specificity (\%)} = \frac{True\ Negatives}{(True\ Negatives + False\ Positives)} * 100$$

$$\text{Sensitivity (\%)} = \frac{True\ Positives}{(True\ Positives + False\ Negatives)} * 100$$

In an ideal setting, there would be no overlap between a normal and a disease population. Then, a cutoff value could be placed between the two populations, and such a test would have 100% sensitivity and 100% specificity (Figure 9–3, left). However, in the real world, there is always some overlap between a normal and disease population (Figure 9–3, right). If a test has very high sensitivity and specificity, it will correctly identify nearly all normals and abnormals; however, there will remain a small number of normal patients misidentified as abnormal (false positive) and a small number of abnormal patients misidentified as normal (false negative).

Often there is a compromise between sensitivity and specificity when setting a cutoff value. Take the example of a normal and a disease population where there is significant overlap between the populations for the value of a test. If the cutoff value is set low, the test will have high sensitivity but very low specificity (Figure 9–4). In this case, the test will correctly diagnose nearly all the abnormals correctly (true positive) and will only misidentify a few as normal (false negative) (Figure 9–4, left). However, the tradeoff for this high sensitivity will be low specificity. In this case, a high number of normal patients will be classified as abnormal (false positive) (Figure 9–4, right).

Conversely, take the example where the cutoff value is set high. The test will now have high specificity but very

FIGURE 9–2 Cutoff values and false results. **Left:** When a test is applied to a population of normal patients, the test will correctly identify all patients who are below the cutoff value as normal (true negative [green in the figure]); however, it will misidentify a small number of normal patients who are above the cutoff value as abnormal (false positive [dark blue in the figure]). **Right:** When a test is applied to a disease population, the test will correctly identify all abnormal patients who exceed the cutoff value (true positive [red in the figure]); however, it will misidentify a small number of abnormal patients who are below the cutoff value as normal (false negative [dark blue in the figure]).

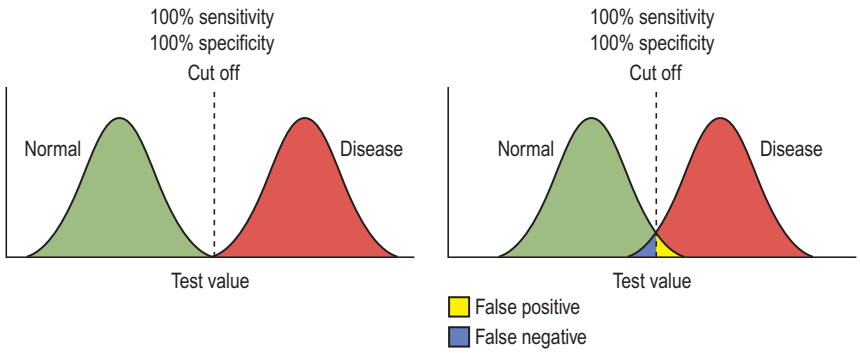


FIGURE 9–3 Selection of cutoff values. **Left:** Ideally, there would be no overlap between a normal (green) and a disease (red) population, and the cutoff value could be placed between the two populations, yielding 100% sensitivity and 100% specificity. **Right:** In biologic populations, there is always some overlap between normal and disease populations. If a test has very high sensitivity and specificity, it will correctly identify nearly all normals and abnormals; however, there will remain a small number of normal patients misidentified as abnormal (false positive [yellow in the figure]) and a small number of abnormal patients misidentified as normal (false negative [dark blue in the figure]).

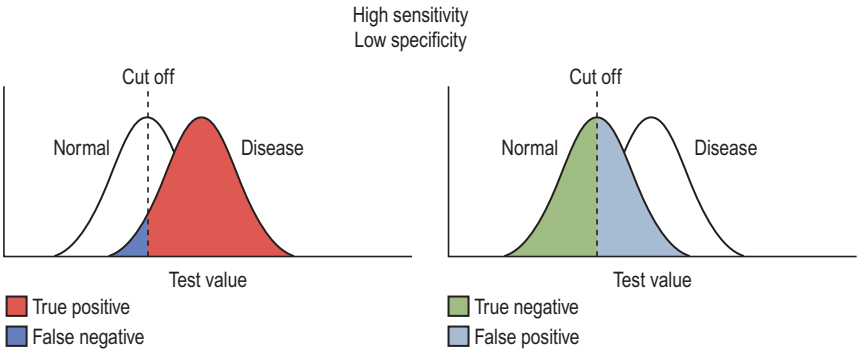


FIGURE 9–4 Advantages and disadvantages: high sensitivity and low specificity. **Left:** If the cutoff value is set low (high sensitivity), the test will correctly diagnose nearly all the abnormals correctly (true positives [red in the figure]) and will misidentify only a few as normal (false negatives [dark blue in the figure]). **Right:** The tradeoff for this high sensitivity will be low specificity. In this case, some normals will be identified as normal (true positives [green in the figure]) but a high number of normal patients will be classified as abnormal (false positives [light blue in the figure]).

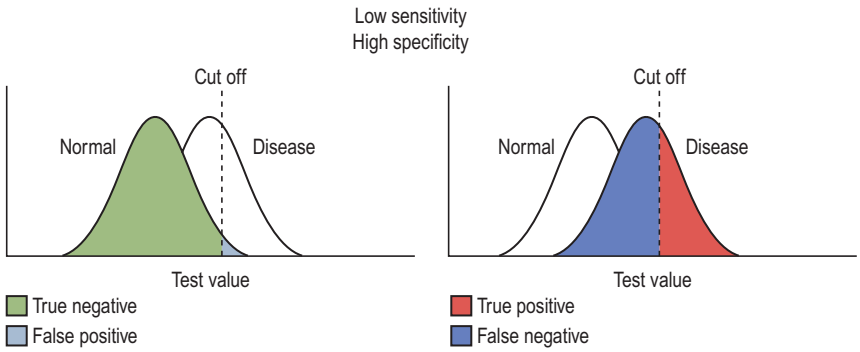


FIGURE 9–5 Advantages and disadvantages: high specificity and low sensitivity. **Left:** If the cutoff value is set high (high specificity), the test will correctly identify nearly all of the normals correctly (true negatives [green in the figure]) and will misidentify only a few normals as abnormal (false positives [light blue in the figure]). **Right:** The tradeoff for this high specificity will be low sensitivity. Here, some abnormal patients will be identified as abnormal (true positives [red in the figure]) but a high number of abnormal patients will be classified as normal (false negatives [dark blue in the figure]).

low sensitivity (Figure 9–5). In this case, the test will correctly identify nearly all the normals correctly (true negative) and will only misidentify a few normals as abnormal (false positive) (Figure 9–5, left). However, the tradeoff for this high specificity will be low sensitivity. Here, a high number of abnormal patients will be classified as normal (false negative) (Figure 9–5, right).

False positives and false negatives result in what are termed type I and type II errors, respectively. In a type I error, a diagnosis of an abnormality is made when none is present (i.e., convicting an innocent man). Conversely, in a type II error, a diagnosis of no abnormality is made when one actually is present (i.e., letting a guilty man go free). Although both are important, type I errors are generally considered more unacceptable (i.e., labeling patients as having an abnormality when they are truly normal, because this can lead to a host of problems, among them inappropriate testing and treatment). Thus, the specificity of a test should take precedence over the sensitivity, unless the test is being used as a screening tool alone (i.e., any positive screening test must be confirmed by a much more specific test before any conclusion is reached).

The tradeoff between sensitivity and specificity can be appreciated by plotting a receiver operator characteristic (ROC) curve that graphs various cutoff values by their sensitivity on the *y*-axis and specificity on the *x*-axis (actually in a typical ROC curve, the *x*-axis is 1 minus the specificity, which can alternatively be graphed as the specificity going from 100 to 0, instead of 0 to 100). Figure 9–6 shows an ROC curve for the digit 4 sensory nerve conduction study in patients with mild carpal tunnel syndrome. For this nerve conduction study, the sensory latency stimulating the ulnar nerve at the wrist and recording digit 4 is subtracted from the sensory latency stimulating the median nerve at the wrist and recording digit 4, using identical distances. In normals, one expects there to be no significant difference. In patients with carpal tunnel syndrome, the median latency is expected to be longer than the ulnar latency. Note in Figure 9–6 that there is a tradeoff between specificity and sensitivity as the cutoff value changes. For any cutoff value 0.4 ms or greater, there is a very high specificity. As the cutoff value is lowered, the sensitivity increases but at a significant cost to the specificity. In this example, it is easy to appreciate that the 0.4 ms cutoff is where the

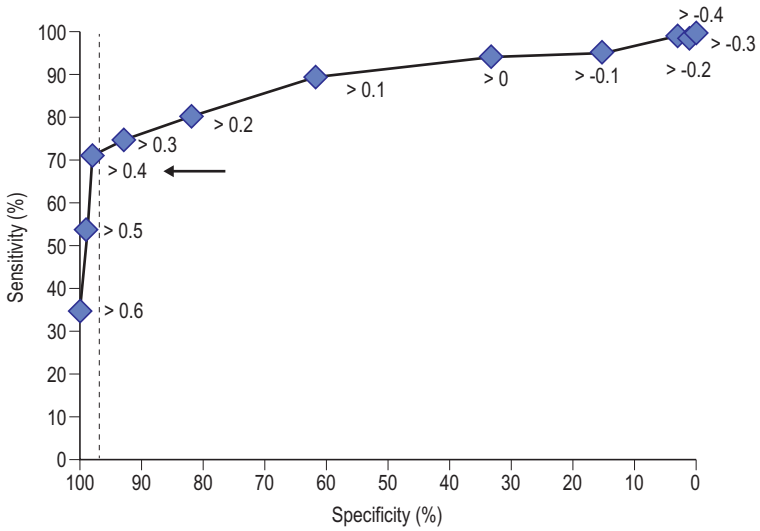


FIGURE 9–6 Receiver operator characteristic (ROC) curve for the digit 4 (D4) study. The graph demonstrates the tradeoff between sensitivity and specificity for various test values of the D4 study. Normal cutoff value (arrow) was set to obtain a 97.5% specificity (dashed line). The ROC curve shows a sharp turn at the cutoff value, maximizing sensitivity and specificity.
(Adapted from Nodera, H., Herrmann, D.N., Holloway, R.G., et al., 2003. A Bayesian argument against rigid cutoffs in electrodiagnosis of median neuropathy at the wrist. Neurology 60, 458–464.)

graph abruptly changes its slope. Setting the cutoff value at 0.4 ms or greater achieves a specificity greater than 97%. The sensitivity is approximately 70%. One could place the cutoff value at 0.1 ms and achieve a sensitivity of 90%; however, the specificity would fall to about 60%, meaning 40% of normal patients would be misidentified as abnormal, a clearly unacceptable level.

Important clinical–electrophysiologic implications are as follows:

1. Because of the normal variability and overlap between normal and disease populations, all EDX studies will have a small number of false-positive results and false-negative results.
2. Thus, EDX studies can never completely "rule out" any condition. Likewise, they can never completely "rule in" any condition.
3. Remember that a small number of false-positive results are expected. Always keep in mind the possibility of a type I error (i.e., convicting an innocent man) and the ramifications such an error can have.

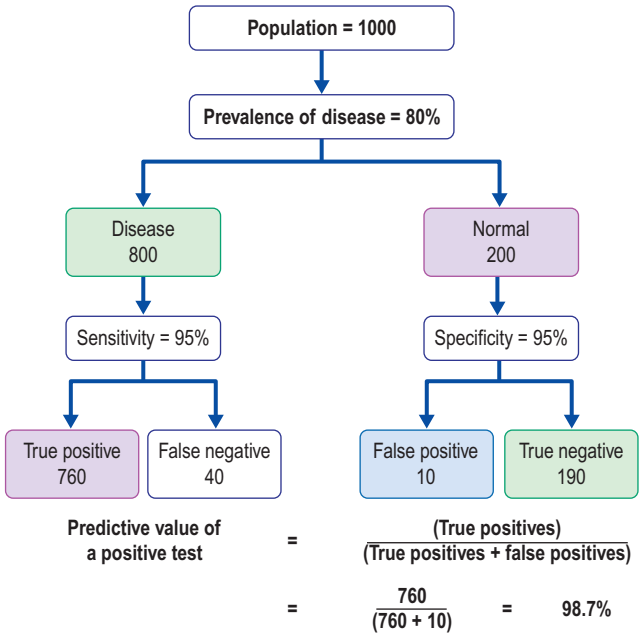


FIGURE 9–7 Predictive value of a positive test: high prevalence of disease. See text for details.

BAYES' THEOREM AND THE PREDICTIVE VALUE OF A POSITIVE TEST

Bayes' theorem states that the probability of a test demonstrating a true positive depends not only on the sensitivity and specificity of a test but also on the prevalence of the disease in the population being studied. The chance of a positive test being a true positive is markedly higher in a population with a high prevalence of the disease. In contrast, if a very sensitive and specific test is applied to a population with a very low prevalence of the disease, most positive tests will actually be false positives. The predictive value of a positive test is best explained by contrasting two examples (Figures 9–7 and 9–8). In both examples, the same test with a 95% sensitivity and a 95% specificity is applied to a population of 1000 patients. In Figure 9–7, the prevalence of the disease in the population is high (80%); in Figure 9–8, the prevalence is low (1%). In the population with a disease prevalence of 80%, 760 of the 800 patients with the disease will be correctly identified; of the 200 normals, 10 will be misidentified as abnormal (false positives). The predictive value of a positive test is defined as the number of true positives divided by the number of total positives. The total positives are the true positives added to the false positives. In Figure 9–7, the predictive value that a positive test is a true positive is 760/(760+10) =98.7%. Thus, in this example, where the

disease prevalence in the population is high, a positive test is extremely helpful in correctly identifying the patient as having the disease.

In the example where the disease prevalence is 1% (Figure 9–8), of the 10 patients with the disease, 9.5 will be correctly identified. However, of the 990 normals, 49.5 will be misidentified as abnormal. Thus, the predictive value that a positive test is a true positive is 9.5/(9.5+49.5) =16.1%. *This means that 83.9% of the positive results will actually be false!* In this setting, where the disease prevalence in the population is low, a highly sensitive and specific test is of absolutely no value.

Although this analysis may seem distressing, the good news is that EDX studies are generally performed in patients with a high index of suspicion for the disorder being questioned; hence, the prevalence of the disease is high. For instance, take the example of a patient referred to the EDX laboratory for possible carpal tunnel syndrome. If the patient has pain in the wrist and hand, paresthesias of the first four fingers, and symptoms provoked by sleep, driving, and holding a phone, the prevalence of carpal tunnel syndrome in patients with such symptoms would be extremely high. Thus, if EDX studies are performed and demonstrate delayed median nerve responses across the wrist, there is a very high likelihood that these positive tests are true positives. However, if the same tests are performed in a patient with back pain and no symptoms in the hands and fingers, the prevalence of carpal tunnel syndrome would be low in such a population. In this situation, any positive finding would have a high likelihood of being a false positive and would likely not be of any clinical significance.

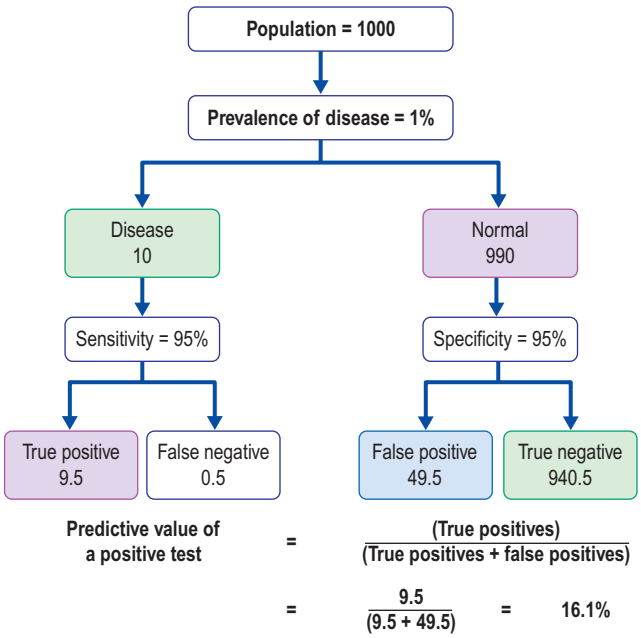


FIGURE 9–8 Predictive value of a positive test: low prevalence of disease. See text for details.

Less well appreciated is that the problem of a false positive in a population with a low prevalence of disease can be overcome by making the cutoff value more stringent (i.e., increasing the specificity). Take the example shown in Figure 9–9 of the palmar mixed latency difference test in patients with suspected carpal tunnel syndrome. For this nerve conduction study, the latency for the ulnar palm-to-wrist segment is subtracted from the latency for the median palm-to-wrist segment, using identical distances. In normals, one expects there to be no significant difference. In patients with carpal tunnel syndrome, the median latency is expected to be longer than the ulnar latency. In this example, the post-test probability (i.e., the predictive value of a positive test) is plotted against different cutoff values for what is considered abnormal for patients in whom there is a high pre-test probability of disease and for those in whom there is a low pre-test probability. In the patients with a high pre-test probability of disease, a cutoff value of 0.3 ms (i.e., any value >0.3 ms is abnormal) achieves a 95% or greater chance that a positive test is a true positive. However, the same 0.3 ms

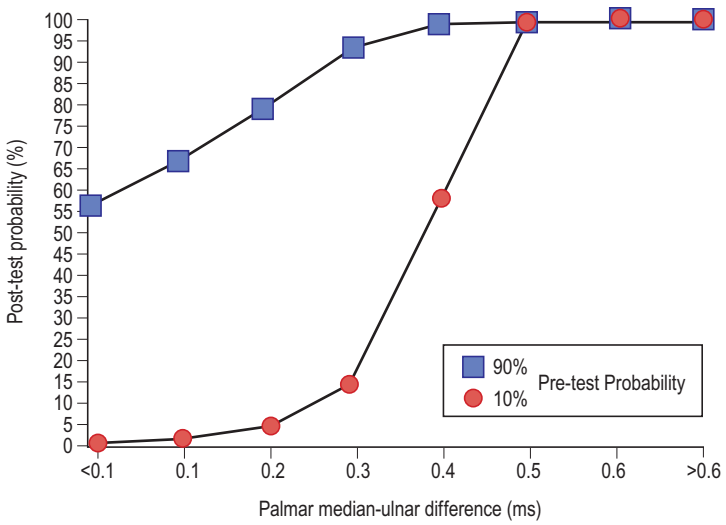


FIGURE 9–9 Post-test probabilities (PostTP) calculated with different pre-test probabilities (PreTP). In this example, the commonly used test for median neuropathy at the wrist, the palmar median–ulnar difference, is plotted using different PreTPs (■90%, ●10%) against PostTPs (i.e., a positive test result is a true positive). Note that PostTP depends on both the actual test value and PreTP, with higher PreTP yielding higher PostTP. A borderline abnormal test value (i.e., 0.4 ms) yields very high PostTP (95%) when PreTP is high, whereas the same test value results in only intermediate PostTP when PreTP is low. In contrast, very abnormal test values (i.e., ≥0.5 ms) result in PostTPs of 100%, regardless of the PreTP. (Adapted from Nodera, H., Herrmann, D.N., Holloway, R.G., et al., 2003. A Bayesian argument against rigid cutoffs in electrodiagnosis of median neuropathy at the wrist. Neurology 60, 458–464.)

cutoff in the low pre-test probability population results in only a 55% chance that a positive test is a true positive (and a corresponding 45% false-positive rate). These findings are in accordance with Bayes' theorem wherein the chance of a positive test being a true positive depends not only on the sensitivity and specificity of the test, but on the prevalence of the disease in the population being sampled (i.e., the pre-test probability). However, if the cutoff value is increased to 0.5 ms, then the post-test probability that a positive test is a true positive jumps to greater than 95%, even in the population with a low probability of disease.

Important clinical–electrophysiologic implications are as follows:

1. Every EDX study must be individualized, based on the patient's symptoms and signs and the corresponding differential diagnosis. When the appropriate tests are applied for the appropriate reason, any positive test is likely to be a true positive and of clinical significance.
2. A test result that is minimally positive has significance only if there is a high likelihood of the disease being present, based on the presenting symptoms and differential diagnosis.
3. A test that is markedly abnormal is likely a true positive, regardless of the clinical likelihood of the disease.
4. An abnormal test, especially when borderline, is likely a false positive if the clinical symptoms and signs do not suggest the possible diagnosis.

MULTIPLE TESTS AND THE INCREASING RISK OF FALSE POSITIVES

The last relevant statistical issue that every electromyographer needs to appreciate is the increased risk of a false positive when many different tests are applied in an attempt to reach a diagnosis. The most common situation occurs in the electrodiagnosis of median neuropathy at the wrist (i.e., carpal tunnel syndrome) where numerous useful nerve conduction studies have been described. However, when normal values for each individual test are set, an upper limit of normal usually is selected at 2 SD beyond the mean so that approximately 97.5% of the normal population will be correctly identified. Thus, each test carries a 2.5% false-positive rate. If these tests are independent and used sequentially, the false-positive rate increases and quickly rises to unacceptable levels. For instance, if 10 tests are applied, each with a 2.5% false-positive rate, and only one abnormal test is required to make a diagnosis, the false-positive rate rises above 20%. This situation is similar to a

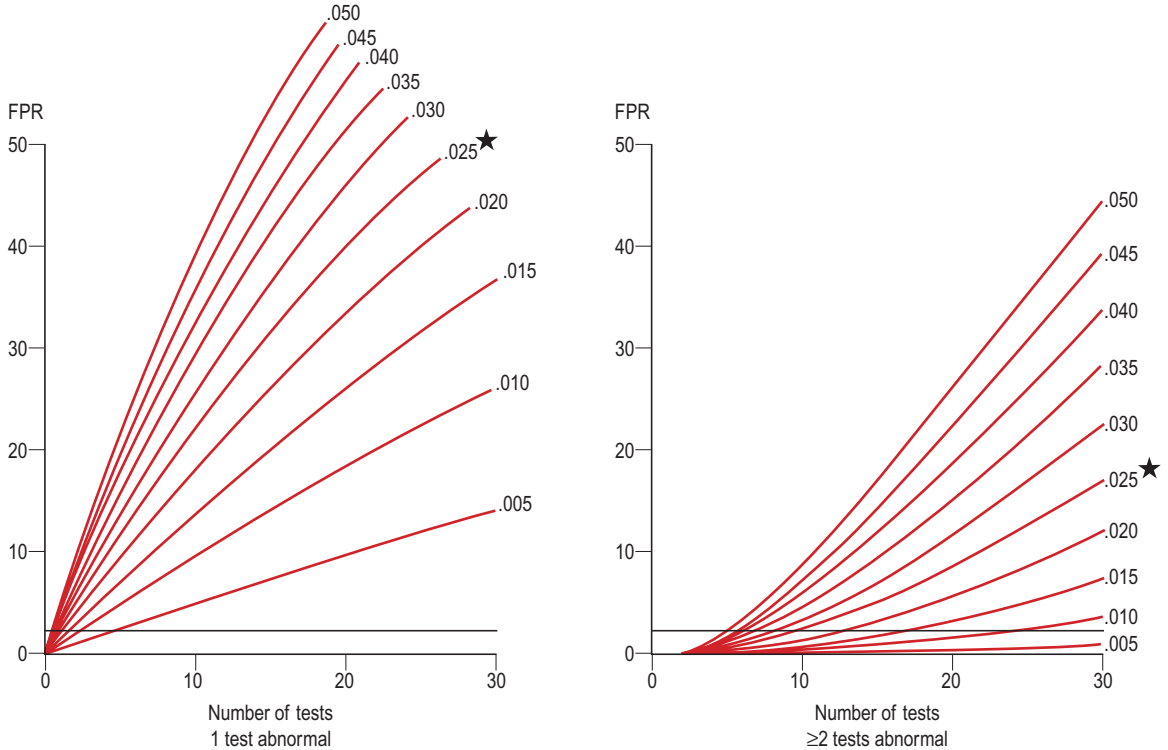


FIGURE 9–10 Multiple tests and the risk of false positives. The number of tests is plotted against the cumulative false-positive rate (FPR) for a variety of different individual test FPRs. Note the curve with the (★); this represents a false-positive rate of 2.5%, which carries the most common test specificity of 97.5%. **Left:** Cumulative FPR is calculated based on the assumption that only one test needs to be abnormal to diagnose the condition. Note that if 10 different tests are done, the cumulative FPR is almost 25%. **Right:** If two or more tests are required to be abnormal before a diagnosis is reached, the statistics change. When 10 tests are done with an individual FPR of 2.5%, the cumulative FPR remains less than 2.5%, an acceptable level.
(Adapted from Van Dijk, J.G., 1995. Multiple tests and diagnostic validity. Muscle Nerve 18, 353–355.)

normal person undergoing an SMA-20 blood screen. It is not uncommon that a single test is above or below the cutoff range and, in nearly every case, represents a false positive.

Fortunately, there is a relatively simple remedy to this problem of multiple tests and the increasing risk of false positives. In Figure 9–10, the number of tests performed is plotted against the cumulative false-positive rate for a variety of different individual test false-positive rates (FPRs). Note the curve with the (★); this represents a false-positive rate of 2.5%, which carries the most common test specificity of 97.5%. In the graph to the left, the cumulative false-positive rate is calculated based on the assumption that only one test needs to be abnormal to diagnose the condition. Note that if 10 different tests are performed, with each individual test carrying a false-positive rate of 2.5%, the cumulative false-positive rate is almost 25%. In contrast, the statistics change significantly *if two or more tests are required to be abnormal to diagnose the condition*. In the graph to the right, if 10 tests are done, each with an individual false-positive test rate of 2.5%, the cumulative false-positive rate remains less than 2.5%, an acceptable level, if two or more of the tests are required to be abnormal.

Important clinical–electrophysiologic implications are as follows:

1. Be very cautious about making any diagnosis based on only one piece of data; if that piece of data is in error, it will be a false positive.
2. Be very cautious about making any diagnosis based on only one piece of data; 2.5% of all tests will be false positives, simply based on how the cutoff values are selected (i.e., 2 SD beyond the mean).
3. Be very cautious about making any diagnosis based on only one piece of data, especially if multiple tests are used; the cumulative false-positive rate quickly rises to unacceptable levels.
4. When multiple tests are used, the false-positive rate can be reduced to an acceptable level if two or more tests must be abnormal before a diagnosis is made.

Suggested Readings

Nodera, H., Herrmann, D.N., Holloway, R.G., et al., 2003. A Bayesian argument against rigid cut-offs in electrodiagnosis of median neuropathy at the wrist. Neurology 60, 458–464.

Rivner, M.H., 1994. Statistical errors and their effect in electrodiagnostic medicine. Muscle Nerve 17, 811–814.

Van Dijk, J.G., 1995. Multiple tests and diagnostic validity. Muscle Nerve 18, 353–355.

10 Routine Upper Extremity, Facial, and Phrenic Nerve Conduction Techniques

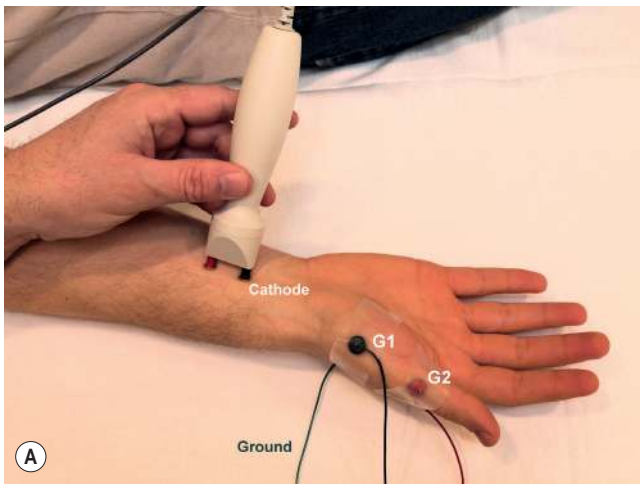
MEDIAN MOTOR STUDY *(Figure 10–1)*

Recording Site:

Abductor pollicis brevis (APB) muscle (lateral thenar eminence):

G1 placed over the muscle belly

G2 placed over the first metacarpal-phalangeal joint



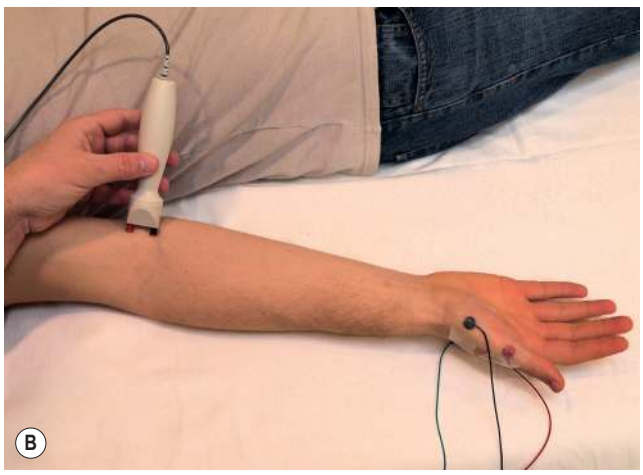


FIGURE 10–1 Median motor study. **A:** Distal stimulation site over the median nerve at the wrist, recording the abductor pollicis brevis muscle. **B:** Proximal stimulation site at the antecubital fossa.

Stimulation Sites:

Wrist: Middle of the wrist between the tendons to the flexor carpi radialis and palmaris longus

Antecubital fossa: Over the brachial artery pulse

Distal Distance:

7 cm

Key Points:

- The study is easy to perform.
- Excessive stimulation at the wrist or antecubital fossa may result in co-stimulation of the ulnar nerve.
- If the amplitude of the compound muscle action potential (CMAP) is larger at the antecubital fossa than at the wrist, consider a Martin–Gruber anastomosis.

MEDIAN MOTOR PALMAR STUDY

(Figure 10–2)

Recording Site:

Abductor pollicis brevis (APB) muscle:

G1 placed over the muscle belly

G2 placed over the first metacarpal–phalangeal joint

Stimulation Sites:

Wrist: Middle of the wrist between the tendons to the flexor carpi radialis and palmaris longus at a distance of 7 cm from the recording electrode

Palm: Stimulate in the palm, 7 cm distal to the wrist site on a line drawn from the median wrist to the web space between the index and middle fingers

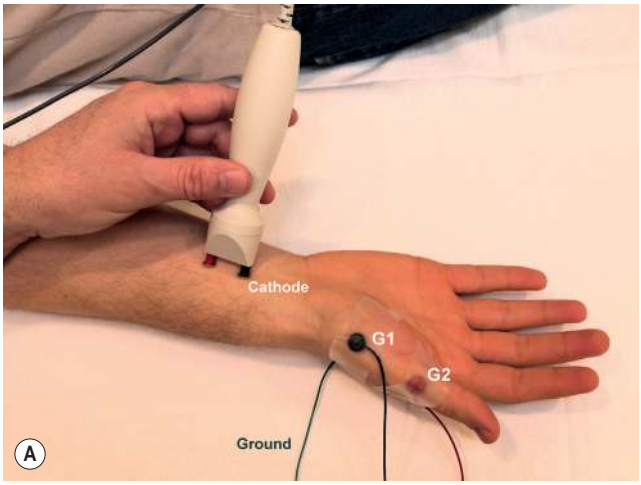
Distance:

7 cm from the wrist to the APB (wrist stimulation)

Key Points:

- The APB is innervated via the recurrent thenar motor branch of the median nerve, which runs into the palm and then curves back to the thenar muscles.
- A palm/wrist CMAP amplitude ratio >1.2 implies some conduction block across the wrist.

DOI: 10.1016/B978-1-4557-2672-1.00010-6



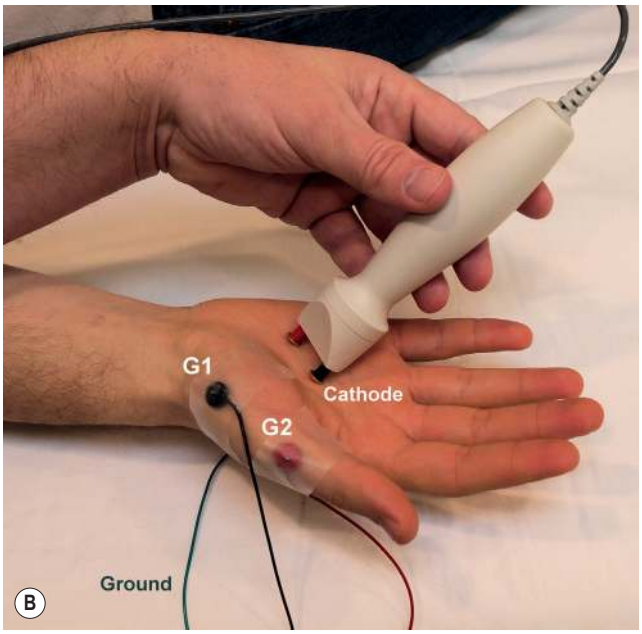


FIGURE 10–2 Median motor palmar study. **A:** Stimulation site over the median nerve at the wrist, recording the abductor pollicis brevis muscle. **B:** Stimulation site over the median nerve in the palm, recording the abductor pollicis brevis muscle.

- Calculation of conduction velocity is not reliable because of the short distances and the course of the recurrent branch of the thenar motor branch.
- If palm stimulation results in baseline distortion due to stimulus artifact, the anode should be rotated until a suitable baseline is obtained.

MEDIAN SENSORY STUDY *(Figure 10–3)*

Recording Site:

Index or middle finger (digit 2 or 3):

Ring electrodes with G1 placed over the metacarpal–phalangeal joint

G2 placed 3–4 cm distally over the distal interphalangeal joint

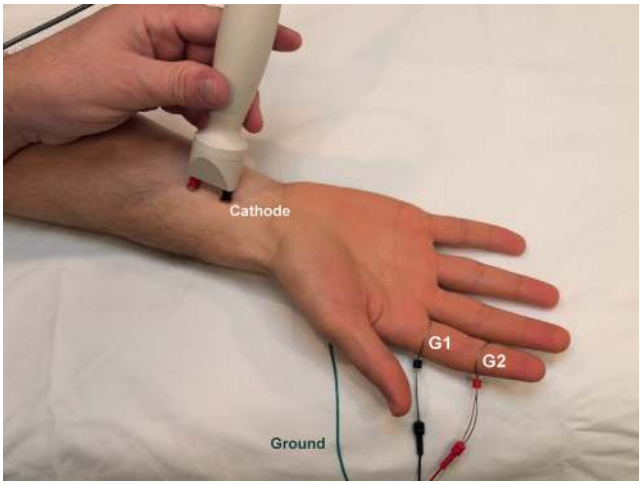


FIGURE 10–3 Median sensory study. Stimulation site over the median nerve at the wrist, recording the index finger.

Stimulation Site:

Wrist: Middle of the wrist between the tendons to the flexor carpi radialis and palmaris longus

Distal Distance:

13 cm

Key Points:

- The study is easy to perform.
- Antidromic study described. For orthodromic study, recording and stimulation sites are reversed.
- A volume-conducted motor potential occasionally may obscure the sensory potential in antidromic studies. If this occurs, have the patient slightly spread their fingers and stimulate again.
- Stimulation also can be performed proximally at the antecubital fossa, similar to the median motor study; however, the proximal sensory response is normally smaller and more difficult to record because of normal temporal dispersion and phase cancellation.
- Digits 1 and 4 both are partially innervated by the median nerve and can also be used for median sensory studies.

MEDIAN SENSORY PALMAR STUDY

(Figure 10–4)

Recording Site:

Middle finger:

Ring electrodes with G1 placed over the proximal interphalangeal joint

G2 placed over the distal interphalangeal joint

Stimulation Sites:

Wrist: Middle of the wrist between the tendons to the flexor carpi radialis and palmaris longus at a distance of 14 cm

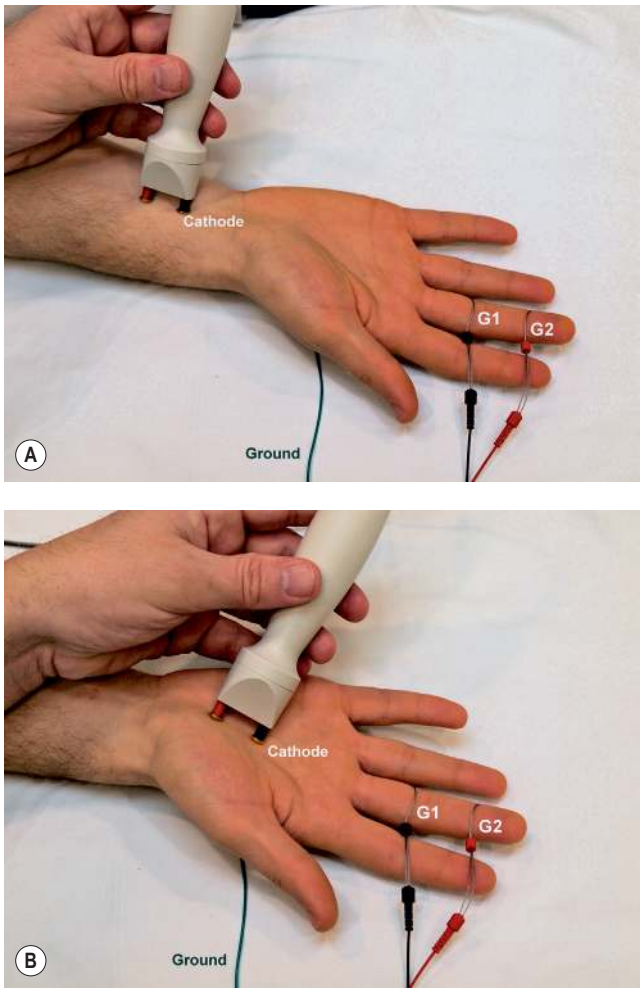


FIGURE 10–4 Median sensory palmar study. **A:** Stimulation site over the median nerve at the wrist, recording the middle finger. **B:** Stimulation site over the median nerve in the palm, recording the middle finger.

Palm: Stimulate in the palm, 7 cm distal to the wrist site on a line drawn from the median wrist to the middle finger

Distal Distance:

7 cm

Proximal Distance:

14 cm

Key Points:

- A palm/wrist sensory nerve action potential (SNAP) amplitude ratio >1.6 implies some conduction block across the wrist.
- It is essential to obtain a clear onset latency at both sites (electronic averaging is often helpful).
- At the palm stimulation, stimulus artifact may contaminate the onset latency. It is essential to obtain a clear onset latency at both the palm and wrist sites. If palm stimulation results in baseline distortion due to stimulus artifact, the anode should be rotated until a suitable baseline is obtained.
- From this study, the conduction velocities for the wrist-to-digit 3 segment and the palm-to-digit 3 segment are displayed on the machine. On some EMG machines, the wrist-to-palm segment conduction velocity is also calculated and displayed on the machine. However, if the EMG machine does not calculate the conduction velocity, it must be mathematically calculated, by subtracting the palm-to-digit 3 onset latency from the wrist-to-digit 3 onset latency. Then a conduction velocity for the wrist–palm segment (i.e., across the carpal tunnel) can be calculated by taking the distance (7 cm) and dividing it by the calculated latency. The wrist-to-palm conduction velocity (i.e., across the carpal tunnel) is normally faster than the palm-to-digit 3 segment. In carpal tunnel syndrome, there is a reversal of this pattern, with relative slowing of the wrist-to-palm segment (see Chapter 17).
- Note that any distance can be used at the wrist and at the palm. However, if the palm-to-digit 3 distance is half the distance of the wrist-to-digit 3, the mathematical calculation is much simpler (see Chapter 17).
- This study is also known as the median segmental sensory study, as two sensory segments of the median nerve (wrist-to-palm and palm-to-digit) are compared.

ULNAR MOTOR STUDY *(Figure 10–5)*

Recording Site:

Abductor digiti minimi (ADM) muscle (medial hypothenar eminence):

G1 placed over the muscle belly

G2 placed over the fifth metacarpal–phalangeal joint

Stimulation Sites:

Wrist: Medial wrist, adjacent to the flexor carpi ulnaris tendon

Below elbow: 3 cm distal to the medial epicondyle

Above elbow: Over the medial humerus, between the biceps and triceps muscles, at a distance of 10–12 cm from the below-elbow site

Axilla (optional): In the proximal axilla, medial to the biceps over the axillary pulse

Distal Distance:

7 cm

Key Points:

- The optimal position is with the elbow flexed between 90° and 135°. If performed in a straight-elbow position, factitious slowing across the elbow will be seen due to underestimation of the true nerve length.
- Higher current intensity usually is needed to achieve supramaximal stimulation at the below-elbow site

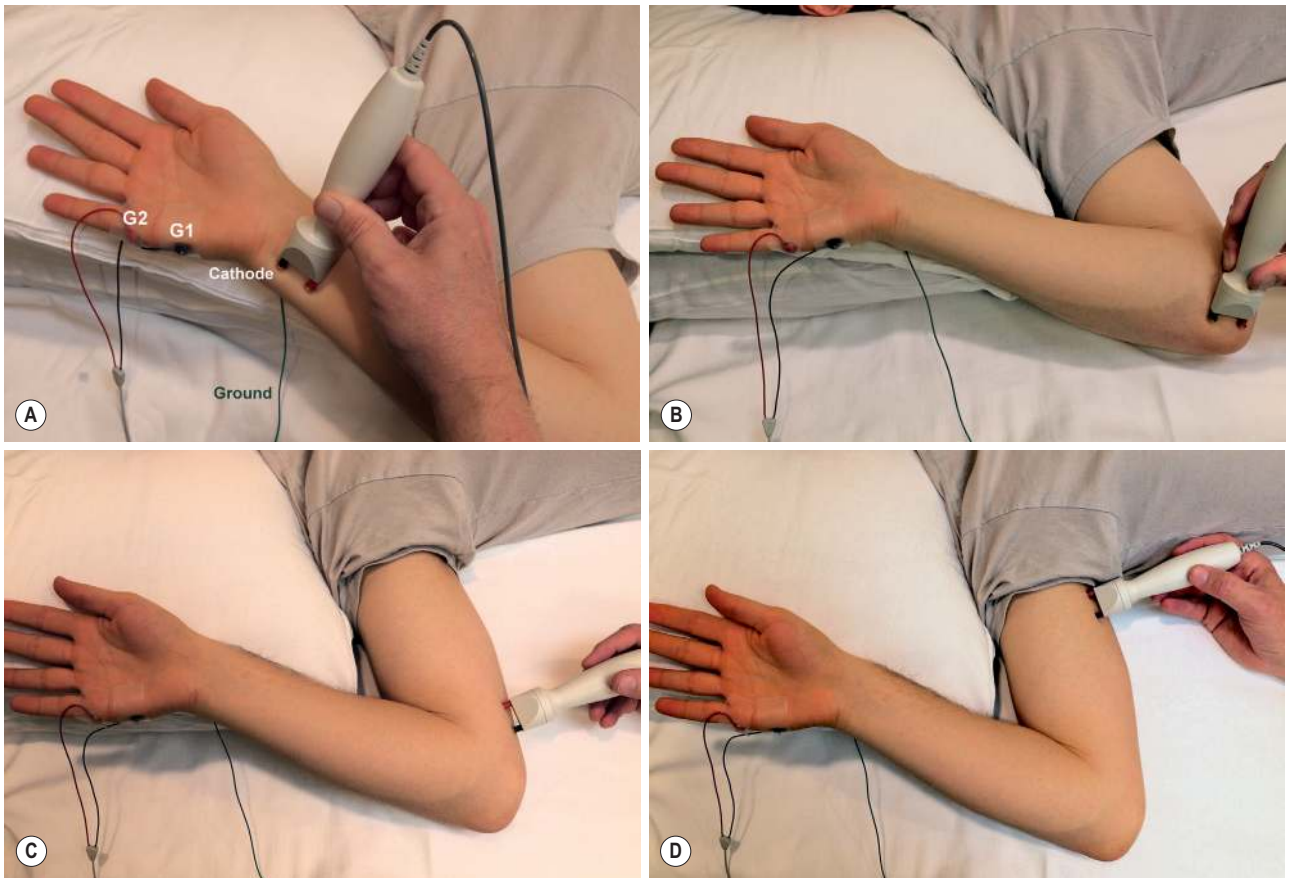


FIGURE 10–5 Ulnar motor study. **A:** Distal stimulation site over the ulnar nerve at the wrist, recording the abductor digiti minimi muscle. **B:** Proximal stimulation site below the elbow. **C:** Proximal stimulation site above the elbow. **D:** Proximal stimulation site in the axilla.

compared with the wrist and above-elbow sites because the nerve lies deep to the flexor carpi ulnaris muscle at this location.

- Stimulation must be at least 3 cm distal to the medial epicondyle at the below-elbow site to ensure that stimulation is distal to the cubital tunnel, a common site of ulnar nerve compression at the elbow. However, if stimulation at the below-elbow site is too distal (>4 cm), the nerve is very deep and very difficult to stimulate, reinforcing that the optimal stimulation site is 3 cm distal to the medial epicondyle.
- Always perform wrist, below-elbow, and above-elbow stimulations. If only the wrist and above-elbow stimulations are performed, one can miss ulnar slowing across the elbow.
- The distance across the elbow must be measured along a curved line, with the elbow flexed, and not as a straight line. This approximates the true anatomic course of the nerve.
- If the CMAP amplitude at the below-elbow site is more than 10% smaller than that at the wrist, consider a Martin–Gruber anastomosis.

ULNAR SENSORY STUDY *(Figure 10–6)*

Recording Site:

Little finger (digit 5):

Ring electrodes with G1 placed over the metacarpal–phalangeal joint

G2 placed 3–4 cm distally over the distal interphalangeal joint

Stimulation Site:

Wrist: Medial wrist, adjacent to the flexor carpi ulnaris tendon

Distal Distance:

11 cm

Key Points:

- Antidromic study described. For orthodromic study, stimulation and recording sites are reversed.
- A volume-conducted motor potential occasionally may obscure the sensory potential in antidromic studies. If this occurs, have the patients slightly spread their fingers and stimulate again.

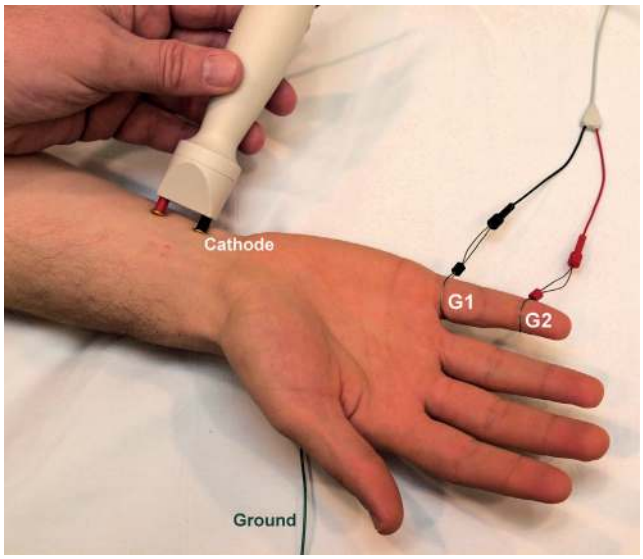


FIGURE 10–6 Ulnar sensory study. Stimulation site over the ulnar nerve at the wrist, recording the little finger.

- May be abnormal in ulnar neuropathy or lower trunk brachial plexopathy (e.g., thoracic outlet syndrome).
- Stimulation also can be performed proximally at the below- and above-elbow sites, similar to the ulnar motor study; however, the proximal sensory responses are normally smaller and more difficult to record because of normal temporal dispersion and phase cancellation.

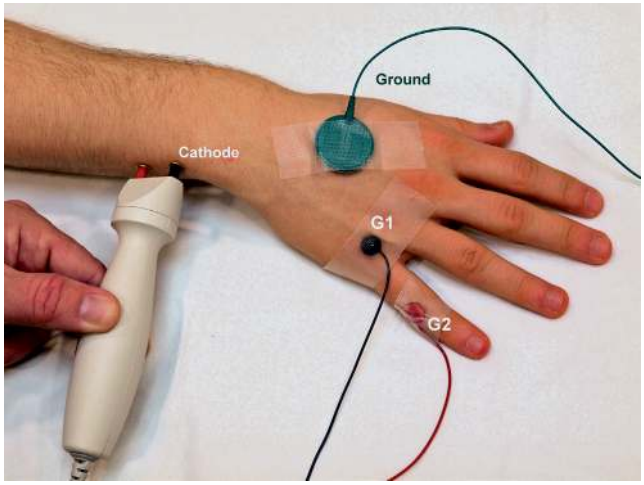


FIGURE 10–7 Dorsal ulnar cutaneous sensory study. Stimulation site slightly proximal to the ulnar styloid, recording in the web space between the fourth and fifth fingers.

DORSAL ULNAR CUTANEOUS SENSORY STUDY *(Figure 10–7)*

Recording Site:

Dorsal hand:

G1 placed over the web space between the little and ring fingers

G2 placed 3–4 cm distally over the little finger

Stimulation Site:

Slightly proximal and inferior to the ulnar styloid with the hand pronated

Distal Distance:

8–10 cm

Key Points:

- Supramaximal stimulation usually can be achieved with low stimulation intensities (e.g., 5–15 mA) because the nerve is quite superficial.
- Often helpful to compare side-to-side amplitudes in cases where one side is symptomatic and the other is not.
- Always spared in lesions of the ulnar nerve at Guyon's canal.
- May be abnormal in some, but not all, cases of ulnar neuropathy at the elbow.

DEEP ULNAR MOTOR BRANCH STUDY *(Figure 10–8)*

Recording Site:

First dorsal interosseous (FDI) muscle (dorsal web space between the thumb and index finger):

G1 placed over the muscle belly

G2 placed over the metacarpal–phalangeal joint of the thumb

Stimulation Sites:

Wrist: Medial wrist, adjacent to the flexor carpi ulnaris tendon

Below elbow: 3 cm distal to the medial epicondyle

Above elbow: Over the medial humerus, between the biceps and triceps muscles, at a distance of 10–12 cm from the below-elbow site

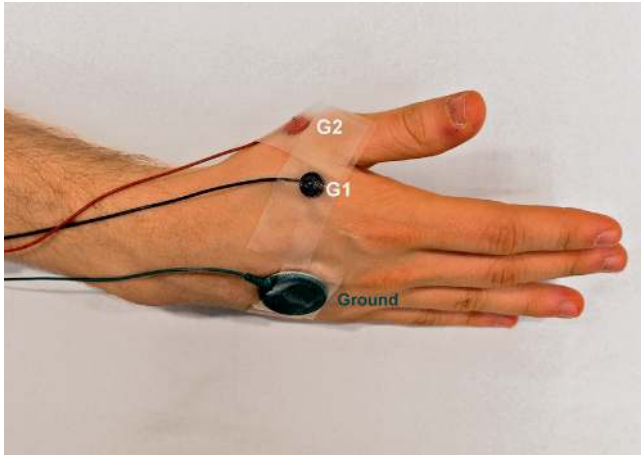


FIGURE 10–8 Deep ulnar motor branch study. Recording the first dorsal interosseous muscle (stimulation sites are the same as the routine ulnar motor studies recording the abductor digiti minimi muscle).

Distal Distance:

8–12 cm (distance measured with obstetrical calipers)

Key Points:

- The deep ulnar motor branch often is preferentially affected in lesions of the ulnar nerve at Guyon's canal.
- Recording the FDI may be more useful than recording the ADM for demonstrating focal slowing of the ulnar nerve across the elbow.
- G2 must be on the metacarpal–phalangeal joint of the *thumb*; if G2 is place on the metacarpal–phalangeal joint of the *index finger*, there will always be an initial positive deflection of the CMAP.
- Always perform the wrist, below-elbow and above-elbow stimulations. If only the wrist and above-elbow stimulations are performed, one can miss ulnar slowing across the elbow.
- Stimulation must be at least 3 cm distal to the medial epicondyle at the below-elbow site to ensure that stimulation is distal to the cubital tunnel, a common site of ulnar nerve compression at the elbow. However, if stimulation at the below-elbow site is too distal (>4 cm), the nerve is very deep and very difficult to stimulate, reinforcing that the optimal stimulation site is 3 cm distal to the medial epicondyle.
- If the CMAP amplitude at the below-elbow site is more than 10% smaller than that at the wrist, consider a Martin–Gruber anastomosis.

MEDIAN VERSUS ULNAR – LUMBRICAL–INTEROSSEI STUDIES

(Figure 10–9)

Recording Site:

Second lumbrical (2L: median innervated) and first palmar interosseous (INT: ulnar innervated); same recording electrodes for both:

G1 placed slightly lateral to the midpoint of the third metacarpal

G2 placed distally over the metacarpal–phalangeal joint of digit 2

Stimulation Sites:

Median nerve at the wrist: Middle of the wrist between the tendons to the flexor carpi radialis and palmaris longus

Ulnar nerve at the wrist: Medial wrist, adjacent to the flexor carpi ulnaris tendon

Distal Distance:

8–10 cm (the same distance must be used for both the median and ulnar studies)

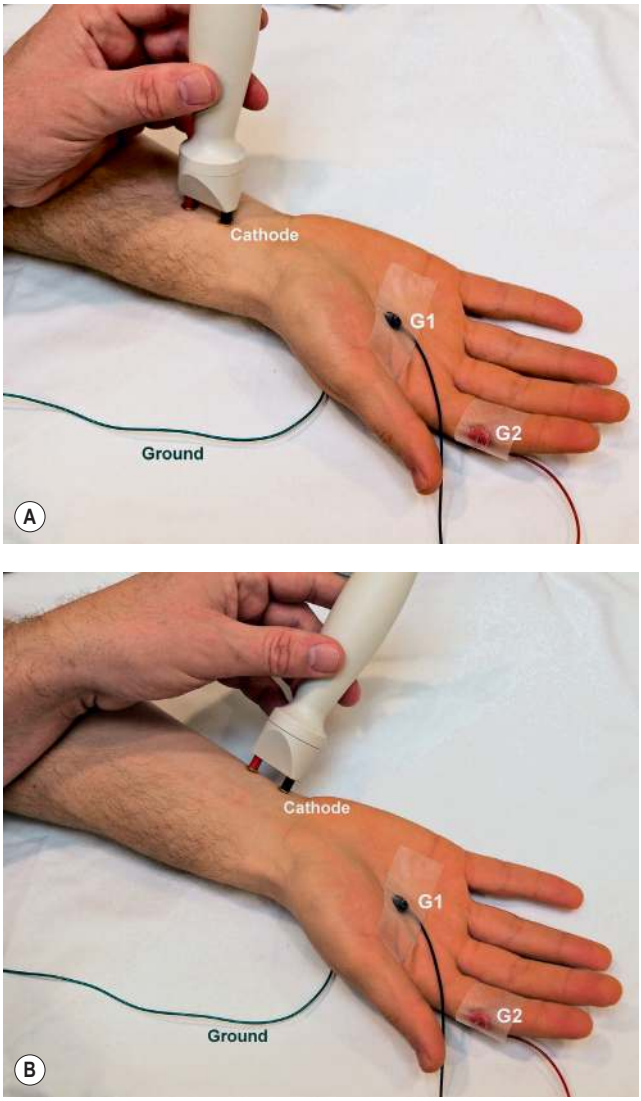


FIGURE 10–9 Lumbrical–interossei studies. **A:** Stimulating the median nerve at the wrist, recording the second lumbrical muscle **B:** Stimulating the ulnar nerve at the wrist, recording the first palmar interosseous muscle.

Key Points:

- Using the same recording electrodes, the second lumbrical is recorded when the median nerve is stimulated at the wrist, whereas the first palmar interosseous is recorded when the ulnar nerve is stimulated at the wrist.
- In normal subjects, the difference between the two distal latencies is <0.5 ms when the same distance is used for both studies.
- Useful internal comparison study to demonstrate either median neuropathy at the wrist (i.e., carpal tunnel syndrome) or ulnar neuropathy at Guyon's canal.
- This technique is especially useful to demonstrate median neuropathy at the wrist in patients with

coexistent polyneuropathy, in whom sensory and mixed nerve potentials may be absent.

- In healthy individuals, one will often see a small brief spike in front of the lumbrical CMAP (especially if one increases the gain) – this is actually the median palmar mixed nerve potential. If this is seen, mark the onset latency after this mixed potential at the onset of the motor potential.
- If the initial lumbrical CMAP does not have an abrupt deflection from the baseline, the active recording electrode should be repositioned.
- Excessive stimulation must be avoided to prevent co-stimulation of the median and ulnar nerves.
- The interosseous amplitude usually is substantially higher than the lumbrical amplitude.

MEDIAN VERSUS ULNAR – DIGIT 4 SENSORY STUDIES *(Figure 10–10)*

Recording Site:

Ring finger (digit 4):

Ring electrodes with G1 placed over the metacarpal–phalangeal joint

G2 placed 3–4 cm distally over the distal interphalangeal joint

Stimulation Sites:

Median nerve at the wrist: Middle of the wrist between the tendons to the flexor carpi radialis and palmaris longus

Ulnar nerve at the wrist: Medial wrist, adjacent to the flexor carpi ulnaris tendon

Distal Distance:

12–14 cm (same distance must be used for both studies)

Key Points:

- Sensory innervation to the ring finger usually is split, with the lateral half supplied by the median nerve and the medial half supplied by the ulnar nerve. Thus, using the same recording electrodes, median sensory fibers are recorded with median nerve stimulation at the wrist, and ulnar sensory fibers are recorded with ulnar nerve stimulation at the wrist.
- In normal subjects, the difference between the median and ulnar digit 4 latencies is <0.5 ms when the same distance is used for both studies.
- Useful internal comparison study to demonstrate median neuropathy at the wrist (i.e., carpal tunnel syndrome).
- Excessive stimulation must be avoided to prevent co-stimulation of the median and ulnar nerves.
- Antidromic study described. For orthodromic study, recording and stimulation sites are reversed.

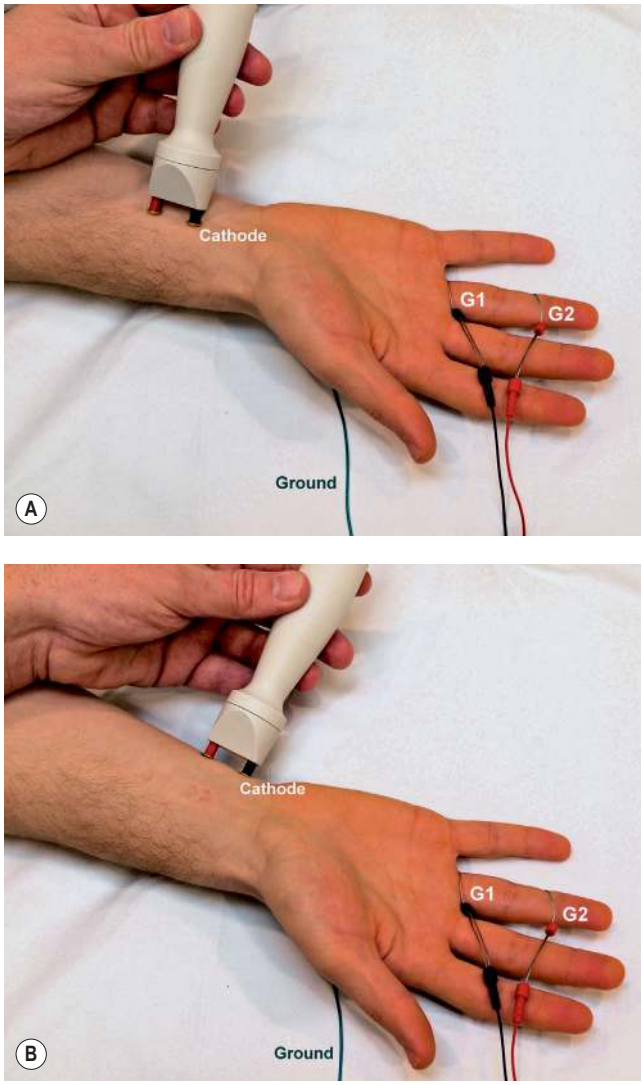


FIGURE 10–10 Digit 4 sensory studies. **A:** Stimulating the median nerve at the wrist, recording the fourth digit. **B:** Stimulating the ulnar nerve at the wrist, recording the fourth digit.

MEDIAN VERSUS RADIAL – DIGIT 1 SENSORY STUDIES

(Figure 10–11)

Recording Site:

Thumb (digit 1):

Ring electrodes with G1 placed over the metacarpal–phalangeal joint

G2 placed distally over the distal interphalangeal joint

Stimulation Sites:

Median nerve at the wrist: Middle of the wrist between the tendons to the flexor carpi radialis and palmaris longus

Radial nerve at the wrist: Medial forearm, over the radial bone

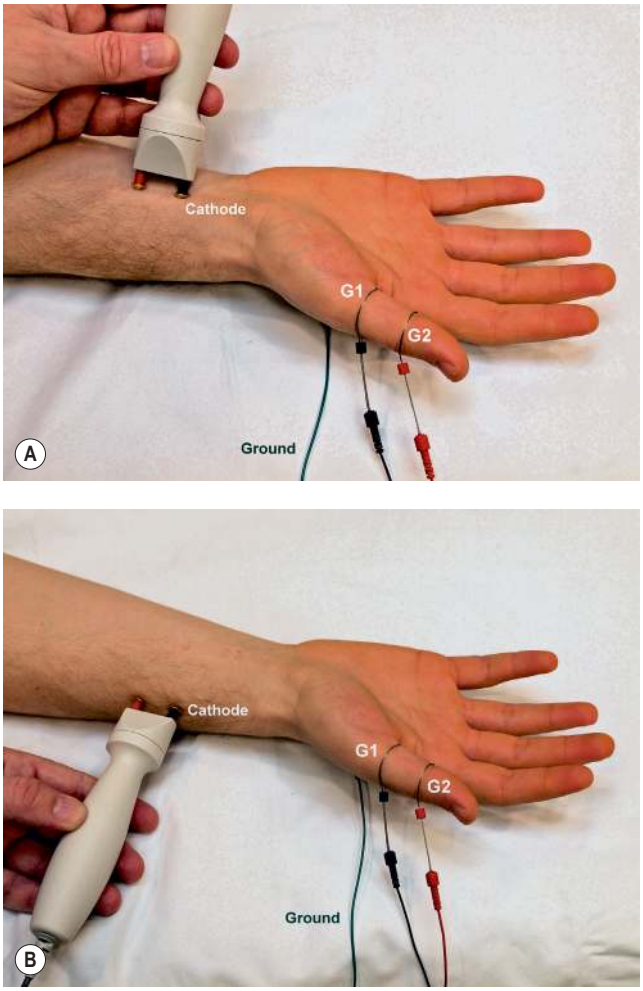


FIGURE 10–11 Digit 1 sensory studies. **A:** Stimulating the median nerve at the wrist, recording the first digit. **B:** Stimulating the radial nerve at the forearm, recording the first digit.

Distal Distance:

10–12 cm (same distance must be used for both studies)

Key Points:

- Sensory innervation to the thumb usually is split, with the lateral half supplied by the radial nerve and the medial half supplied by the median nerve. Thus, using the same recording electrodes, median sensory fibers are recorded with median nerve stimulation at the wrist, and radial sensory fibers are recorded with radial nerve stimulation at the forearm.
- In normal subjects, the difference between the median and radial digit 1 latencies is <0.5 ms when the same distance is used for both studies.
- Useful internal comparison study to demonstrate median neuropathy at the wrist (i.e., carpal tunnel syndrome).
- Excessive stimulation must be avoided to prevent co-stimulation of the median and radial nerves.
- Antidromic study described. For orthodromic study, recording and stimulation sites are reversed.

MEDIAN VERSUS ULNAR – PALMAR MIXED NERVE STUDIES

Median Nerve *(Figure 10–12A)*

Recording Site:

Median nerve at the wrist:

G1 placed over the middle of the wrist between the tendons to the flexor carpi radialis and palmaris longus

G2 placed 3–4 cm proximally

Stimulation Site:

Median nerve in the palm: In the palm, 8 cm from the active recording electrode on a line drawn from the median wrist to the web space between the index and middle fingers

Distal Distance:

8 cm

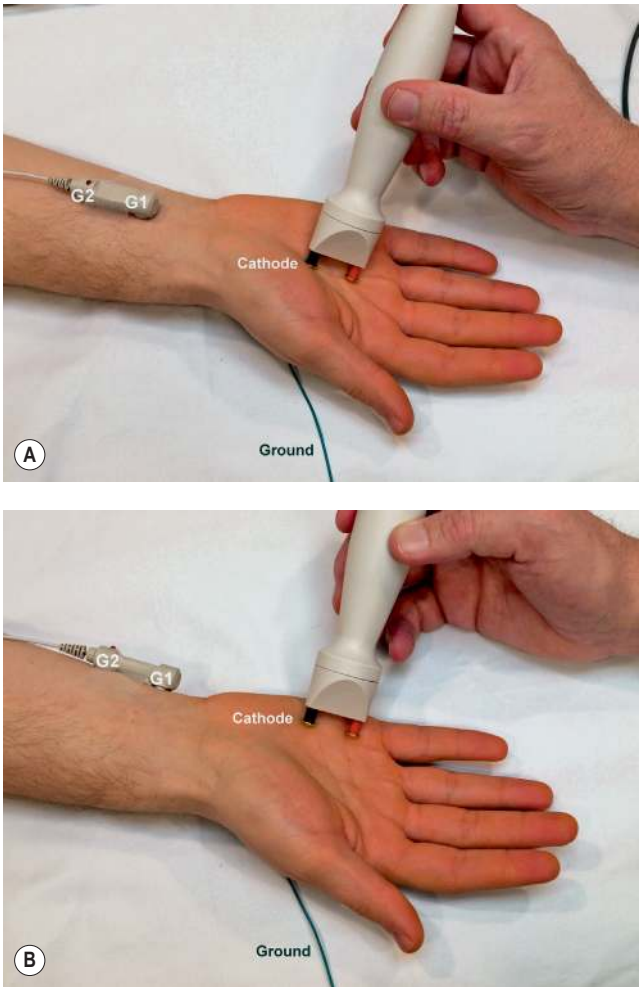


FIGURE 10–12 Palmar mixed nerve studies. **A:** Median mixed nerve palmar studies. Stimulating the median nerve in the palm, recording the median nerve at the wrist. **B:** Ulnar mixed nerve palmar studies. Stimulating the ulnar nerve in the palm, recording the ulnar nerve at the wrist.

Ulnar Nerve *(Figure 10–12B)*

Recording Site:

Ulnar nerve at the wrist:

G1 placed over the medial wrist, adjacent to the flexor carpi ulnaris tendon

G2 placed 3–4 cm proximally

Stimulation Site:

Ulnar nerve in the palm: In the palm, 8 cm from the active recording electrode on a line drawn from the ulnar wrist to the web space between the ring and little fingers

Distal Distance:

8 cm

Key Points:

- In normal subjects, the difference between the median and ulnar palmar latencies is <0.4 ms when the same distance is used for both studies.
- Useful internal comparison study to demonstrate subtle median slowing across the wrist (i.e., carpal tunnel syndrome).
- Caution: as the distance used is short, be very careful in measuring the distance of 8 cm correctly.
- Excessive stimulation must be avoided to prevent co-stimulation of the median and ulnar nerves.

RADIAL MOTOR STUDY *(Figure 10–13)*

Recording Site:

Extensor indicis proprius (EIP) muscle:

With hand pronated, G1 placed two fingerbreadths proximal to the ulnar styloid

G2 placed over the ulnar styloid

Stimulation Sites:

Forearm: Over the ulna, 4–6 cm proximal to the active recording electrode

Elbow: In the groove between the biceps and brachioradialis muscles

Below spiral groove: Lateral midarm, between the biceps and triceps muscles

Above spiral groove: Posterior proximal arm over the humerus

Distal Distance:

5–7 cm

Key Points:

- The radial CMAP usually has an initial positive deflection due to other nearby radial-innervated muscles; thus, no need to change the active recording electrode site to try to get on the motor point.
- Surface-measured distances often are inaccurate in radial motor studies, especially at proximal stimulation sites. Distances to the sites below and above the spiral groove are best measured with obstetric calipers.
- Useful in the diagnosis and assessment of posterior interosseous neuropathy and especially radial neuropathy at the spiral groove.

RADIAL SENSORY STUDY

(Figure 10–14)

Recording Site:

Superficial radial nerve:

G1 placed over the superficial radial nerve as it runs over the extensor tendons to the thumb

G2 placed 3–4 cm distally over the thumb

Stimulation Site:

Over the distal-mid radius

Distal Distance:

10 cm

Key Points:

- The study is easy to perform.
- In most patients, you can actually feel the nerve as it runs over the extensor tendon to the thumb (have the patient extend their thumb and palpate over the tendon feeling for the nerve). Thus, it is easy to place the recording electrode directly over the nerve.
- May be abnormal in radial neuropathy or lesions of the posterior cord and upper or middle trunks of the brachial plexus.
- Spared in posterior interosseous neuropathy.

MEDIAL ANTEBRACHIAL CUTANEOUS SENSORY STUDY

(Figure 10–15)

Recording Site:

Medial forearm:

G1 placed 12 cm distal to the stimulation site, on a line drawn between the stimulation site and the ulnar wrist

G2 placed 3–4 cm distally

Stimulation Site:

Medial elbow: At the midpoint between the biceps tendon and medial epicondyle

Distal Distance:

12 cm

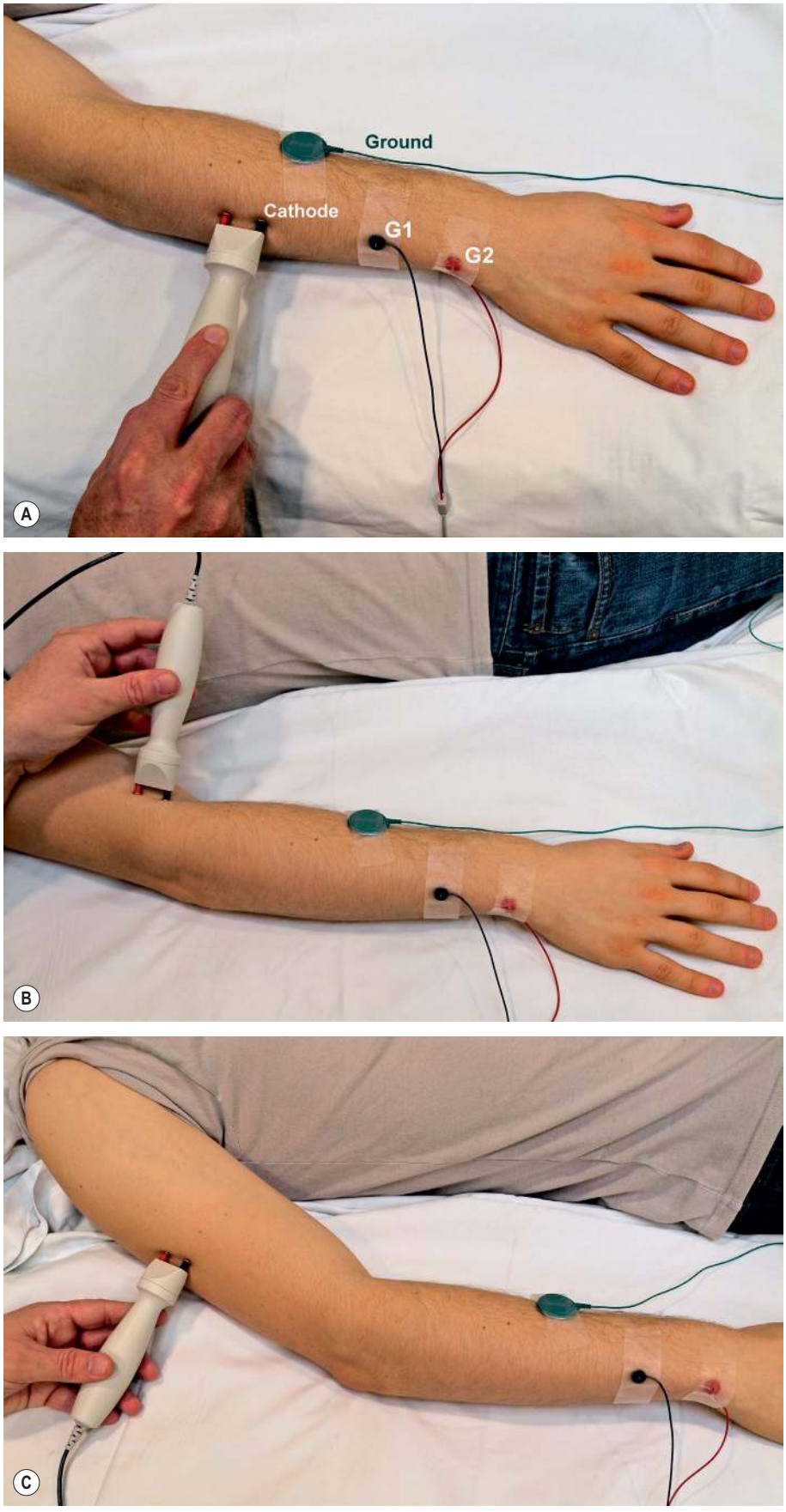


FIGURE 10–13 Radial motor study. **A:** Distal stimulation site in the forearm, recording the extensor indicis proprius muscle. **B:** Proximal stimulation site at the elbow, between the brachioradialis muscle and biceps tendon. **C:** Proximal stimulation site in the arm, below the spiral groove.

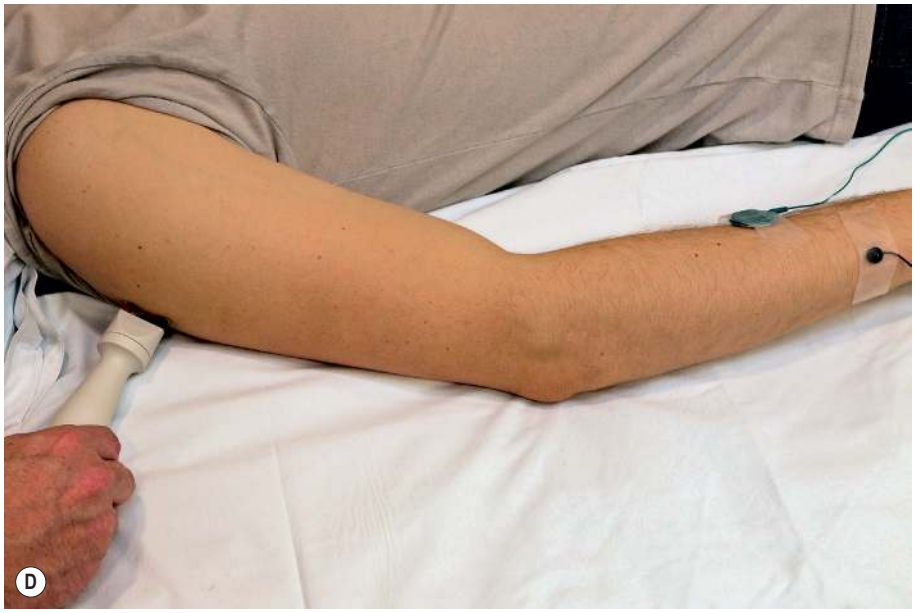


FIGURE 10–13, cont'd D: Proximal stimulation site in the arm, above the spiral groove.

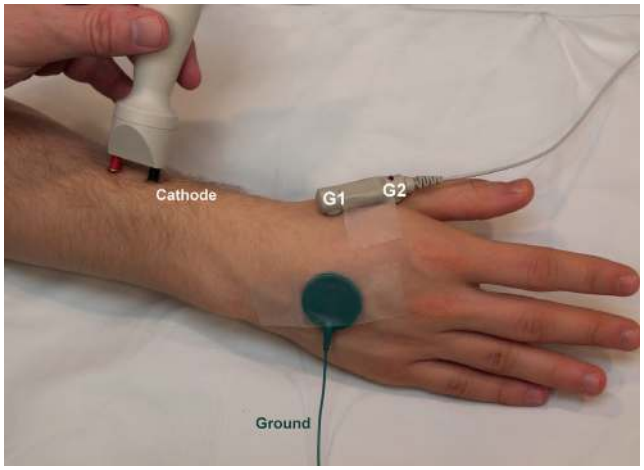


FIGURE 10–14 Radial sensory study. Stimulation site over the radius, recording electrodes placed over the radial sensory nerve as it runs over the extensor tendons to the thumb.

Key Points:

- May be abnormal in lesions of the medial cord or lower trunk of the brachial plexus.
- Typically absent or very low in true neurogenic thoracic outlet syndrome.
- Because the nerve is quite superficial, supramaximal stimulation usually can be achieved with low stimulator intensities (e.g., 5–15 mA).
- To maximize the response, the recording electrodes may have to be repositioned either slightly medially or laterally to the original position.
- Side-to-side comparisons of amplitude and latency often are helpful.

LATERAL ANTEBRACHIAL CUTANEOUS SENSORY STUDY

(Figure 10–16)

Recording Site:

Lateral forearm:

G1 placed 12 cm distal to the stimulator site, on a line drawn between the stimulator site and the radial wrist

G2 placed 3–4 cm distally

Stimulation Site:

Antecubital fossa: Slightly lateral to the biceps tendon

Distal Distance:

12 cm

Key Points:

- The study is easy to perform.
- May be abnormal in lesions of the musculocutaneous nerve, lateral cord, or upper trunk of the brachial plexus.
- Because the nerve is quite superficial, supramaximal stimulation usually can be achieved with low stimulation intensities (e.g., 5–15 mA).
- Excessive stimulation may result in direct stimulation of the biceps.
- To maximize the response, the recording electrodes may have to be repositioned either slightly medially or laterally to the original position.
- Side-to-side comparisons of amplitude and latency often are helpful.

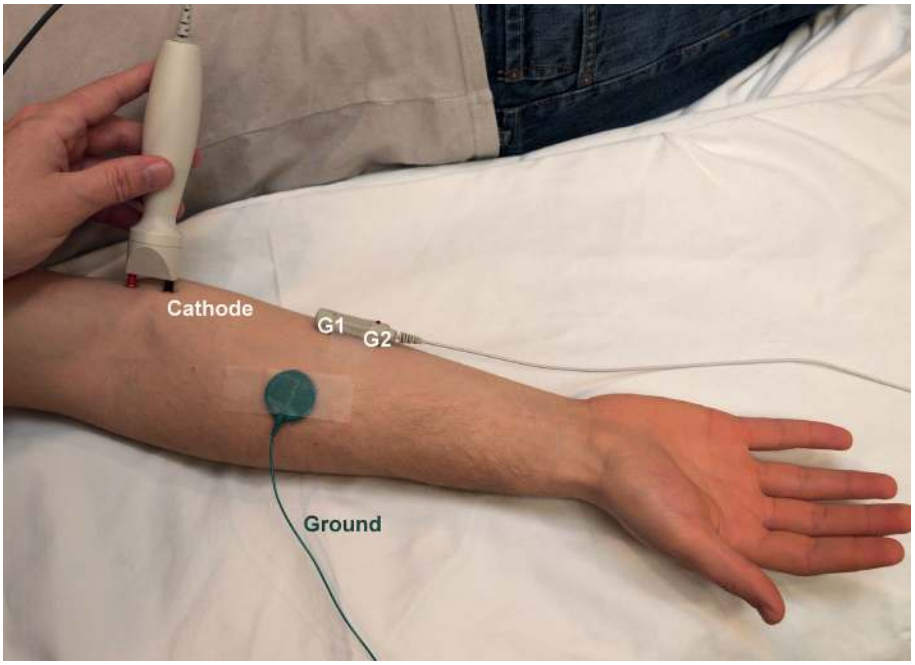


FIGURE 10–15 Medial antebrachial cutaneous sensory study. Stimulation site in the medial elbow, recording over the medial forearm.

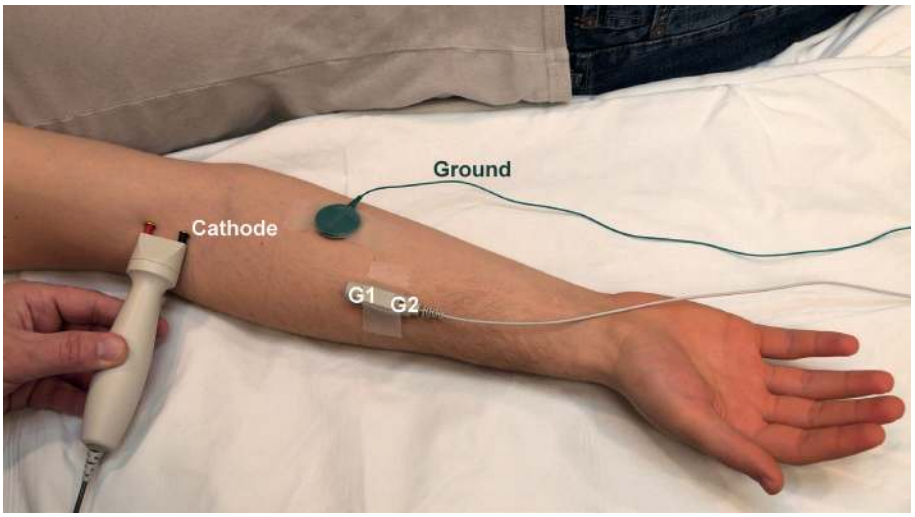


FIGURE 10–16 Lateral antebrachial cutaneous sensory study. Stimulation site just lateral to the biceps tendon in the antecubital fossa, recording over the lateral forearm.

UPPER EXTREMITY PROXIMAL STIMULATION STUDIES

(Figure 10–17)

Recording Sites:

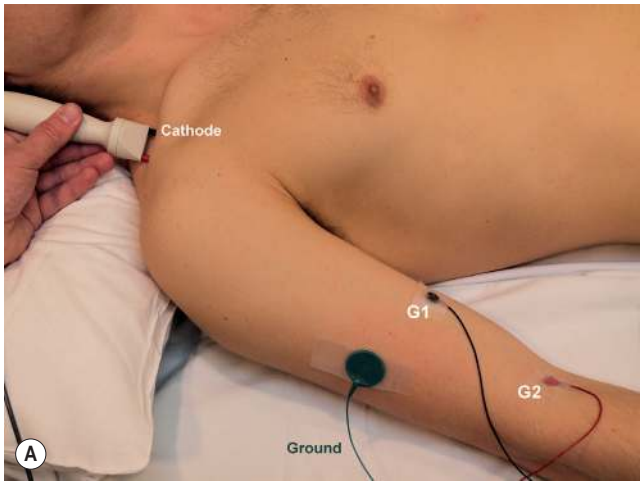
Any upper extremity muscle:
Belly-tendon method:
- G1 placed over muscle belly
- G2 placed over the tendon

Common muscles recorded:
- Deltoid
- Infraspinatus
- Biceps
- Triceps

Stimulation Sites:

Erb's point: Supraclavicular fossa, just posterior to the sternocleidomastoid muscle

Cervical nerve roots: Monopolar needle used as the stimulator cathode, inserted into the paraspinal muscles, 1–2 cm lateral to the spinous process, down to the lamina (surface disc electrode over the spinous process serves as the stimulator anode). The cervical level selected for study depends on the root innervation of the muscle being studied.



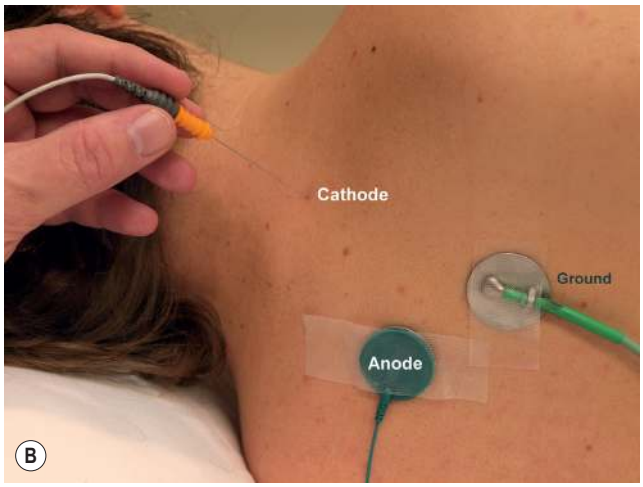
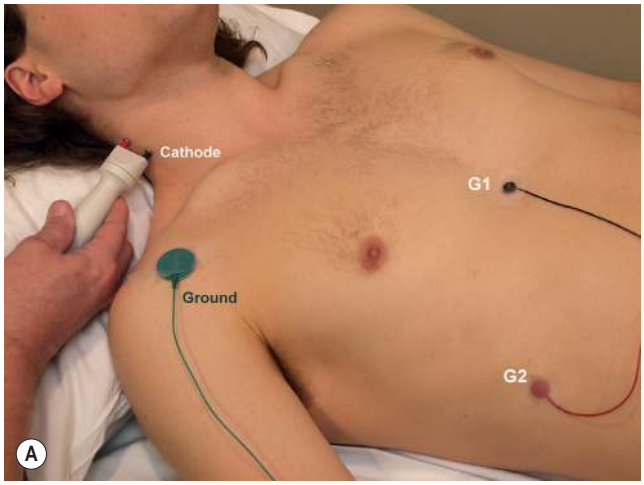


FIGURE 10–17 Upper extremity proximal stimulation studies. **A:** Stimulation site at Erb's point, just posterior to the sternocleidomastoid muscle in the supraclavicular fossa. In this example, the biceps brachii is recorded with surface recording electrodes. **B:** Stimulation site at the cervical roots. A monopolar needle is inserted at the desired level as the cathode, with an additional surface electrode serving as the anode.



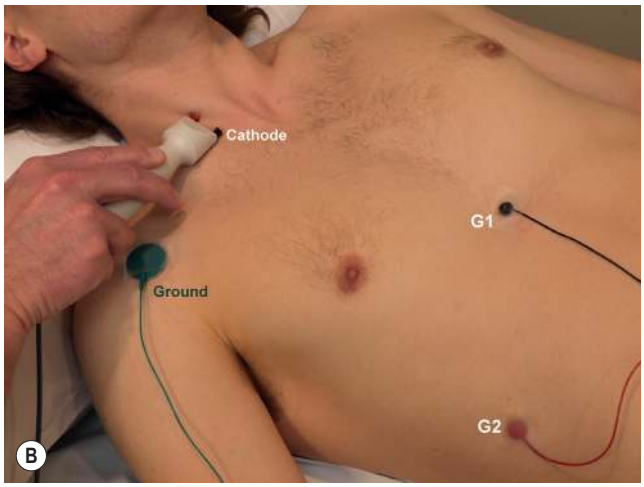


FIGURE 10–18 Phrenic motor study. Recording the diaphragm with G1 placed two fingerbreadths above the xiphoid process and G2 placed over the anterior costal margin 16 cm from G1. **Stimulation Option A:** Posterior to the sternocleidomastoid (SCM) muscle, approximately 3 cm above the clavicle. **Stimulation Option B:** Stimulating between sternal and clavicular heads of the SCM, just above the clavicle.

Key Points:

- Supramaximal stimulation may be difficult to achieve at Erb's point and at the root level.
- Recording of proximal muscles also can be done with a monopolar needle inserted into the muscle as G1 and a surface disc electrode as G2.
- Side-to-side comparisons of amplitude and latency are necessary when performing motor studies to proximal muscles.
- Surface measured distances often are inaccurate at proximal stimulation sites. Proximal distances are best measured with obstetric calipers.
- *Caution*: Rare cases of pneumothorax have been reported with root stimulation with improper needle placement too laterally.

PHRENIC MOTOR STUDY

(Figure 10–18A,B)

Recording Site:

Diaphragm muscle:

G1 placed two fingerbreadths (5 cm) above the xiphoid process

G2 placed over the anterior costal margin 16 cm from G1

Stimulation Site:

Option 1: Lateral neck: Posterior to the sternocleidomastoid muscle (SCM), approximately 3 cm above the clavicle (Figure 10–18A)

Option 2: Anterior-lateral neck: Between sternal and clavicular heads of the SCM, just above the clavicle.

Both heads of the SCM can be easily seen by having the patient flex their neck for a few seconds (Figure 10–18B)

Distal Distance:
Variable

Key Points:
- Firm pressure is needed when holding the stimulator.
- If the stimulator is not in the correct location, the spinal accessory nerve can be stimulated (causing contraction of the trapezius).
- If the stimulator is not in the correct location, the brachial plexus can be stimulated (causing movement of the shoulder).
- In thin individuals, the diaphragm contraction often can be visualized and appears similar to a hiccup.
- Difficult study to perform in obese individuals.
- Amplitudes are slightly larger during inspiration (see detailed phrenic nerve normal values at the end of this chapter).
- Do not perform this study in the intensive care unit in patients who have an external pacemaker (risk of current spread to the heart); caution if an internal jugular catheter, implanted cardiac pacemaker, or cardioverter-defibrillator is nearby (see Chapter 40).

FACIAL MOTOR STUDY *(Figure 10–19)*

Recording Site:
Nasalis muscle:
G1 placed lateral to mid-nose
G2 placed on the contralateral side of the nose at the same location

Stimulation Site:
Anterior tragus: directly in front of the lower ear

Distal Distance:
Variable

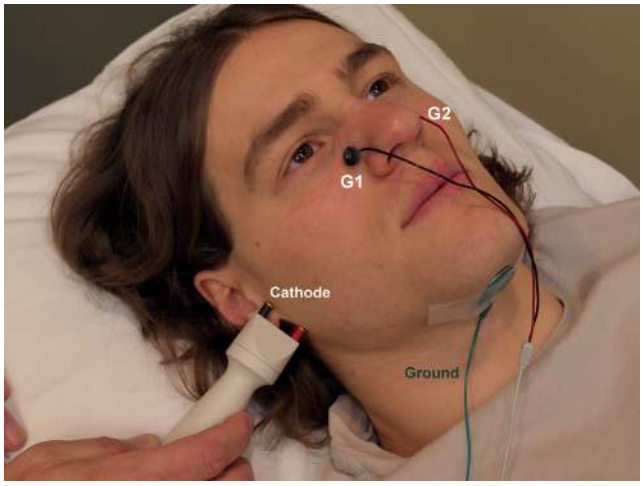


FIGURE 10–19 Facial motor study. Stimulating the facial nerve anterior to the tragus, recording the nasalis muscle.

Key Points:
- Excessive stimulus may result in direct stimulation of the masseter muscle.
- Other facial muscles may be used as recording sites, including the frontalis, mentalis, and orbicularis oculi, using similar montages. G1 is placed over the center of the muscle; the contralateral muscle is used as the site for G2.
- This technique stimulates the entire facial nerve where it exits the skull at the stylomastoid foramen. Often higher currents are needed, and the study can be uncomfortable. Individual facial branch stimulation is often much easier and more comfortable for the patient (see Facial Motor Branch Study below).

FACIAL MOTOR BRANCH STUDY
(Figure 10–20)

Frontal Branch *(Figure 10–20A)*

Recording Site:
Frontalis muscle:
G1 placed over the frontalis, above the eyebrow, slightly medial to the center of the brow
G2 placed on the contralateral frontalis muscle

Stimulation Site:
Three to four fingerbreadths lateral to the eye

Distal Distance:
Variable

Zygomatic Branch *(Figure 10–20B)*

Recording Site:
Nasalis muscle:
G1 placed lateral to mid-nose
G2 placed on the contralateral side of the nose at the same location

Stimulation Site:
Over the zygomatic bone just anterior to the ear

Distal Distance:
Variable

Mandibular Branch *(Figure 10–20C)*

Recording Site:
Mentalis muscle:
G1 placed over the mentalis muscle in the chin
G2 placed over the contralateral mentalis muscle

Stimulation Site:
Over the angle of the jaw

Distal Distance:
Variable

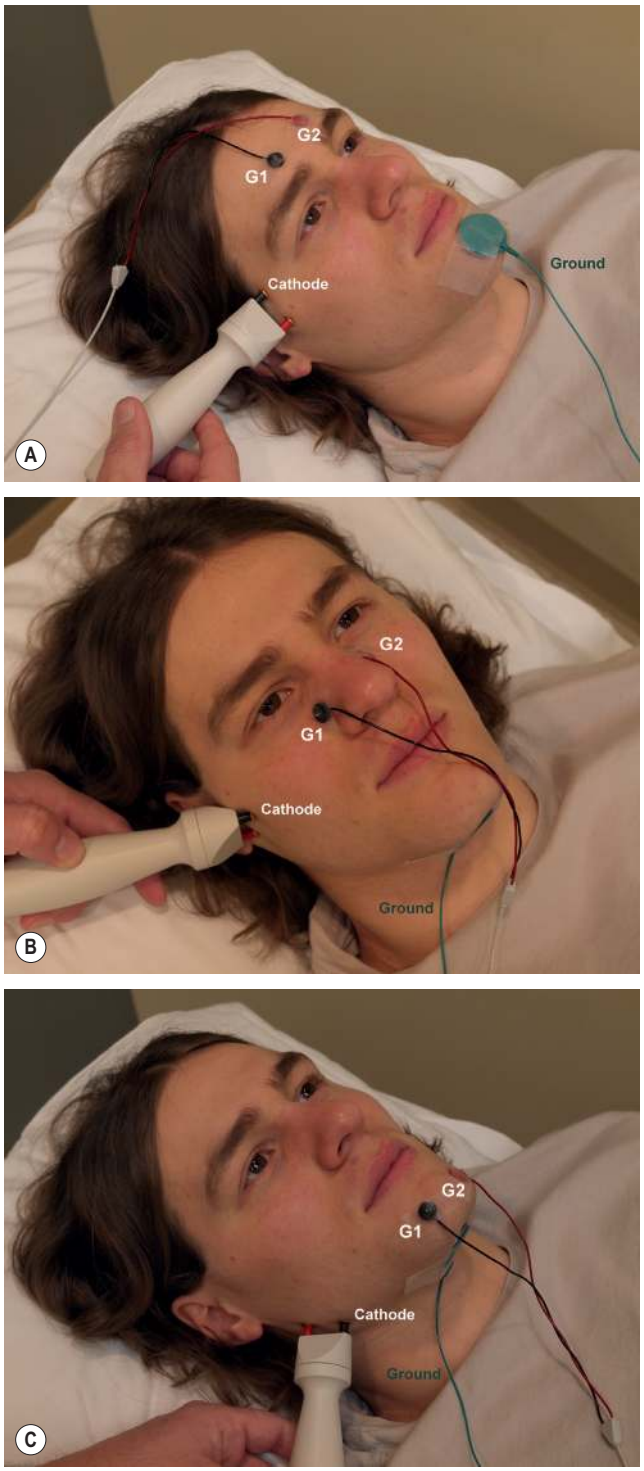


FIGURE 10–20 Facial motor branch studies. **A:** Frontal branch study, recording the frontalis. **B:** Zygomatic branch study, recording the nasalis muscle. **C:** Mandibular branch study, recording the mentalis muscle.

Key Points:

- Stimulating the separate facial branches is technically easier than stimulating the entire facial nerve at the stylomastoid foramen.
- Always do both sides. In most cases, the contralateral normal side will serve as the control and the presumed baseline value.

BLINK REFLEX (TRIGEMINAL AND FACIAL NERVES) *(Figure 10–21)*

Recording Site:

Bilateral orbicularis oculi muscles:

For each side, G1 placed on the face over inferior eye socket, just lateral and inferior to the pupil at mid-position

G2 placed over the lateral canthus of the eye

Stimulation Site:

Supraorbital notch: Medial superior eye socket over the supraorbital notch

Distal Distance:

Variable

Key Points:

- The study is easy to perform.
- The patient should be in a relaxed state, lying supine on the examining table, with the eyes either open or gently closed
- Supramaximal stimulation can be achieved with low currents, typically 10–15 mA.
- For each side, both the ipsilateral and contralateral sides are recorded. Usually 2–5 traces are superimposed to determine the minimal R1 and R2 latencies.
- This study is useful in assessing facial nerve palsies, demyelinating neuropathies, and brainstem lesions.

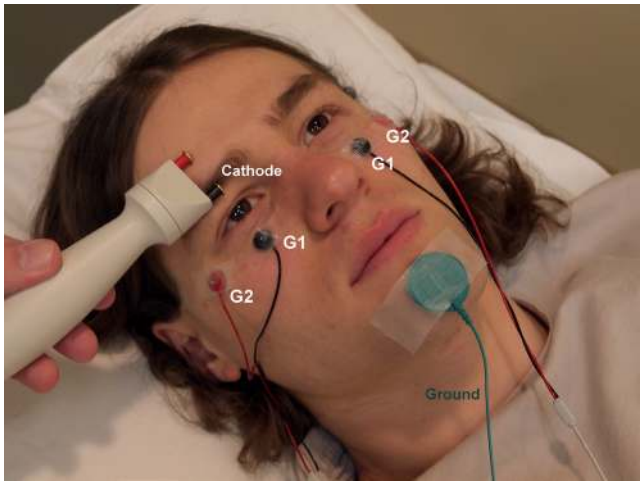


FIGURE 10–21 Blink reflex. Stimulating the supraorbital nerve over the medial eyebrow, recording both orbicularis oculi muscles.

NERVE CONDUCTION STUDIES: NORMAL ADULT VALUES

Upper Extremity

Motor

Nerve	Record	Amplitude (mV)	Conduction Velocity (m/s)	Distal Latency (ms)	Distal Distance (cm)
Median	Abductor pollicis brevis (APB)	≥4.0	≥49	≤4.4	7
Ulnar	Abductor digiti minimi (ADM)	≥6.0	≥49	≤3.3	7
Ulnar	First dorsal interosseous (FDI)	≥7.0	≥49	≤4.5	Variable (8–12*)
Radial	Extensor indicis proprius (EIP)	≥2.0	≥49	≤2.9	4–6

*Distance measured with calipers.

Antidromic Sensory

Nerve	Record	Amplitude (μV)	Conduction Velocity (m/s)	Distal Peak Latency (ms)	Distal Distance (cm)
Median	Digit 2	≥20	≥50	≤3.5	13
Ulnar	Digit 5	≥17*	≥50	≤3.1	11
Radial	Snuffbox	≥15	≥50	≤2.9	10
Dorsal ulnar cutaneous†	Dorsal D4–5 web space	≥8	≥50	≤2.5	8
Lateral antebrachial cutaneous†	Lateral forearm	≥10	≥55	≤3.0	12
Medial antebrachial cutaneous†	Medial forearm	≥5	≥50	≤3.2	12

*Many consider ulnar antidromic sensory amplitudes that are higher than 10 μV to be normal in adults older than 60.

†In these less commonly performed studies, side-to-side comparisons, especially of amplitude, often are more useful than normal value tables, when symptoms and signs are limited to one side.

Palmar mixed Nerve Studies

Nerve	Amplitude (μV)	Conduction Velocity (m/s)	Peak Distal Latency (ms)	Distance (cm)
Median mixed	≥50	≥50	≤2.2	8
Ulnar mixed	≥12	≥50	≤2.2	8

F Responses*

Nerve	Minimal F Latency (ms)
Median	≤31
Ulnar	≤32

*For tall or short patients, F responses must be normalized for height (see Chapter 4).

Median–Ulnar Internal Comparison Studies

Study*	Significant Latency Difference (ms)†
Median mixed: Palm-to-wrist Ulnar mixed: Palm-to-wrist	≥0.4
Median motor: Wrist to second lumbrical Ulnar motor: Wrist to interossei	≥0.5
Median sensory: Wrist to digit 4 Ulnar sensory: Wrist to digit 4	≥0.5
Median sensory: Wrist to digit 1 Radial sensory: Wrist to digit 1	≥0.5

*For each paired study, identical distances are used for both the median and the ulnar study.

†Values that exceed these cutoffs imply focal slowing and are useful in the electrodiagnosis of both median neuropathy across the carpal tunnel and ulnar neuropathy across Guyon's canal.

Median Palmar Stimulation Studies

Study	Significant Palm/Wrist Amplitude Ratio*
Median motor: Wrist to abductor pollicis brevis Median motor: Palm to abductor pollicis brevis	>1.2
Median sensory: Wrist to digit 2 Median sensory: Palm to digit 2	>1.6

*Values that exceed these cutoffs imply some element of conduction block of the median nerve across the carpal tunnel.

Major Upper Extremity Motor Latencies from Erb's Point Stimulation

Nerve	Muscle	Latency (ms)	Distances (cm)†
Axillary*	Deltoid	≤4.9	15–21
Musculocutaneous*	Biceps	≤5.7	23–29
Suprascapular	Supraspinatus	≤3.7	7–12
Suprascapular	Infraspinatus	≤4.3	10–15

*The axillary and musculocutaneous nerves also can be stimulated in the axilla, with typical distal motor latencies of up to 3.3 ms. Both axillary and Erb's point stimulations often are technically difficult. In patients with symptoms limited to one side, comparing both latencies and amplitudes side to side always is preferable to using normal value tables.

†Distances measured with calipers (need the call out sign here) – then skips aline between this and the source.

Source: Data from Kraft, G.H., 1972; Axillary, musculocutaneous, and suprascapular nerve latency studies. Arch Phys Med Rehab 53, 382; and Currier, D.P., 1971; Motor conduction velocity of axillary nerve. Phys Ther 51, 503.

Phrenic Motor Study*

Nerve	Record	Amplitude (μV)	Distal latency (ms)
Phrenic	Diaphragm	597 ± 139 >320	6.3 ± 0.8 <8.0

*From Markand ON, Kincaid, J.C., Pourmand, R.A., 1984; et al. Electrophysiologic evaluation of diaphragm by transcutaneous phrenic nerve stimulation. Neurology 34, 606–614.

Phrenic Motor Study: Detailed Normal Studies[†]

		Absolute Values			Interside Differences		
Parameter	Phase	Mean ± SD	L/U Limits	5th/95th	Mean ± SD	Mean + 2SD	95th
Onset latency (ms)	Inspiration	6.55 ± 0.69	5.18/7.92	5.53/7.72	0.23 ± 0.19	0.61	0.53
	Expiration	6.59 ± 0.67	5.25/7.92	5.58/7.72	0.40 ± 0.36	1.9	1.11
Amplitude (mV)	Inspiration	1.00 ± 0.27	0.46/1.54	0.66/1.46	0.25 ± 0.18	0.61	0.6
	Expiration	0.71 ± 0.19	0.33/1.10	0.50/1.06	0.14 ± 0.10	0.35	0.33
Duration (ms)	Inspiration	14.99 ± 3.14	8.70/21.28	11.18/20.25	2.14 ± 1.72	5.57	4.71
	Expiration	20.98 ± 3.30	16.13/28.32	11.18/20.25	2.44 ± 1.65	5.74	5.54

[†]From Resman-Gaspersc, A., Podnar, S., 2008; Phrenic nerve conduction studies: technical aspects and normative data. Muscle Nerve 37, 36–41.
L/U, lower/upper limits; 5th/95th, 5th/95th percentile limits.

Craniobulbar

Motor

Nerve	Record	Amplitude (mV)	Distal Latency (ms)
Facial	Nasalis	≥1.0	≤4.2
Facial	Orbicularis oculi	≥1.0	≤3.1

Blink Reflex

Response	Latency (ms)	Side-to-Side Latency Difference (ms)
R1 (ipsilateral)	≤13	≤1.2
R2 (ipsilateral)	≤41	≤5
R2 (contralateral)	≤44	≤7

Notes:

1. All normal value tables assume normal controlled temperature and standard distances.
2. All motor and sensory amplitudes are measured from baseline to negative peak.
3. All sensory and mixed nerve distal latencies are peak latencies; however, all sensory and mixed nerve conduction velocities are calculated based on the onset latency.
4. Some values may need to be adjusted for extremes of height or age (see Chapter 8).
5. Comparison between the affected and unaffected limb often is very useful and may be more useful than normal value tables.
6. This is one set of normal values; others exist. Ideally, each laboratory should develop its own set of normal values.

11 Routine Lower Extremity Nerve Conduction Techniques

Tibial Motor Study *(Figure 11–1)*

Recording Site:

Abductor hallucis brevis (AHB) muscle:

G1 placed 1 cm proximal and 1 cm inferior to the navicular prominence

G2 placed over the metatarsal–phalangeal joint of the great toe

Stimulation Sites:

Medial ankle: Slightly proximal and posterior to the medial malleolus

Popliteal fossa: Mid-posterior knee over the popliteal pulse

Distal Distance:

9 cm

Key Points:

- The tibial compound muscle action potential (CMAP) often has an initial positive deflection, indicating that G1 is not over the motor endplate. If this occurs, the position of G1 should be changed slightly.
- CMAP amplitude at the popliteal fossa stimulation site often is lower than at the medial ankle stimulation site (normal controls may drop up to 50%). Thus, caution must be used whenever interpreting a drop in amplitude between the ankle and popliteal fossa as a conduction block on tibial motor studies. Side-to-side comparisons often are useful in this situation.
- High stimulation intensities often are required at the popliteal fossa to ensure supramaximal stimulation.
- Recording also can be done to the flexor hallucis brevis (FHB) muscle.

Peroneal Motor Study *(Figure 11–2)*

Recording Site:

Extensor digitorum brevis (EDB) muscle:

Dorsal lateral foot with G1 placed over the muscle belly

G2 placed distally over the metatarsal–phalangeal joint of the little toe

Stimulation Sites:

Ankle: Anterior ankle, slightly lateral to tibialis anterior tendon

Below fibular head: Lateral calf, one to two fingerbreadths inferior to fibular head (one can straddle the fibular neck with the stimulator)

Lateral popliteal fossa (above fibular neck): Lateral knee, adjacent to external hamstring tendons, at a distance of 10–12 cm from the below-fibular head site

Distal Distance:

9 cm

Key Points:

- Higher stimulation currents are needed at the below-fibular head site because the nerve lies deep at that location.
- Always perform the ankle, below-fibular neck, and above-fibular neck stimulations. If only the ankle and above-fibular neck stimulations are done, one can miss peroneal slowing across the fibular neck.
- Avoid excessive stimulation at the lateral popliteal fossa site to prevent co-stimulation of the tibial nerve.
- If there is a higher CMAP amplitude at the below-fibular head and popliteal fossa sites than at the ankle, consider an accessory peroneal nerve.

Peroneal Motor Study *(Figure 11–3)*

Recording Site:

Tibialis anterior (TA) muscle:

Proximal to mid-anterior lateral calf with G1 placed over the muscle belly

G2 placed distally over the anterior ankle

Stimulation Sites:

Below fibular head: Lateral calf, one to two fingerbreadths inferior to fibular head (one can straddle the fibular neck with the stimulator)

Lateral popliteal fossa (above fibular neck): Lateral knee, adjacent to external hamstring tendons, at a distance of 10–12 cm from the below-fibular head site

DOI: 10.1016/B978-1-4557-2672-1.00011-8

Distal Distance:
Variable (5–10 cm)

Key Points:
- Recording the TA is especially valuable in patients with suspected peroneal neuropathy at the fibular neck. Demonstrating a conduction block, focal slowing across the fibular neck or both may be easier when recording the TA than the EDB.
- Higher stimulation currents are needed at the below-fibular head site because the nerve lies deep at that location.
- Avoid excessive stimulation at the lateral popliteal fossa site to prevent co-stimulation of the tibial nerve.

Femoral Motor Study *(Figure 11–4)*

Recording Site:
Rectus femoris muscle:
G1 placed over the anterior thigh, halfway between the inguinal crease and knee
G2 placed over a bony prominence at the knee

Stimulation Site:
Middle of the inguinal area: Slightly lateral to the femoral pulse, below the inguinal ligament

Distal Distance:
Variable

Key Points:
- Firm pressure is needed when holding the stimulator.
- Difficult study to perform in obese individuals; high currents are typically needed (e.g., >50 mA).
- Limited indications; this study usually is used to compare motor amplitudes from side to side to quantitate the degree of axonal loss in femoral neuropathies, lumbar plexopathies, and severe L4 radiculopathies.
- Normal amplitude is >3 mV; however, side-to-side comparisons are most useful when symptoms are unilateral.

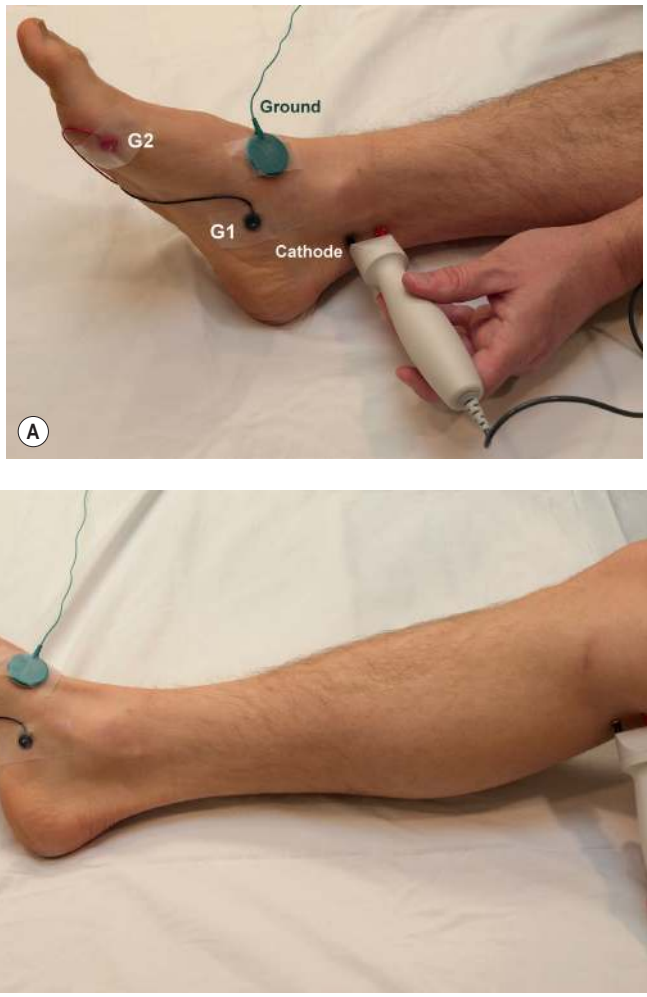


FIGURE 11–1 Tibial motor study. **A:** Distal stimulation site slightly proximal and posterior to the medial malleolus, recording the abductor hallucis brevis muscle. **B:** Proximal stimulation site in the middle of the popliteal fossa.

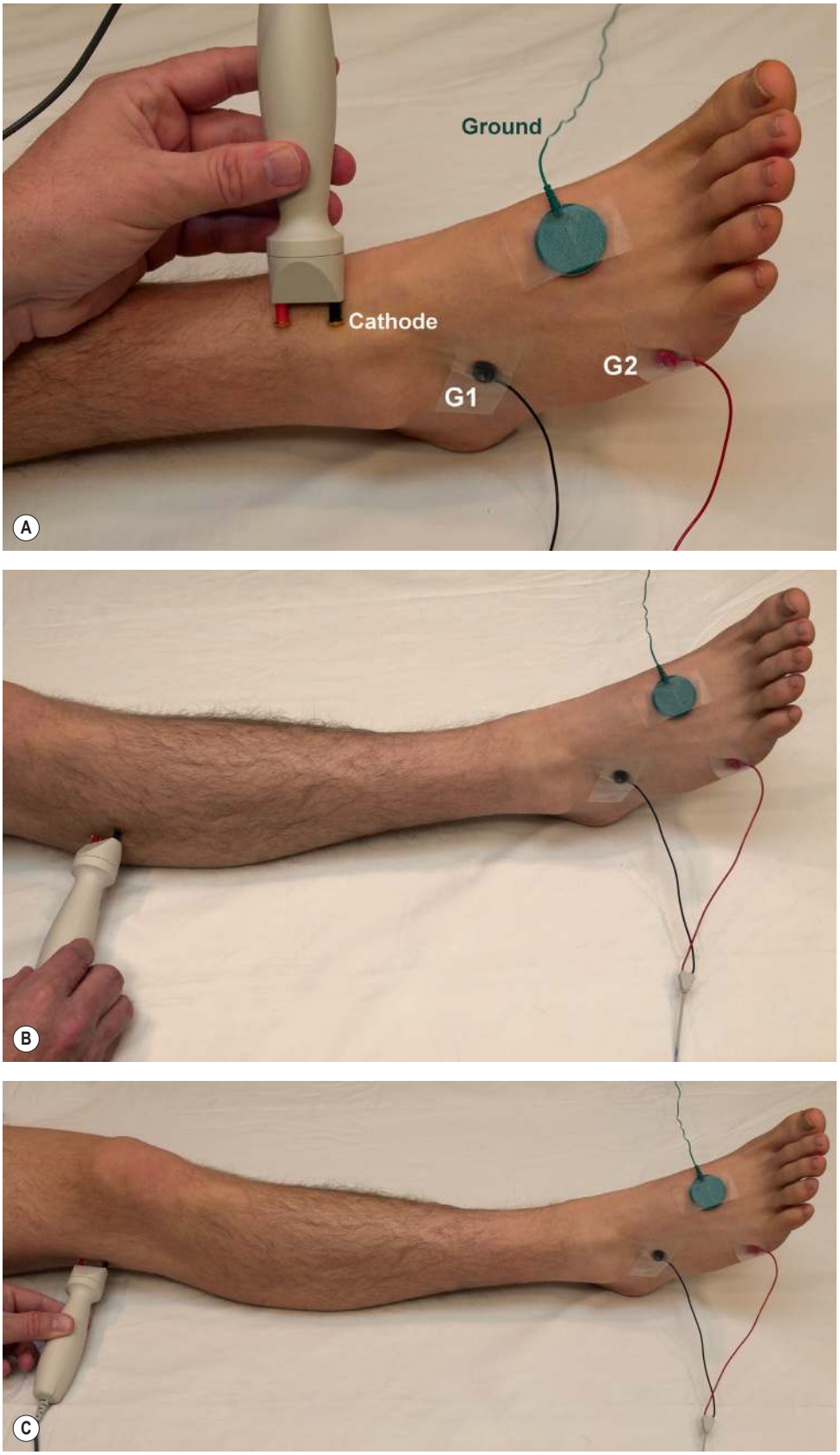


FIGURE 11–2 Peroneal motor study. **A:** Distal stimulation site over the anterior ankle, slightly lateral to the tibialis anterior tendon, recording the extensor digitorum brevis muscle. **B:** Proximal stimulation site below the fibular head. **C:** Proximal stimulation site in the lateral popliteal fossa above the fibular neck.

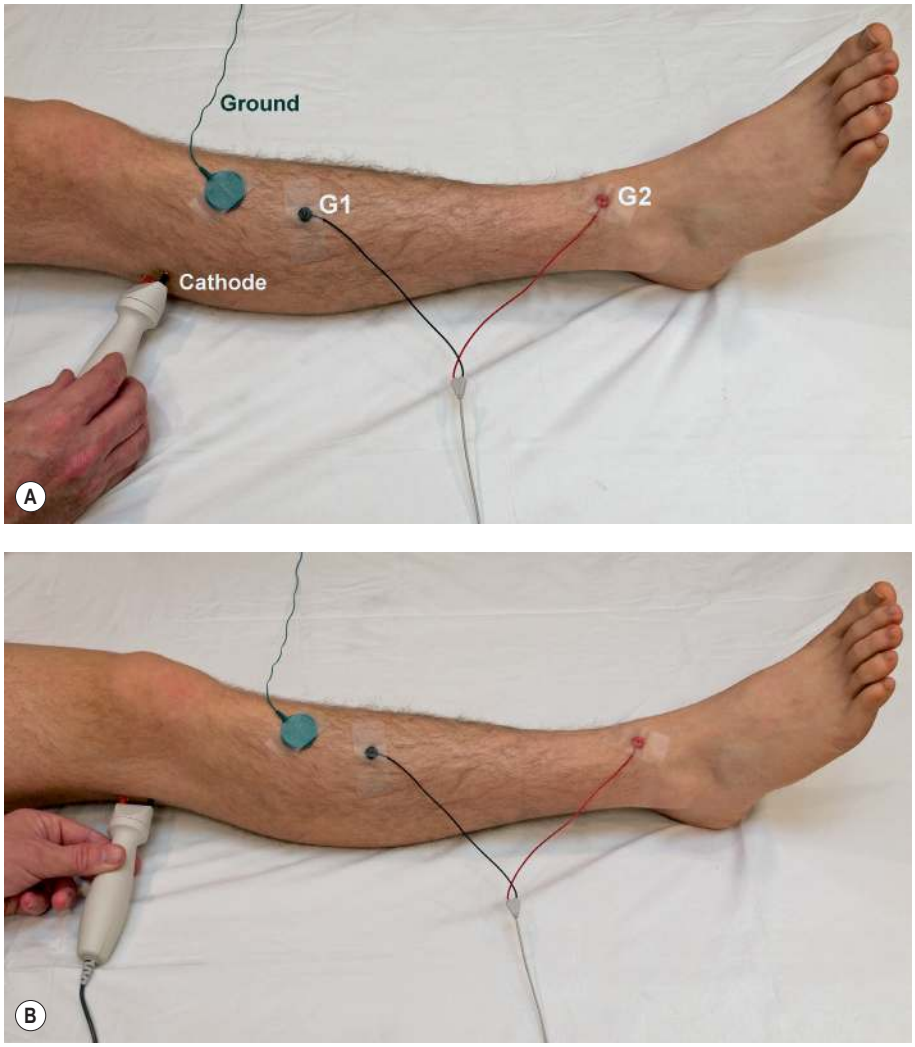


FIGURE 11–3 Peroneal motor study. **A:** Distal stimulation site below the fibular head, recording the tibialis anterior muscle **B:** Proximal stimulation site in the lateral popliteal fossa above the fibular neck.

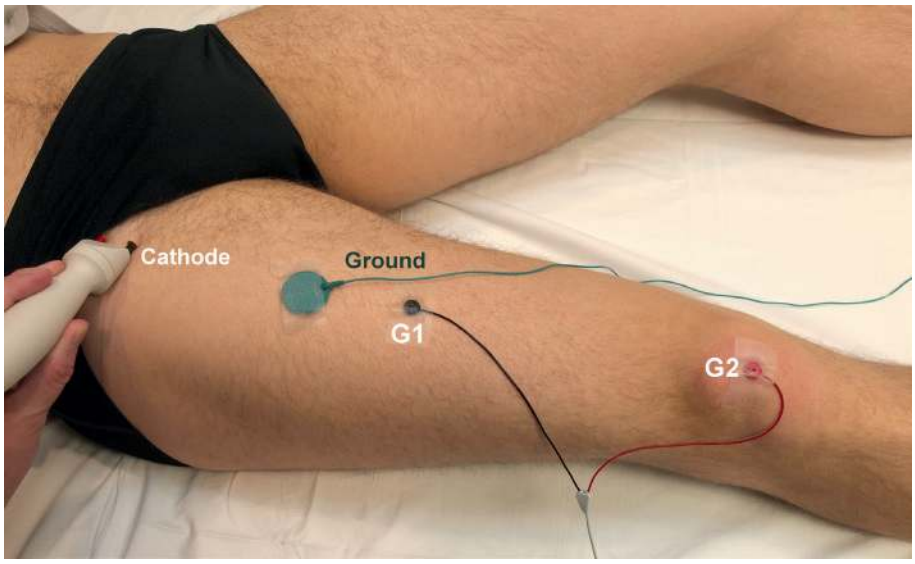


FIGURE 11–4 Femoral motor study. Stimulation site is slightly lateral to the femoral pulse, below the inguinal ligament. The rectus femoris is recorded, with G1 placed over the anterior thigh, halfway between the inguinal crease and knee, and G2 placed over a bony prominence at the knee.

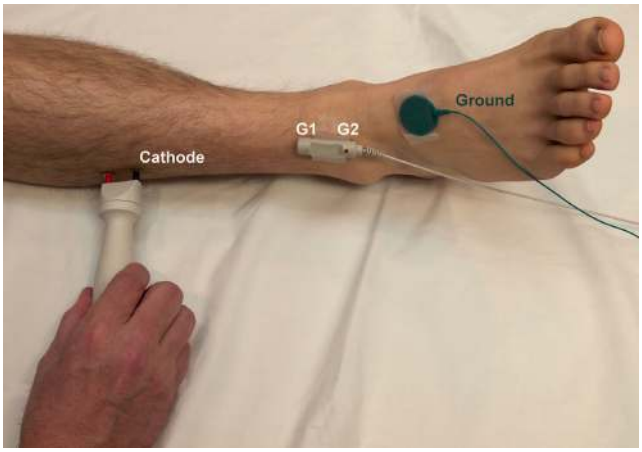


FIGURE 11–5 Superficial peroneal sensory study. Stimulation site is in the lateral calf; recording electrodes are placed between the tibialis anterior tendon and lateral malleolus.

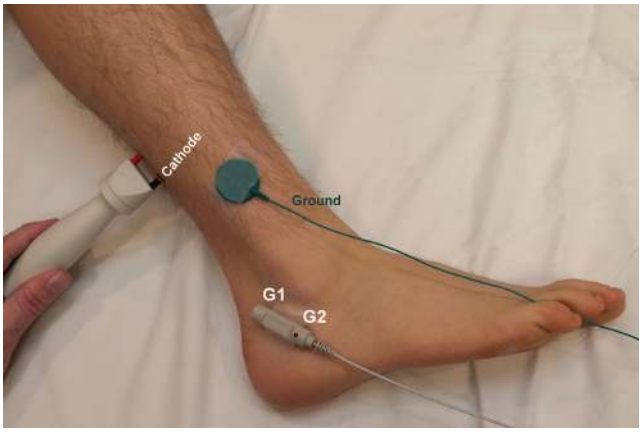


FIGURE 11–6 Sural sensory study. Stimulation site is in the posterior–lateral calf; recording electrodes are placed posterior to the lateral malleolus.

Superficial Peroneal Sensory Study *(Figure 11–5)*

Recording Site:

Lateral ankle:

G1 placed between the tibialis anterior tendon and lateral malleolus

G2 placed 3–4 cm distally

Stimulation Site:

Lateral calf

Distal Distance:

14 cm is the standard, but shorter distances may be helpful (see below)

Key Points:

- Although the normal value for peak latency is based on the standard distance of 14 cm, in many individuals, the nerve is much easier to stimulate at a shorter distance (typically 10–12 cm, and in some individuals as short as 7–9 cm). Supramaximal stimulation usually can be achieved with low stimulation intensities (e.g., 5–25 mA). Thus, if the response is not present stimulating at 14 cm or if high currents are needed, try a shorter distance of 10–12 cm, or 7–9 cm. If a good response is obtained at a shorter distance, do not use the peak latency to determine if the response is normal, but rather the calculated conduction velocity based on the onset latency and the distance used.
- May be abnormal in lesions of the peroneal nerve, sciatic nerve, or lumbosacral plexus.
- To maximize the response, the recording electrodes may have to be repositioned either slightly medially or laterally to the original position.
- Side-to-side comparisons of amplitude and latency often are helpful.
- Antidromic study described; for orthodromic study, recording and stimulation sites are reversed.

Sural Sensory Study *(Figure 11–6)*

Recording Site:

Posterior ankle:

G1 placed posterior to the lateral malleolus

G2 placed 3–4 cm distally

Stimulation Site:

Posterior–lateral calf

Distal Distance:

14 cm is the standard, but shorter distances may be helpful (see below)

Key Points:

- Although the normal value for peak latency is based on the standard distance of 14 cm, in many individuals, the nerve is much easier to stimulate at a shorter distance (typically 10–12 cm). Supramaximal stimulation usually can be achieved with low stimulation intensities (e.g., 5–25 mA). Thus, if the response is not present stimulating at 14 cm or if high currents are needed, try a shorter distance of 10–12 cm. If a good response is obtained, do not use the peak latency to determine if the response is normal, but rather the calculated conduction velocity based on the onset latency and the distance used.
- The study is best performed with the patient lying on his or her side, with the recording leg facing up.
- May be abnormal in lesions of the tibial nerve, sciatic nerve, or lumbosacral plexus.
- To maximize the response, the recording electrodes may have to be repositioned either slightly medially or laterally to the original position.

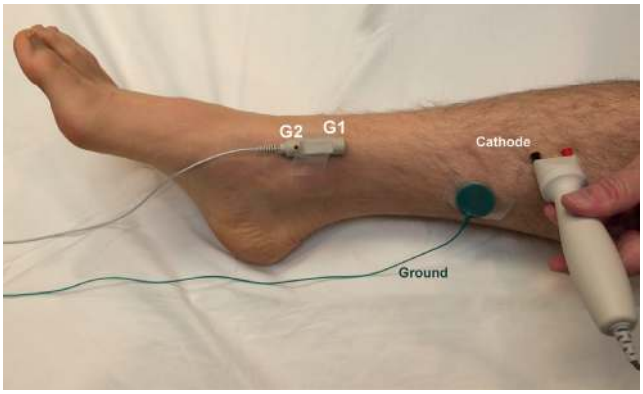


FIGURE 11–7 Saphenous sensory study. Stimulation site in the medial calf between the tibia and medial gastrocnemius; recording electrodes are placed between the medial malleolus and tibialis anterior tendon.

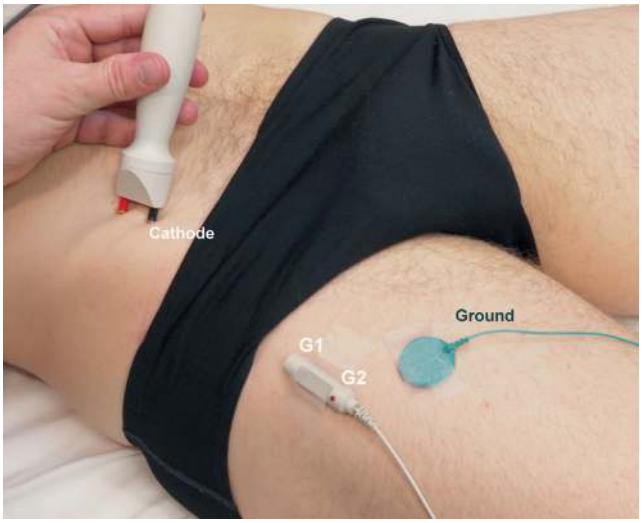


FIGURE 11–8 Lateral femoral cutaneous sensory study. Stimulation site in the inguinal area, above the inguinal ligament, and 1 cm medial to the anterior superior iliac spine (ASIS); recording electrodes are placed over the anterior thigh 12 cm distal to the stimulation site, on a line drawn directly from the ASIS to the lateral patella. Alternate recording site is 2 cm medial to the initial site.

- Side-to-side comparisons of amplitude and latency often are helpful.
- Antidromic study described; for orthodromic study, recording and stimulation sites are reversed.

Saphenous Sensory Study *(Figure 11–7)*

Recording Site:

Medial/Anterior ankle:

G1 placed between the medial malleolus and tibialis anterior tendon

G2 placed 3–4 cm distally

Stimulation Site:

Medial calf: Stimulator placed in the groove between the tibia and the medial gastrocnemius muscle

Distal Distance:

14 cm is the standard, but shorter distances may be helpful (see below)

Key Points:

- Although the normal value for peak latency is based on the standard distance of 14 cm, in many individuals, the nerve is much easier to stimulate at a shorter distance (typically 10–12 cm). Supramaximal stimulation usually can be achieved with low stimulation intensities (e.g., 5–25 mA). Thus, if the response is not present stimulating at 14 cm or if high currents are needed, try a shorter distance of 10–12 cm. If a good response is obtained, do not use the peak latency to determine if the response is normal, but rather the calculated conduction velocity based on the onset latency and the distance used.
- May be abnormal in lesions of the femoral nerve or lumbar plexus.
- To maximize the response, the recording electrodes may have to be repositioned either slightly medially or laterally to the original position.
- Side-to-side comparisons of amplitude and latency are required.
- Response often is small and may be difficult to obtain or absent in normal controls, especially those older than age 40. Side-to-side comparison is necessary before interpreting a low or absent potential as abnormal.
- Antidromic study described; for orthodromic study, recording and stimulation sites are reversed.

Lateral Femoral Cutaneous Sensory Study *(Figure 11–8)*

Recording Site:

Anterior thigh:

Option 1

G1 placed over anterior thigh, 12 cm distal to the stimulation site, on a line drawn directly from the anterior superior iliac spine (ASIS) to the lateral patella

G2 placed 3–4 cm distally

Option 2

Recording electrodes placed 2 cm medial to the Option 1 site

Stimulation Site:

Stimulator placed in the inguinal area above the inguinal ligament, 1 cm medial to the ASIS

Distal Distance:

12 cm is the standard, but shorter distances may be helpful (see below)

Key Points:

- Although the normal values are based on a standard distance of 12 cm, in some individuals, the nerve may be easier to stimulate at a shorter distance (typically 10 cm).
- There are some anatomical variations in terms of where the nerve runs in relationship to the anterior superior iliac spine (see Chapter 32). In more than 80% of individuals, the nerve lies between 0–1.5 cm lateral to the ASIS. However, rarely the nerve runs 5–8.5 cm medial to the ASIS. Thus, if no response is obtained, move the stimulator slightly lateral and then medial to the original stimulation site.
- Firm pressure is needed when holding the stimulator.
- Limited indications; may be abnormal in lesions of the lateral femoral cutaneous nerve (meralgia paresthetica) or lumbar plexus.
- Difficult study to perform in some obese individuals; high currents may be needed. One should always be cautious interpreting a low-amplitude or absent response as abnormal unless comparison studies are made side to side when symptoms are unilateral.
- A motor artifact may be present, which can be recognized by its longer duration than a typical sensory response.

Medial and Lateral Plantar Motor Studies

(Figure 11–9)

Recording Sites:

Abductor hallucis brevis (AHB) muscle:

G1 placed 1 cm proximal and 1 cm inferior to the navicular prominence

G2 placed over the metatarsal–phalangeal joint of the great toe

Abductor digiti quinti pedis (ADQP) muscle:

On lateral foot, G1 placed halfway between the lateral sole of the foot and the lower margin of the lateral malleolus

G2 placed over the metatarsal–phalangeal joint of the little toe

Stimulation Site:

Medial ankle: Slightly proximal and posterior to the medial malleolus

Distal Distance:

9 cm for AHB; variable for ADQP (distance measurement with obstetric calipers required)

Key Points:

- AHB is innervated by the medial plantar nerve and ADQP by the lateral plantar nerve.
- This study is useful in the evaluation of distal tibial neuropathy across the ankle (i.e., tarsal tunnel syndrome).
- Side-to-side comparisons of amplitude and latency are required.

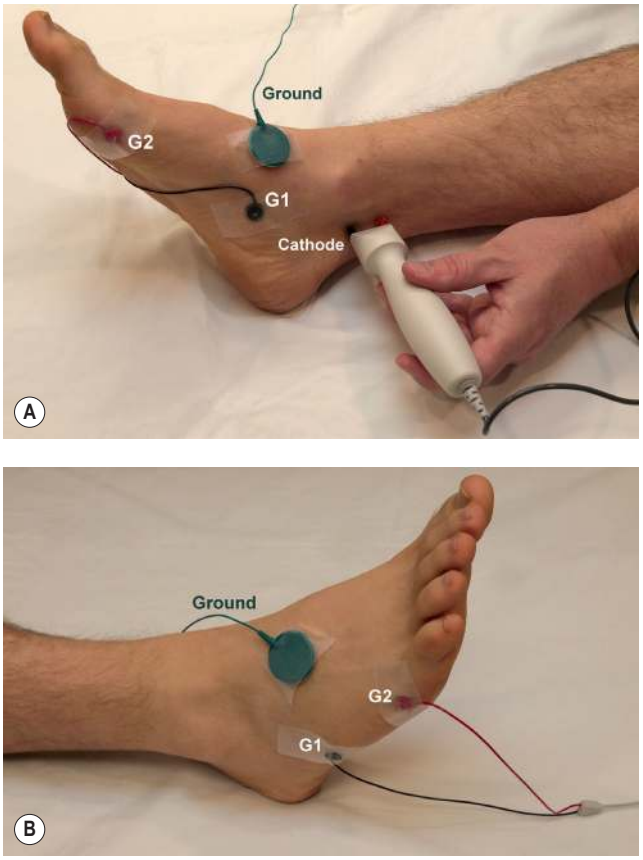


FIGURE 11–9 A: Medial plantar motor study. Stimulation site is slightly proximal and posterior to the medial malleolus, and the abductor hallucis brevis muscle is recorded. **B:** Lateral plantar motor study. Stimulation site is slightly proximal and posterior to the medial malleolus, and the abductor digiti quinti pedis muscle is recorded.

- CMAP of the AHB or ADQP often has an initial positive deflection, indicating that G1 is not over the motor endplate. If this occurs, the position of G1 should be changed slightly.

Medial and Lateral Plantar Sensory Studies

(Figure 11–10)

Recording Site:

Medial ankle:

G1 placed slightly proximal and posterior to the medial malleolus

G2 placed 3–4 cm proximally

Stimulation Sites:

Great toe (medial plantar sensory): Ring electrodes, with cathode placed proximally near the metatarsal–phalangeal joint of the great toe; anode placed 3–4 cm distally

Little toe (lateral plantar sensory): Ring electrodes, with cathode placed proximally near the metatarsal–phalangeal joint of the little toe; anode placed as distally as possible

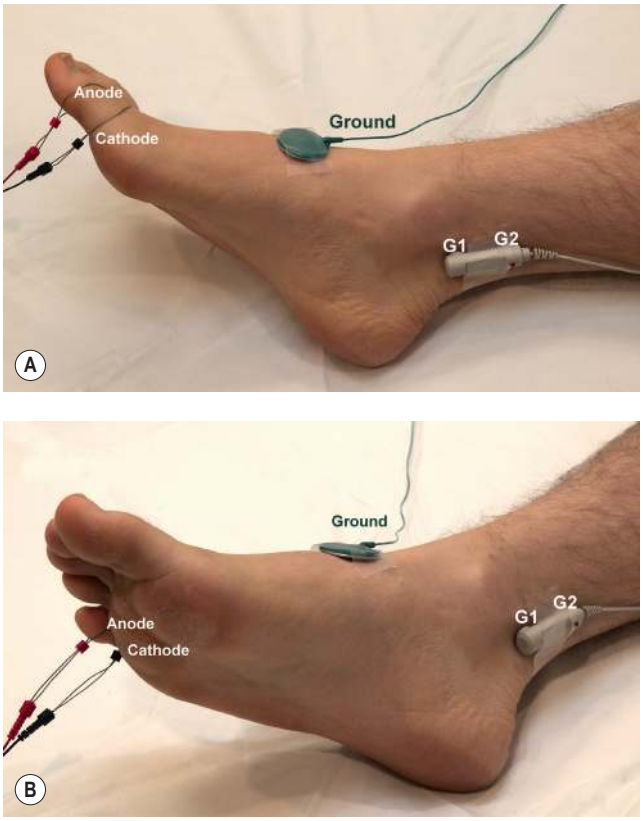


FIGURE 11–10 **A:** Medial plantar sensory study. The great toe is stimulated, and the tibial nerve is recorded slightly proximal and posterior to the medial malleolus. **B:** Lateral plantar sensory study. The little toe is stimulated, and the tibial nerve is recorded slightly proximal and posterior to the medial malleolus.

Distal Distance:

Variable

Key Points:

- Orthodromic study described; for antidromic study, recording and stimulation sites are reversed.
- This study is useful in the evaluation of distal tibial neuropathy across the ankle (i.e., tarsal tunnel syndrome).
- Potentials are very small and difficult to obtain, even in normal controls.
- Averaging often is required.
- Side-to-side comparisons of amplitude and latency are required.
- Side-to-side comparison is necessary before interpreting a low or absent potential as abnormal.

Medial and Lateral Plantar Mixed Nerve Studies *(Figure 11–11)*

Recording Site:

Medial ankle:

G1 placed slightly proximal and posterior to the medial malleolus

G2 placed 3–4 cm proximally

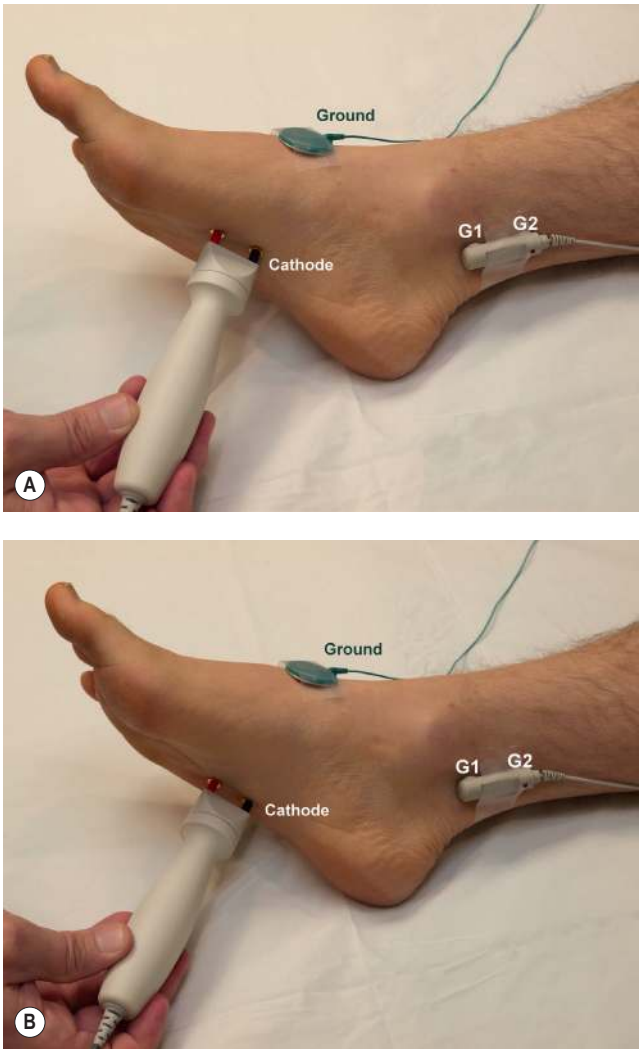


FIGURE 11–11 **A:** Medial plantar mixed study. The medial sole is stimulated, and the tibial nerve is recorded slightly proximal and posterior to the medial malleolus. **B:** Lateral plantar mixed study. The lateral sole is stimulated, and the tibial nerve is recorded slightly proximal and posterior to the medial malleolus.

Stimulation Sites:

Medial sole (medial plantar nerve): At a distance of 14 cm from the recording electrodes (measure 7 cm from the recording site into the sole of the foot, then an additional 7 cm on a line drawn parallel to the web space between the first and second toes)

Lateral sole (lateral plantar nerve): At a distance of 14 cm from the recording electrodes (measure 7 cm from the recording site into the sole of the foot, then an additional 7 cm on a line drawn parallel to the web space between the fourth and fifth toes)

Distal Distance:

14 cm

Key Points:

- Mixed nerve study, technically easier than orthodromic sensory studies.

- This study is useful in the evaluation of distal tibial neuropathy across the ankle (i.e., tarsal tunnel syndrome).
- Potentials may be small and difficult to obtain in normal controls, especially the lateral plantar response.
- Averaging often is required.
- Side-to-side comparisons of amplitude and latency are required.
- Side-to-side comparison is necessary before interpreting a low or absent potential as abnormal.

Soleus H Reflex Study *(Figure 11–12)*

Recording Site:

Soleus muscle:

Posterior calf with G1 placed one to two fingerbreadths distal to where the soleus meets the two bellies of the gastrocnemius

G2 placed over the Achilles tendon

Stimulation Site:

Popliteal fossa: Mid-posterior knee over the popliteal pulse

Distal Distance:

Variable (usually in the range of 20–25 cm)

Key Points:

- Stimulator pulse duration must be set at 1000 µs (i.e., 1 ms) to more selectively activate the Ia sensory fibers.
- H reflex occurs with low stimulation intensities.
- As stimulator current is slowly increased, the H reflex appears first, without a direct muscle response; as the current is increased further, the H reflex increases and a direct muscle response also occurs; as the direct muscle response grows the H reflex decreases.
- H reflex is a late reflex, usually with a triphasic morphology (positive–negative–positive) occurring at 25–34 ms.
- Comparison to the contralateral side is often helpful in determining if a latency is abnormal (latency difference >1.5 ms).
- The distal distance must be the same from side to side to ensure a valid side-to-side comparison
- H reflex is delayed or absent in polyneuropathy, tibial neuropathy, sciatic neuropathy, lumbosacral plexopathy, or S1 radiculopathy.

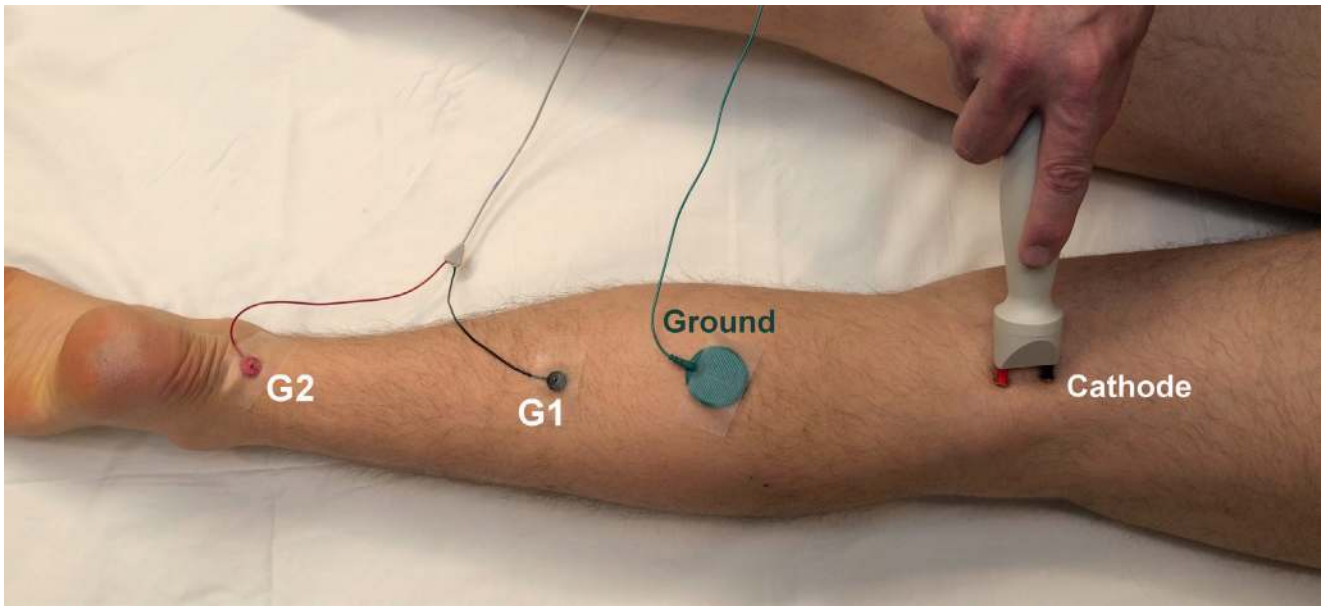


FIGURE 11–12 Soleus H reflex. The tibial nerve is stimulated in the middle of the popliteal fossa; the cathode is pointing rostral, and the soleus muscle is recorded.

NERVE CONDUCTION STUDIES OF THE LOWER EXTREMITY: NORMAL ADULT VALUES

Motor

Nerve	Record	Amplitude (mV)	Conduction Velocity (m/s)	Distal Latency (ms)	Distal Distance (cm)
Peroneal	Extensor digitorum brevis (EDB)	≥2.0	≥44	≤6.5	9
Peroneal†	Tibialis anterior (TA)	≥3.0	≥44	≤6.7	5–10
Tibial	Abductor hallucis brevis (AHB)	≥4.0	≥41	≤5.8	9
Tibial†	Abductor digiti quinti pedis (ADQP)	≥3.0	≥41	≤6.3	Variable*

*Difficult to measure unless calipers are used.

† In cases where one side is symptomatic and the other is not, it is often helpful to compare the amplitudes side to side, rather than use normal value tables.

Antidromic Sensory

Nerve	Record	Amplitude (μV)	Conduction Velocity (m/s)	Peak Latency (ms)	Distal Distance (cm)
Sural	Posterior ankle	≥6	≥40	≤4.4	14†
Superficial peroneal	Lateral ankle	≥6	≥40	≤4.4	14†
Saphenous*	Medial/anterior ankle	≥4	≥40	≤4.4	14†
Medial plantar*	Medial ankle	≥2	≥35	–	Variable
Lateral plantar*	Medial ankle	≥1	≥35	–	Variable
Lateral femoral cutaneous‡	Anterior thigh	≥4		≤2.6	12

*In some normal individuals without symptoms, especially those older than age 40, these responses may be very small, requiring electronic averaging, or may be absent. Thus, a low-amplitude or absent potential should not necessarily be interpreted as abnormal. Side-to-side comparisons often are very useful in this regard if one side is symptomatic and the other is not.

†Although the normal values for peak latency are based on the standard distance of 14 cm, in many individuals, it is much easier to stimulate at a shorter distance (typically 10–12 cm). Supramaximal stimulation usually can be achieved with low stimulation intensities (e.g., 5–25 mA). Thus, if the response is not present stimulating at 14 cm or if high currents are needed, try a shorter distance of 10–12 cm. If a good response is obtained, do not use the peak latency to determine if the response is normal, but rather the calculated conduction velocity based on the onset latency and the distance used.

‡Although the normal value for peak latency is based on the standard distance of 12 cm, in some individuals, the nerve may be easier to stimulate at a shorter distance (typically 10 cm). Difficult study to perform in obese individuals. Thus, a low-amplitude or absent potential should not necessarily be interpreted as abnormal unless side-to-side comparisons are done in patients with symptoms limited to one side.

Source: from Shin, Y.B., Park, J.H., Kwon, D.R., Park, B.K., 2006. Variability in conduction of the lateral femoral cutaneous nerve. Muscle Nerve 33 (5), 645–649. Values based on reported mean minus 2 SD for amplitude, and mean plus 2 SD for peak latency.

Plantar Mixed Nerve Studies

Nerve	Amplitude (μV)	Conduction Velocity (m/s)	Distal Peak Latency (ms)	Distance (cm)
Medial plantar*	≥3	≥45	≤3.7	14
Lateral plantar*	≥3	≥45	≤3.7	14

*In some normal individuals without symptoms, especially those older than age 40, these responses may be very small, requiring electronic averaging, or may be absent. Thus, a low-amplitude or absent potential should not necessarily be interpreted as abnormal. Side-to-side comparisons often are very useful in this regard.

Late Responses*

Nerve	Minimal F Latency (ms)	Minimal H Latency (ms)
Peroneal	≤56	N/A
Tibial	≤56	≤34†

*For tall or short patients, F responses and H reflexes must be normalized for height (see Chapter 4).

†Compare side to side. Any difference in latency >1.5 msec between sides is considered abnormal.

Notes:

1. All normal value tables assume controlled temperature and standard distances.
2. All motor and sensory amplitudes are measured from baseline to negative peak.
3. All sensory and mixed nerve distal latencies are peak latencies; however, all sensory and mixed nerve conduction velocities are calculated based on the onset latency.
4. Some values may have to be adjusted for extremes of height or age (see Chapter 8).
5. Comparison between the affected and unaffected limb often is very useful and may be more useful than normal value tables.
6. This is one set of normal values; others exist. Ideally, each laboratory should develop its own set of normal values.

Basic Overview of Electromyography 12

After the nerve conduction studies are completed, the electrophysiologic evaluation moves on to the needle electromyography (EMG) examination. Like the nerve conduction studies, each needle EMG study must be individualized based on the clinical findings and differential diagnosis and modified as the test proceeds and more data are obtained. Almost every muscle in the body can be studied with EMG. However, to do so is neither practical for the electromyographer nor desirable for the patient. For each study, a balance must be reached between the need to study a sufficient number of muscles to reach or exclude a diagnosis and the limits of the patient's ability to tolerate the examination. Patients' reactions to the needle EMG vary greatly. When the examination is performed skillfully, most patients tolerate it well, with only minor discomfort. Some patients, however, are extremely apprehensive and may have difficulty completing the examination. Young children, who may tolerate the nerve conductions well, frequently have difficulty with the needle examination. It is with these latter groups that the electromyographer must be especially skillful. *Before proceeding with the needle study, it often is useful to consider the possibility that the patient may tolerate EMG of only one or two muscles.* If this occurs, which muscles will one choose? The choice must be based on the following factors:

1. The differential diagnosis, determined by the clinical findings and nerve conduction data.
2. The ease with which the muscle can be located and activated [e.g., although both the tibialis anterior (TA) and medial gastrocnemius (MG) are distal leg muscles, the TA is much easier to activate than the MG].
3. The degree of pain associated with sampling the particular muscle [e.g., both the first dorsal interosseous (FDI) and abductor pollicis brevis (APB) are distal C8–T1 innervated muscles, but the APB is much more painful to sample than the FDI for most patients).

If there is any indication that the patient might not tolerate or complete the entire examination, the most important muscles should be sampled first. For instance, if a patient has proximal muscle weakness and the differential diagnosis rests primarily between a myopathy and a proximal neuropathic process (e.g., plexopathy, radiculopathy, motor neuron disease), it makes sense to sample a weak proximal muscle first. If one begins the examination by sampling distal muscles that are clinically normal and the patient asks to stop the examination after the distal muscles are sampled, the chance to reach a diagnosis may have been lost.

There is no doubt that the needle EMG is the more challenging part of the electrophysiologic examination. A successful study requires not only knowledge of anatomy and physiology but also sound EMG technique and good patient rapport. Two competing influences make the needle EMG study especially demanding. First, many of the abnormalities found on the needle study are subtle. At the same time, however, the range of normal findings is quite large and varies with age and with the muscle being studied. Although the basics of the needle EMG study, such as needle placement and recognition of certain types of abnormal spontaneous activity, usually can be learned in a short time, it is not unusual for it to take years to master recognition of many of the uncommon and subtle needle EMG findings.

EQUIPMENT

In addition to the EMG machine, an EMG needle, needle cable, ground electrode, and gloves are necessary to perform the needle EMG study. The ground electrode is applied to the limb being studied in order to suppress noise and for electrical safety. Disposable gloves must always be worn to prevent the transmission of bloodborne infections between the patient and the electromyographer. The EMG needle is connected to a cable and then plugged into the EMG machine. Either a concentric or monopolar EMG needle can be used (Figure 12–1). When an electrical potential is measured, including the potentials measured during the needle EMG study, voltage is measured as the difference between the active and reference recording electrodes. The concentric needle contains both the active and reference electrodes in the needle itself (Figure 12–2). The shaft of the needle serves as the reference electrode, whereas the active electrode runs as a very small wire through the center of the needle and is exposed at the needle tip. The end of the concentric needle is beveled, resulting in a recording area that has a "teardrop" configuration (Figure 12–3). In contrast, the monopolar needle is Teflon coated, and its exposed end serves as the active recording electrode. Its

DOI: 10.1016/B978-1-4557-2672-1.00012-X

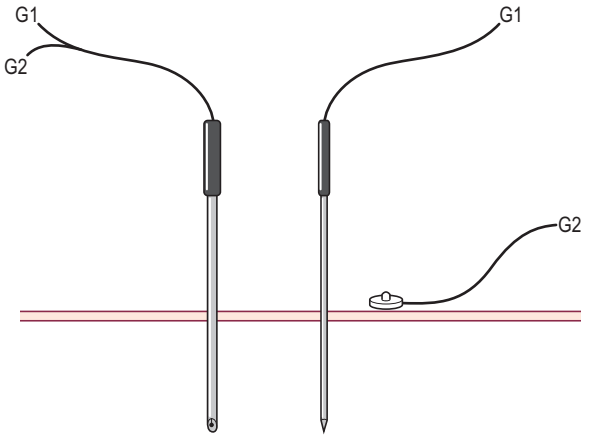


FIGURE 12–1 Electromyography needles. To the left is the concentric needle, which contains both the active (G1) and reference (G2) electrodes. The active electrode runs as a small wire through the needle center and is exposed at the tip, whereas the shaft of the needle serves as the reference electrode. To the right is the monopolar needle. In the monopolar montage, the needle is Teflon coated, and its exposed tip serves as the active electrode (G1). An additional surface disc electrode is needed as the reference electrode (G2).

FIGURE 12–2 Concentric needle electrode. The shaft of the needle serves as the reference electrode (G2), whereas the active electrode (G1) runs as a very small wire through the center of the needle and is exposed at the needle tip, which is beveled. **Inset:** High magnification of the needle bevel. Note that the active electrode can be seen in the center.

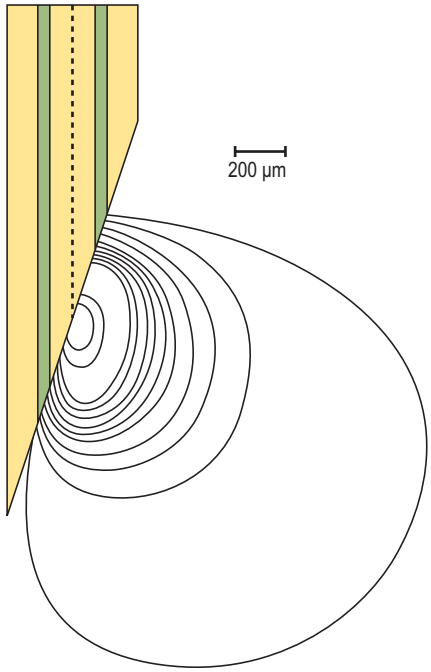


FIGURE 12–3 Recording field shape of the concentric needle electrode. As the end of the concentric needle is beveled, the resultant recording area has a "teardrop" configuration.
(Adapted from King, J.C., Dumitru, D., Nandedkar, S., 1997. Concentric and single fiber electrode spatial recording characteristics. Muscle Nerve 20, 1525–1533. Reprinted by permission of Wiley.)

recording area is that of a sphere around the tip of the needle. For the monopolar needle montage, an additional surface disc electrode is required as the reference electrode.

Both concentric and monopolar needles do a good job of recording the electrical signals from muscle. For recording motor unit action potentials (MUAPs), however, there are small differences between the two types of needle. With a concentric needle, the MUAP amplitude is slightly smaller and the major spike rise time shorter than those obtained with a monopolar needle (likely a reflection of the size and shape of the recording field of each needle) (Figure 12–4). Otherwise, there are no appreciable differences between the two in terms of the recorded waveforms. The concentric needle has the advantage of not requiring an additional reference electrode and is thus easier to use. The monopolar needle has the advantage of having a smaller caliber and a sharper point and may be slightly less painful and easier for patients to tolerate. This advantage, however, is not as critical as it was in the past, when needles were routinely sterilized and reused. Because reused needles often become less sharp with successive use, they are more painful when they penetrate the skin. All needles in use now, however, are disposable and should never be reused. The major disadvantage of the monopolar needle is the need for an additional reference electrode. Because the reference electrode must be placed close to the active electrode, it must be moved from location to location with each muscle sampled.

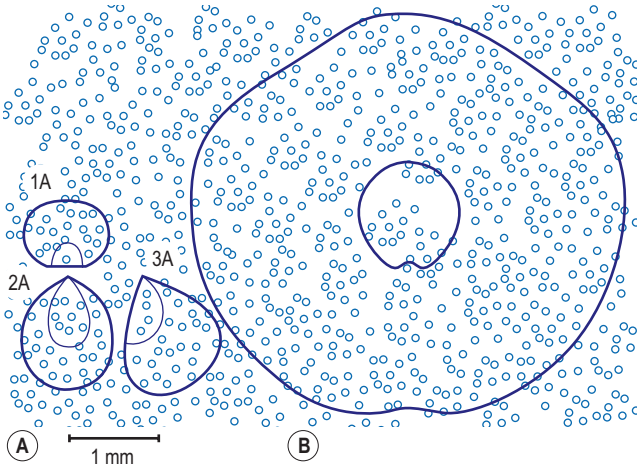


FIGURE 12–4 Comparison of recording fields of concentric and monopolar needle electrodes. **A:** Concentric needle recording field (**1A:** top view; **2A:** front view; **3A:** side view). **B:** Monopolar needle recording field (side view). Recording fields are superimposed upon a typical motor unit fiber distribution. The amplitude of the recorded motor unit action potential is derived primarily from the fibers near the needle tip. In the figure, the inner and outer lines represent the fibers that contribute 90 and 99% of the recorded amplitude, respectively (i.e., any fibers outside of these lines make no significant contribution to the recorded amplitude). Note that the monopolar needle has a much larger recording area.
(Adapted from King, J.C., Dumitru, D., Nandedkar, S., 1997. Concentric and single fiber electrode spatial recording characteristics. Muscle Nerve 20, 1525–1533. Reprinted by permission of Wiley.)

In addition, because the active electrode is an intramuscular needle and the reference is a surface disc, there is a much greater likelihood of electrode impedance mismatch and increased electrical noise. All in all, both needle types are satisfactory, but considering the advantages and disadvantages of each, the concentric needle is preferred by most electromyographers.

PATIENT PREPARATION

Before beginning the needle EMG examination, it is important to explain the procedure to the patient and allay any patient fears. After completing the nerve conduction studies, we usually tell every patient some version of the following before beginning the needle EMG:

We have finished the nerve conduction part of the test and are about to go on to the second part of the test, which usually is much shorter than the first part. There is no electrical stimulation with this part of the test. I will use a very small needle to record electrical potentials from inside your muscles. We will be checking several muscles, but the exact number of muscles will depend on what we find as we go along. For each muscle we look at, I will put this small needle into the muscle, and you will feel a quick pinch. The more relaxed you are when I put the needle in, the less you will feel the needle. We will look at the electrical activity of the muscle while it is relaxed, and then I will ask you to move the muscle slightly to look at the activity of the muscle while it is contracting. I will explain to you exactly what I am doing at each stage, how to relax the muscle, and how to move the muscle when I ask you to. When your muscle is contracting, the electrical signal from the muscle will go to the EMG machine so that I can see it on the screen, but more importantly, it also will go to a loudspeaker so that we both can hear it. This is important because, at certain times, I will ask you to move a little bit more or a little bit less, and by listening, you will know how much you are moving your muscle. Please feel free to ask me any questions as we go along, and let me know if you need to take a break at any time.

Afterward, the examiner should answer any questions from the patient before proceeding to the needle EMG examination. Good patient rapport both before and during the study is essential. Most of the needle study cannot be performed without good patient cooperation. Indeed, the more cooperative the patient, the more reliable the data obtained and the more quickly the test proceeds, leading to less discomfort and a better test for the patient.

TYPICAL NEEDLE ELECTROMYOGRAPHY EXAMINATION *(BOX 12–1)*

For each muscle being studied, one must be able to identify the proper needle insertion point, as well as know how to properly have the patient activate the muscle (see Chapter 13). The skin should always be cleaned with alcohol before the needle is inserted. Once the muscle has been selected for study, the first step is to locate the needle insertion

Box 12–1. Patient Preparation and Typical Needle Electromyography Examination

1. Explain the electromyography procedure to the patient to allay any patient fears.
2. Select first muscle for study.
3. Locate muscle by using anatomic landmarks.
4. Show patient how to activate muscle.
5. Palpate muscle during contraction.
6. Ask patient to relax muscle.
7. Insert needle into relaxed muscle.
8. Ask patient to contract muscle slightly to ensure proper placement.
9. Ask patient to relax muscle fully.
10. Assess insertional and spontaneous activity (sweep speed: 10 ms per division; sensitivity: 50 µV per division).
11. Perform 5–10 brief insertions in all four quadrants.
12. Assess MUAPs (sweep speed: 10 ms per division; sensitivity: 200 µV per division).
    - A. Ask patient to contract muscle slightly and gently move needle until MUAPs become "sharp."
    - B. Assess several locations for MUAP duration, amplitude, phases, recruitment, and activation.
    - C. Use isometric contraction, if possible.
13. Proceed to next muscle.

MUAP, motor unit action potential.

point by identifying the proper anatomic landmarks. Next, one should ask the patient to activate and relax the muscle several times and palpate for muscle movement. Once the muscle location is properly identified and palpated, the patient is asked to relax. Inserting a needle into a contracted muscle is much more painful than putting a needle into a relaxed one. The needle is then quickly inserted through the skin into the muscle. Sometimes the patient finds it less painful if the electromyographer gently pinches the muscle between the fingertips to raise it a bit, before inserting the needle. Before proceeding further, the location of the needle must be confirmed. The patient is asked to activate the muscle of interest ever so slightly. *The low level of activation needs to be emphasized.* Many adjacent muscles will co-contract at higher levels of activation. If the needle is in the proper location, very sharp and crisp MUAPs will be seen with minimal contraction. If sharp MUAPs are not seen with minimal contraction, the needle should be either pulled back slightly or moved a bit deeper into the muscle before the examination proceeds. If this maneuver fails to produce sharp MUAPs, the needle must be removed, the muscle re-palpated, and the needle reinserted. *The important point to remember here is that one should not proceed unless one is certain that the needle is placed correctly in the muscle of interest.*

Once the correct needle placement has been established, the first part of the examination is to assess insertional and spontaneous activity at rest. This should be done with the sweep speed set at 10 ms per division and the sensitivity set at 50 μV per division. Most spontaneous discharges are of low amplitude and may be missed unless the sensitivity is set to at least 50 μV per division (see Chapter 14). Five to 10 brief insertions should be performed, looking for increased insertional activity and spontaneous discharges at rest. Muscle normally is quiet at rest, except for the potentials seen at the endplate zone. When the needle is quickly moved through muscle, there is a brief burst of muscle fiber potentials, typically lasting no longer than 300 ms after the needle has stopped moving. Increased insertional activity is defined as any activity other than endplate potentials that last longer than 300 ms after brief needle movement. Spontaneous activity is defined as any activity at rest that lasts longer than 3 seconds. One effective technique to sample for spontaneous and increased insertional activity is to insert the needle in all four quadrants at the needle site (see Chapter 14). Using this technique, the examiner first inserts the needle in one quadrant, moves it along a line from shallow to deeper, and then pulls it back to sample the next quadrant without removing the needle from the muscle. This is repeated until all four quadrants are sampled.

Once insertional and spontaneous activity have been characterized, the needle is left in place, and the analysis next turns to the evaluation of MUAPs. The sensitivity must be changed to 200 μV per division, while the sweep speed remains at 10 ms per division. MUAPs typically are much larger than abnormal spontaneous activity waveforms and hence require the change in sensitivity. To analyze MUAPs, the examiner asks the patient to slowly contract the muscle of interest. It is always best to have the patient contract the muscle in an even manner. MUAPs are very difficult to interpret in patients whose muscle contraction is uneven, especially those with a tremor.

A clinical pearl in performing needle EMG is to always employ isometric contraction if possible (isometric meaning the same muscle length). Indeed, it is often the physical muscle movement around the needle, especially at higher levels of force, that results in discomfort. This can be minimized by using isometric contraction. Thus, the electromyographer simply has to resist the movement of the muscle as the patient increases force. For example, when sampling the biceps, the electromyographer holds the needle in one hand while using the other hand to hold the patient's forearm steady, as the patient pushes against it. As the patient contracts more, the electromyographer holds the forearm even tighter to prevent the elbow joint from moving. Thus, even though more force is being generated, the muscle remains the same in length (i.e., isometric) as any actual movement is prevented by resistance from the electromyographer.

With the patient minimally activating the muscle, the needle is gently moved until the MUAPs become "sharp," that is, they become louder and crisper. As the needle moves closer to the MUAP, there is less intervening tissue to attenuate and filter the potential. Thus, the closer the needle to the MUAP, the higher the amplitude and the shorter the major spike rise time. It is at this point that the MUAP can be properly evaluated. MUAPs are assessed for duration, amplitude, and number of phases. In addition, the number of MUAPs, their relationship to the firing frequency, and the rate of firing itself (recruitment and activation pattern) are determined (see Chapter 15). As the patient slowly increases force, both the firing frequency and the number of MUAPs normally increase. After the MUAPs are assessed at one location, the needle is moved slightly within the muscle to a different site, and the process is repeated. Ideally, 10 to 20 different MUAPs should be studied.

Once insertional and spontaneous activity are characterized and the MUAP size, recruitment, and activation patterns are determined for each muscle sampled, one can generally determine whether a lesion is present. If there is a lesion, one can use the data to determine its severity and chronicity and, most importantly, whether the primary problem is neuropathic or myopathic. The distribution and pattern of abnormalities in different muscles, along with the nerve conduction studies and the clinical data, should allow one to make the final electrophysiologic diagnosis.

13 Anatomy for Needle Electromyography

UPPER EXTREMITY

MEDIAN NERVE

Abductor Pollicis Brevis (APB) *(Figure 13–1A,B)*

Innervation:

Median nerve, medial cord, lower trunk, **C8–T1**

Needle Insertion:

Insert needle tangentially into the lateral thenar eminence, just lateral to mid-point of first metacarpal

Activation:

Abduct the thumb with arm and hand in the supinated position

Key Clinical Points:

- The APB is the best median muscle to sample distal to the carpal tunnel.
- May be abnormal in carpal tunnel syndrome, proximal median neuropathies, lower trunk/medial cord plexopathy, thoracic outlet syndrome, C8–T1 radiculopathy, and distal polyneuropathy.
- Spared in anterior interosseous nerve syndrome.
- The APB often is perceived as more painful to sample than other intrinsic hand muscles.

Cross-section Anatomy Key Points:

- If the needle is inserted too medially, it may be in the flexor pollicis brevis, which has both median and ulnar innervation.
- If the needle is inserted too deeply, it may be in the opponens pollicis, also innervated by the median nerve.

Opponens Pollicis (OP) *(Figure 13–2A,B)*

Innervation:

Median nerve, medial cord, lower trunk, **C8–T1**

Needle Insertion:

With the needle parallel to the hand, insert needle into the patient's lateral thenar eminence, just above the first metacarpal bone

Activation:

Have the patient oppose the thumb to little finger with the arm and hand in the supinated position

Key Clinical Points:

- May be abnormal in carpal tunnel syndrome, proximal median neuropathies, lower trunk/medial cord plexopathy, thoracic outlet syndrome, C8–T1 radiculopathy, distal polyneuropathy.
- Spared in anterior interosseous nerve syndrome.

Cross-section Anatomy Key Points:

- The OP muscle lies below the APB. If the needle is inserted too medially or superficially, it will be in the APB.

*All cross-section anatomy figures adapted from: A Cross-Section Anatomy by Eycleshymer & Schoemaker, D Appleton Century Company, 1911. All figures are in the public domain.
†Adapted from: Gray's Anatomy of the Human Body, 1918. Figure is in the public domain.

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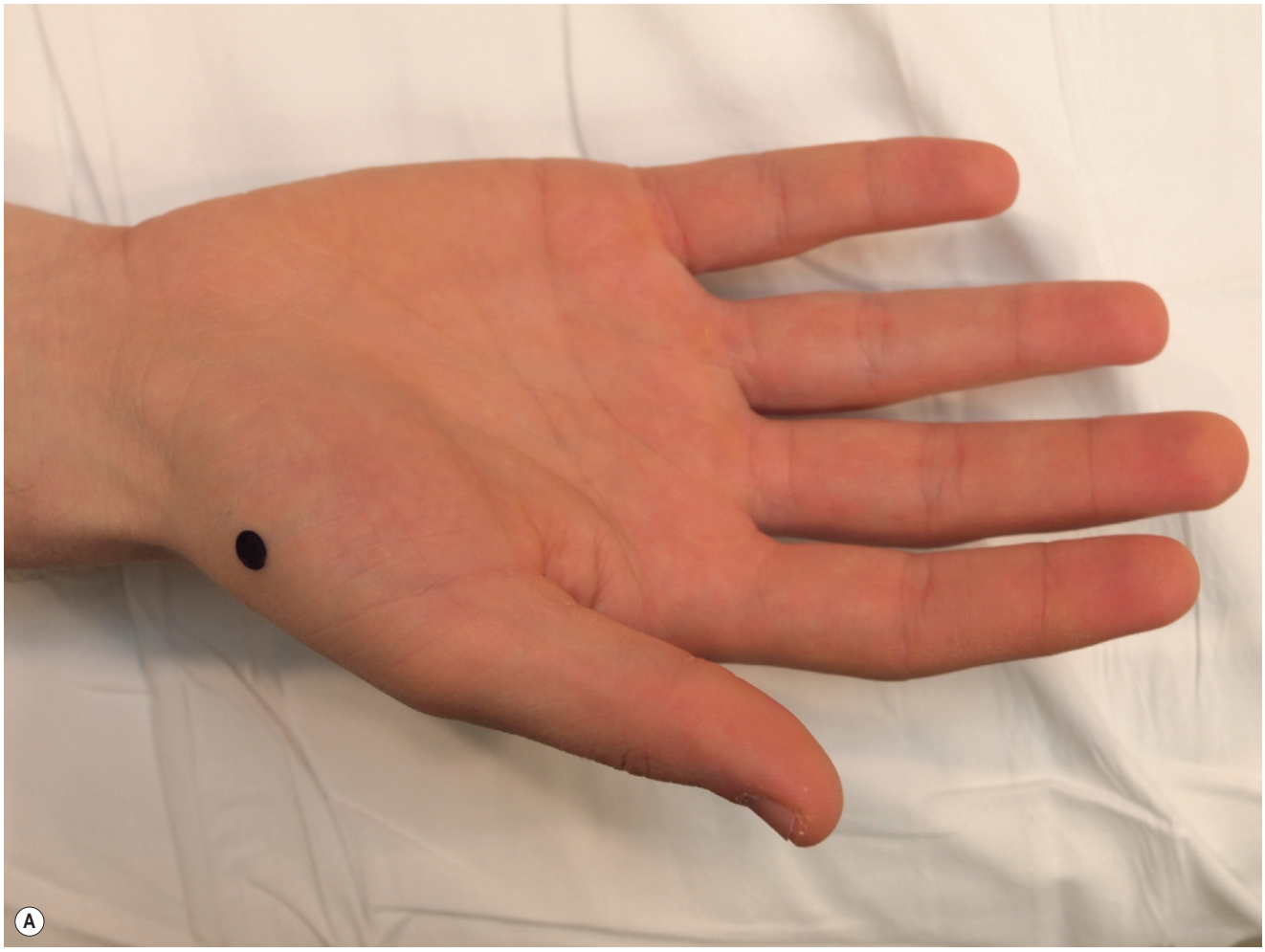


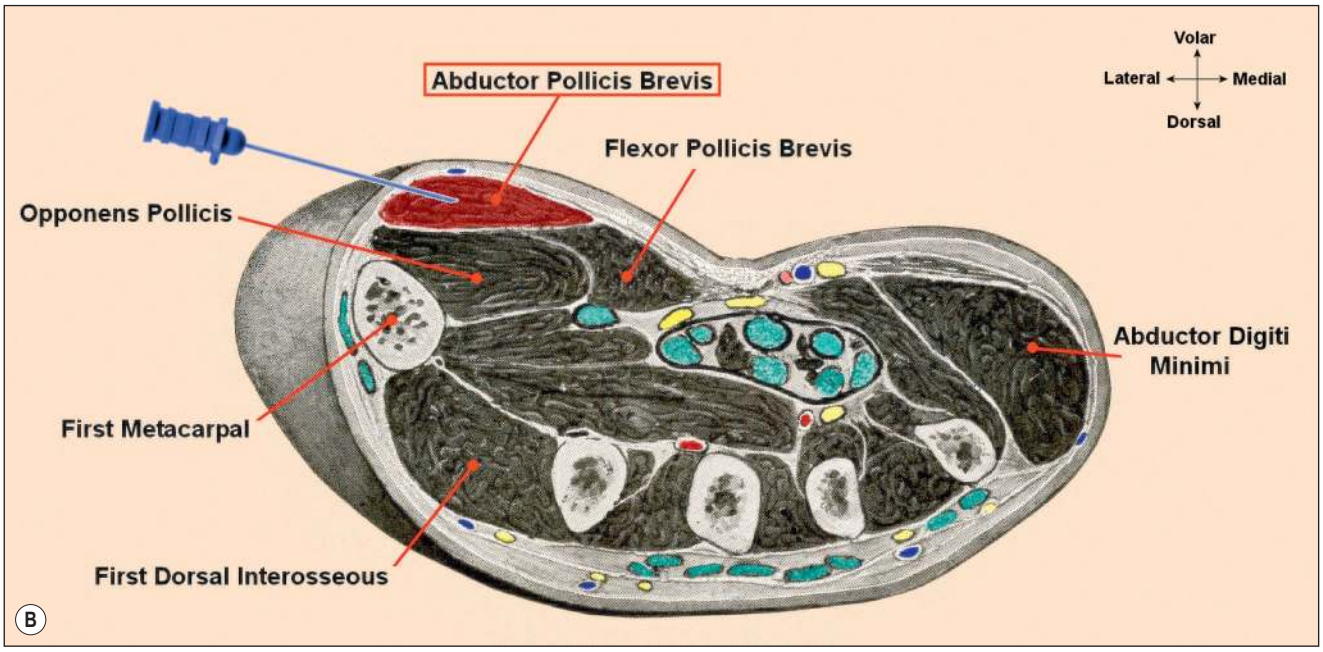
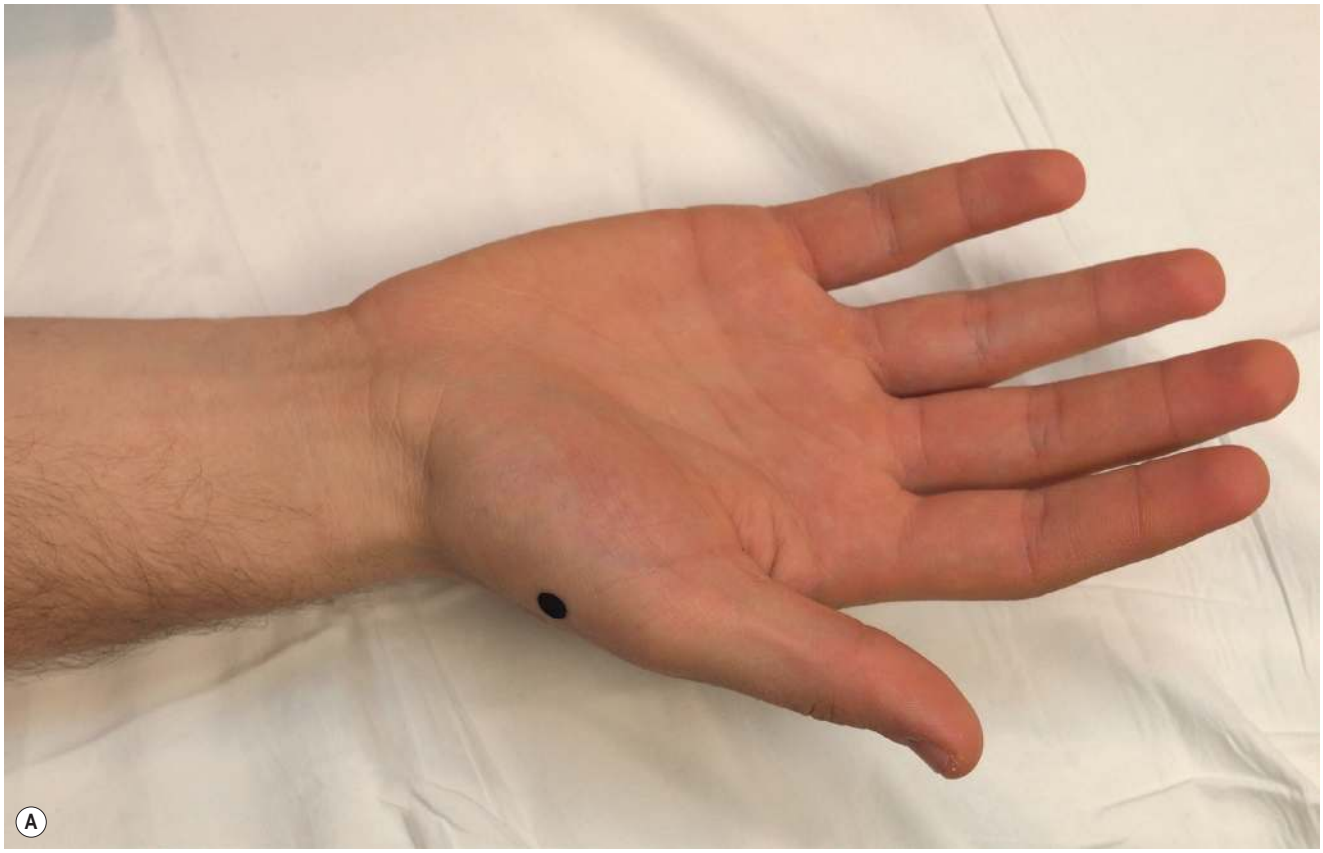


FIGURE 13–1 A. Abductor pollicis brevis insertion point.
B. Cross-section anatomy*.



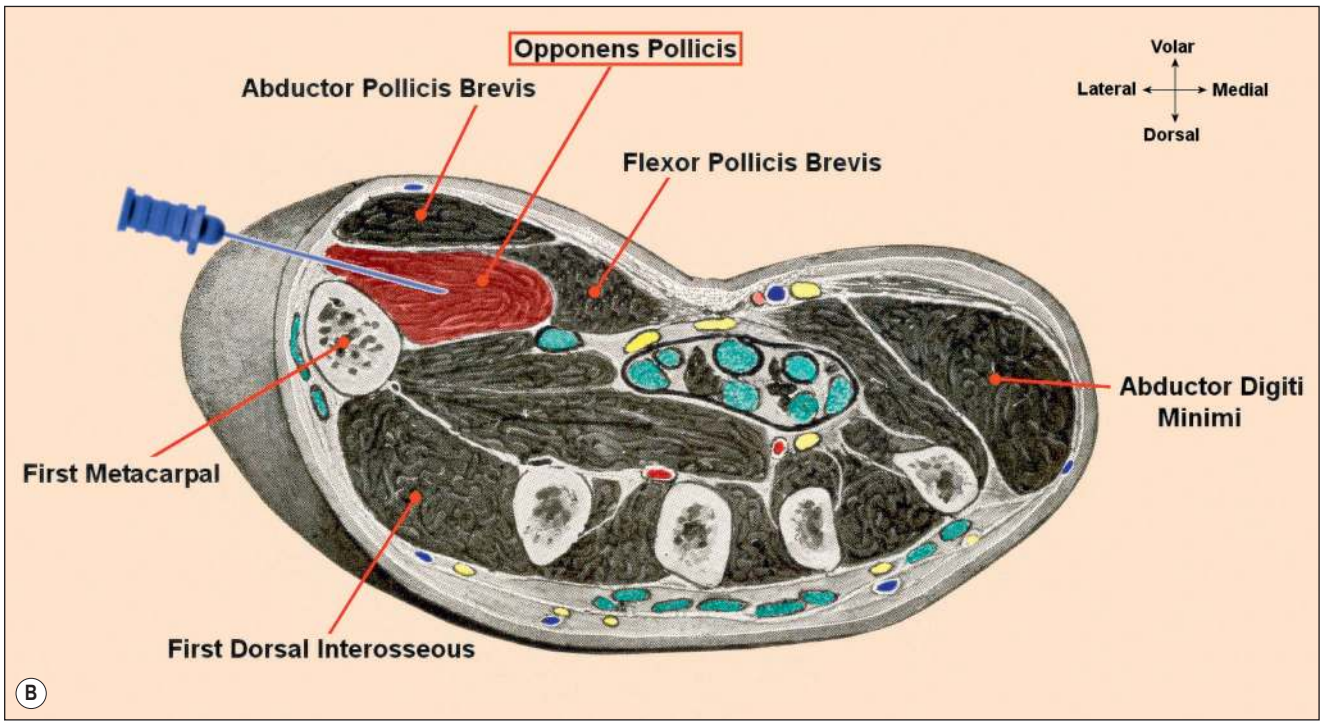


FIGURE 13–2 A. Opponens pollicis insertion point.
B. Cross-section anatomy*.

Flexor Pollicis Brevis (FPB) *(Figure 13–3A,B)*

Innervation:

Median and ulnar nerves, medial cord, lower trunk, **C8–T1**

Needle Insertion:

Insert the needle just medial to mid-point of the first metacarpal in the thenar eminence

Activation:

Have the patient flex the thumb at the metacarpal–phalangeal joint

Key Clinical Points:

- Sampling this muscle is often perceived as more painful than the APB.
- The superficial head usually is median innervated; the deep head usually is ulnar innervated.
- Innervation varies widely in normal subjects. In some individuals, both heads are median innervated; in others, both are ulnar.
- Because of normal anatomic variation, abnormalities should be interpreted with caution when trying to separate median from ulnar lesions.

Cross-section Anatomy Key Points:

- If the needle is inserted too laterally, it will be in the abductor pollicis brevis.

Pronator Quadratus (PQ) *(Figure 13–4A,B)*

Innervation:

Anterior interosseous nerve, median nerve, lateral–medial cords, middle–lower trunks, C7–**C8**–T1

Needle Insertion:

With the patient's hand in mid-position between supination and pronation, insert the needle in the patient's dorsal forearm three fingerbreadths proximal to the mid-point of a line drawn from the ulnar to radial styloids. Insert the needle deep through the interosseous membrane

Activation:

Have the patient pronate the hand with the elbow flexed

Key Clinical Points:

- May be abnormal in anterior interosseous nerve syndrome or proximal median neuropathies.
- The PQ is a distal C8 median-innervated muscle above the wrist.
- Spared in carpal tunnel syndrome.
- The muscle is deep to the finger and thumb extensor muscles and their tendons.

Cross-section Anatomy Key Points:

- Before reaching the muscle, one must go through the thick interosseous membrane.

Flexor Pollicis Longus (FPL) *(Figure 13–5A,B)*

Innervation:

Anterior interosseous nerve, median nerve, lateral–medial cords, middle–lower trunks, C7–**C8**–T1

Needle Insertion:

With the patient's forearm supinated, insert the needle straight down one-third the distance up from the lateral wrist toward the lateral elbow, over the radius

Activation:

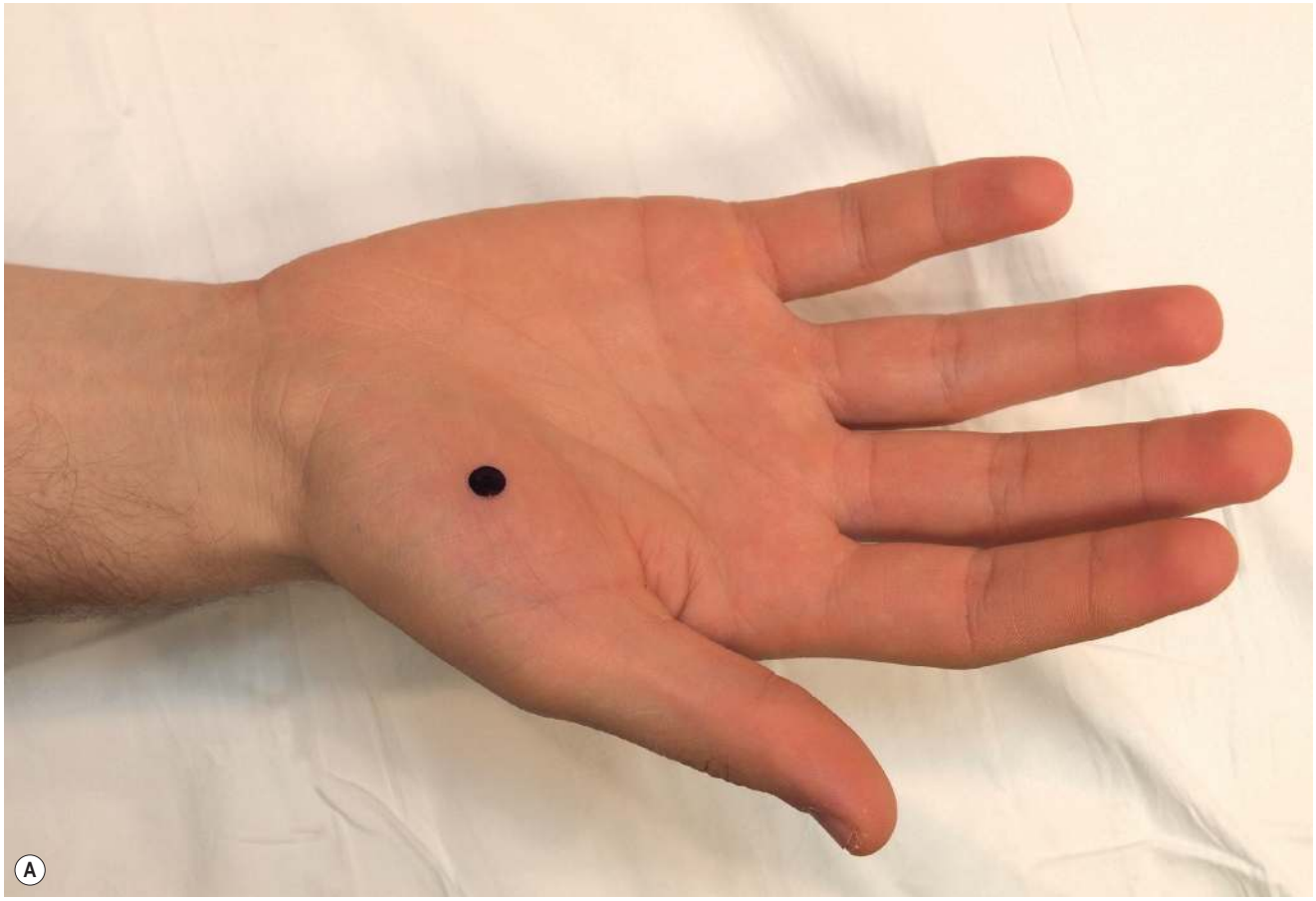
Have the patient flex the thumb at the interphalangeal joint

Key Clinical Points:

- Often abnormal in anterior interosseous nerve syndrome or proximal median neuropathies.
- The FPL is a distal C8 median-innervated muscle above the wrist.
- Spared in carpal tunnel syndrome.

Cross-section Anatomy Key Points:

- *Caution*: the radial artery is just lateral to the insertion point.
- *Caution*: the superficial radial sensory nerve is lateral to the insertion point.
- If the needle is too superficial, it may be in the flexor digitorum sublimis.



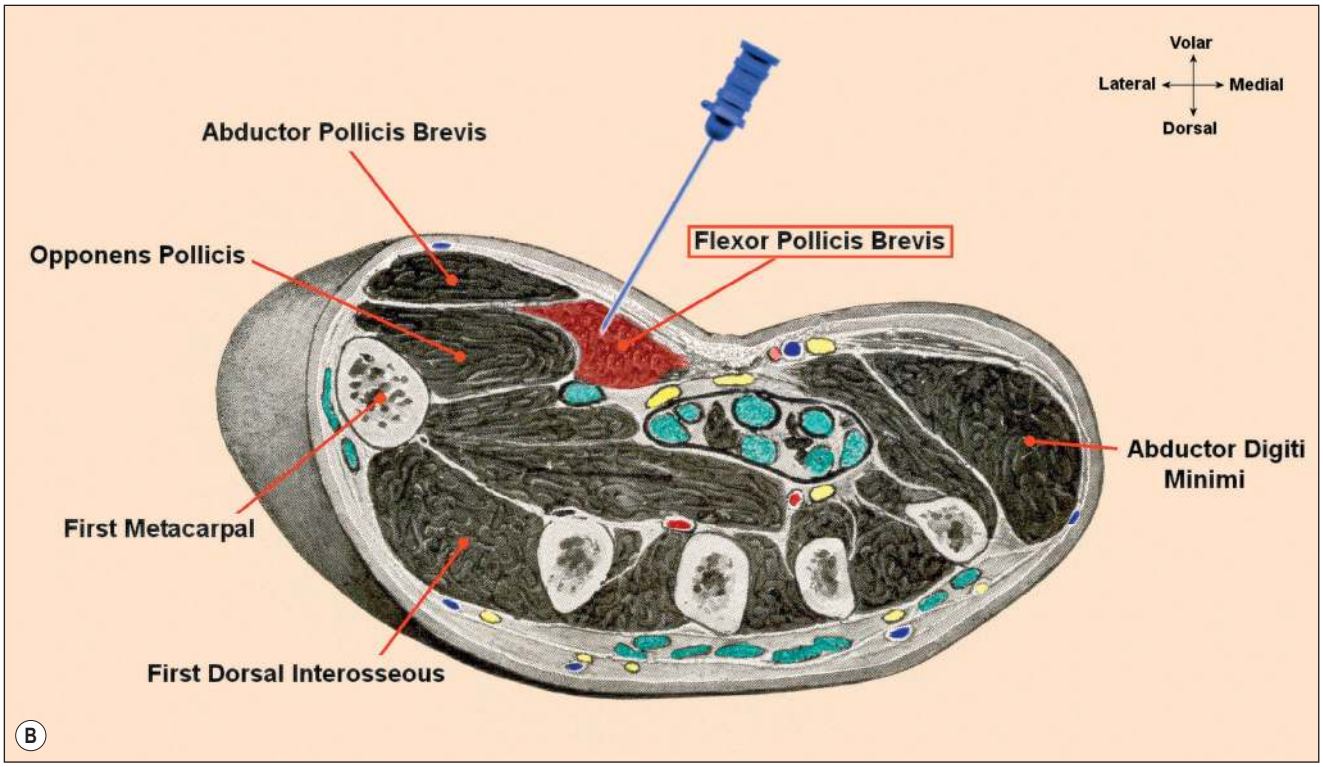
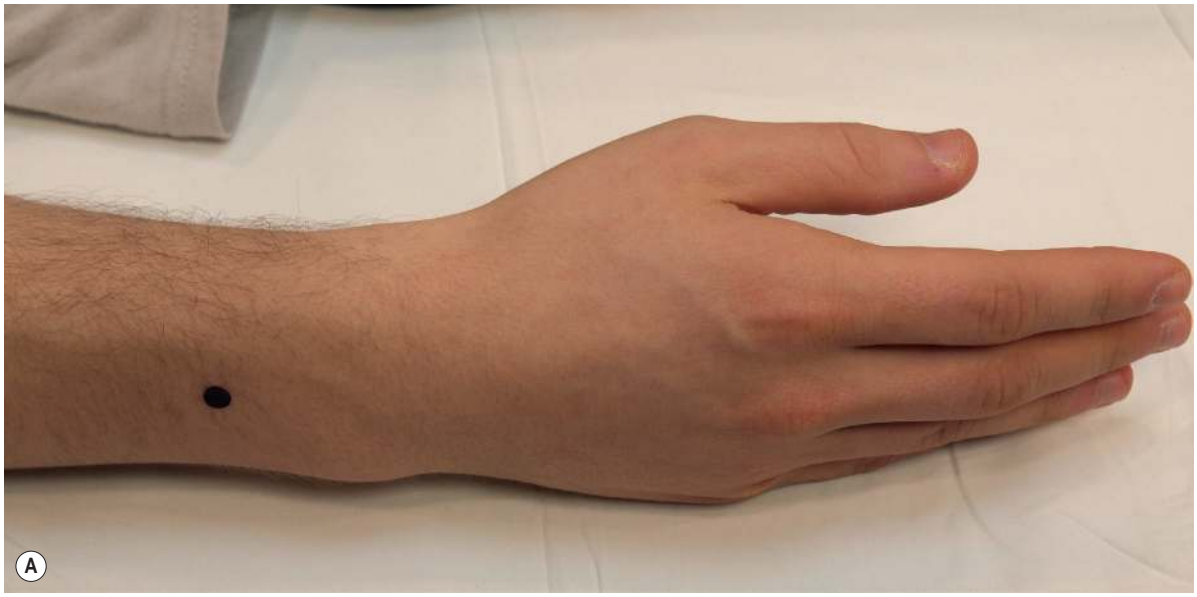


FIGURE 13–3 A. Flexor pollicis brevis insertion point.
B. Cross-section anatomy*.



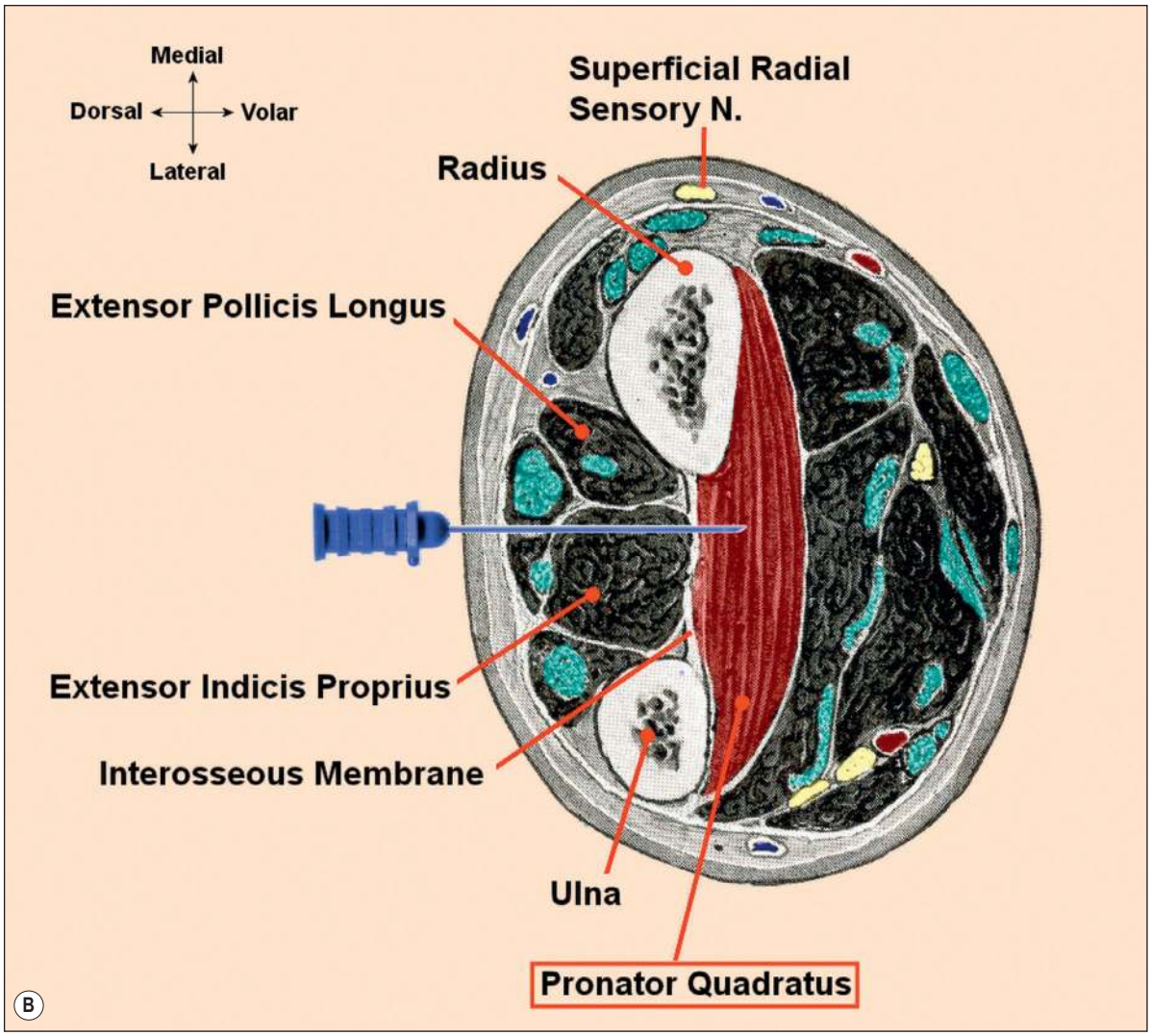
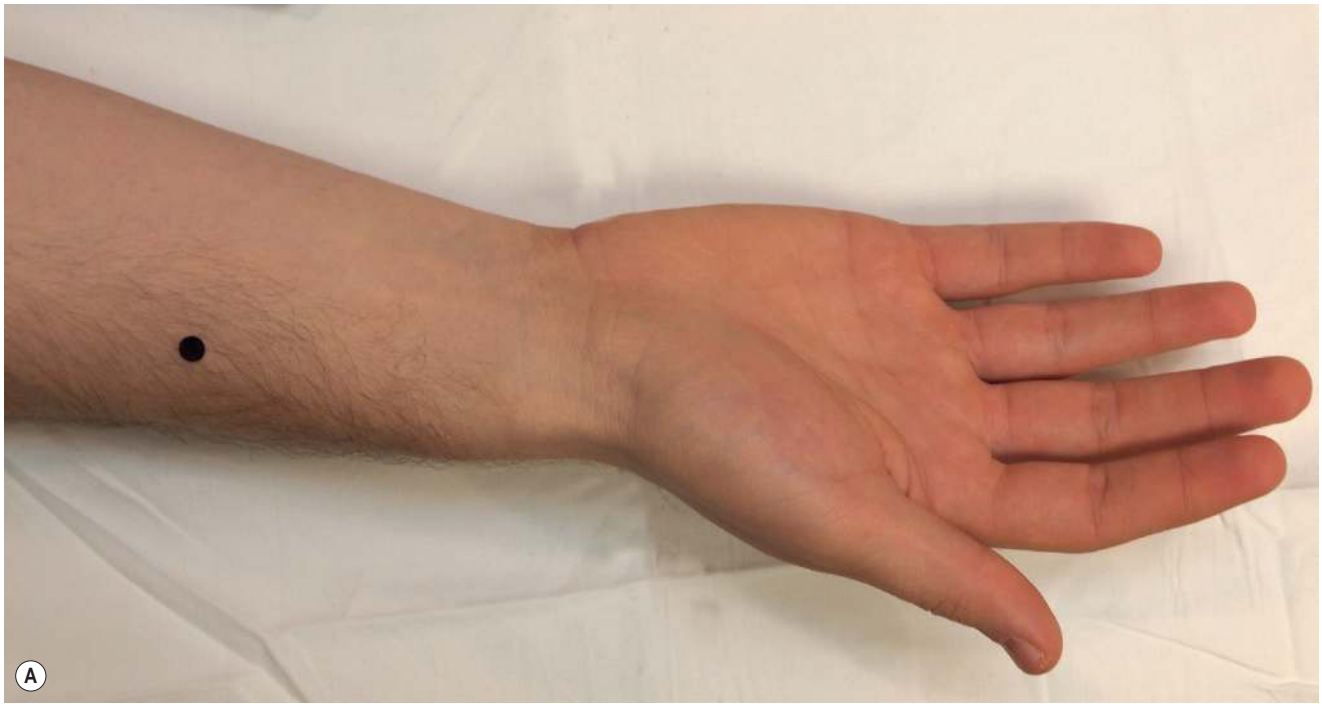


FIGURE 13–4 A. Pronator quadratus insertion point.
B. Cross-section anatomy*.



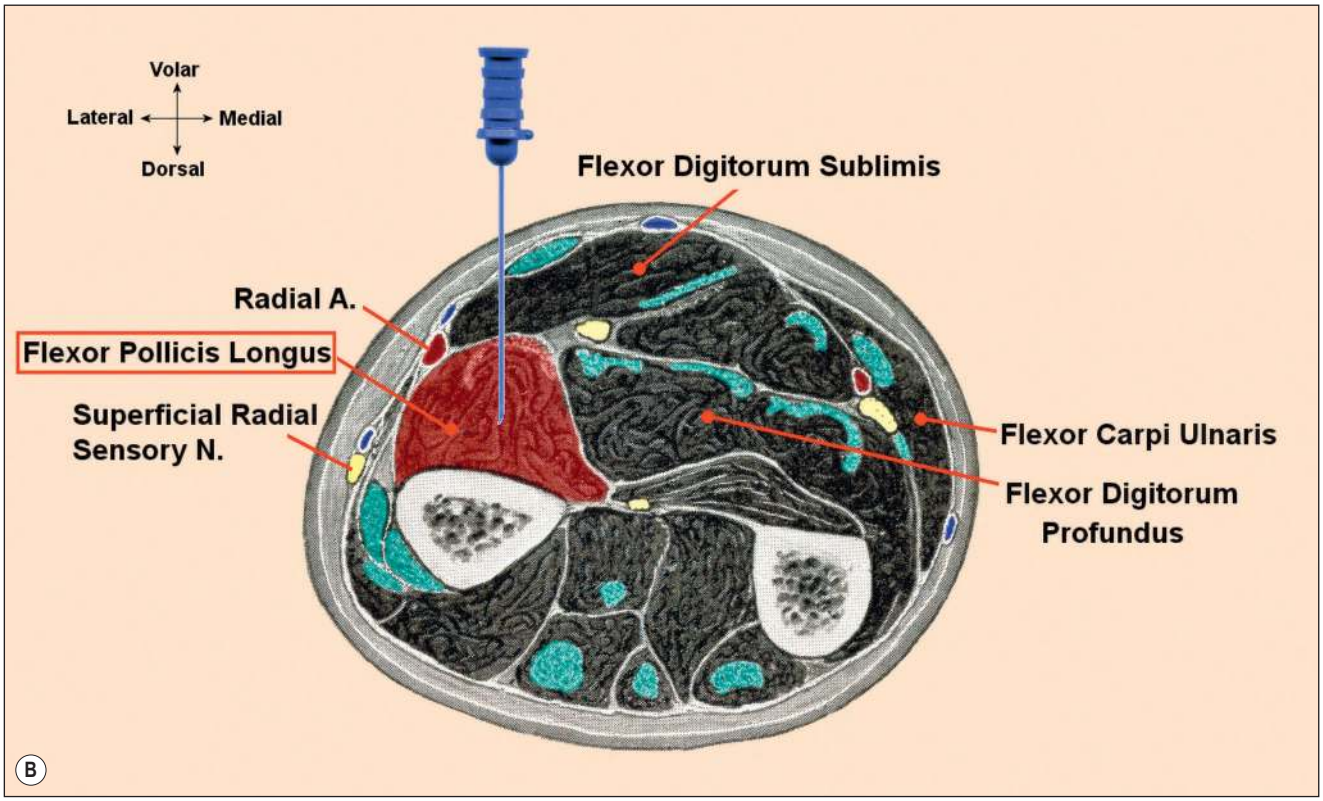


FIGURE 13–5 A. Flexor pollicis longus insertion point.
B. Cross-section anatomy*.

Flexor Digitorum Profundus to Digits 2, 3 (FDP 2, 3) *(Figure 13–6A,B)*

Innervation:

Anterior interosseous nerve, median nerve, medial cord, lower trunk, C7–**C8**–T1

Needle Insertion:

With the patient's elbow flexed, hand pointing toward the head and the back of the hand facing down, insert the needle three to four fingerbreadths distal to the olecranon

Activation:

Have the patient flex the fingers (digit 2 or digit 3) at the distal interphalangeal (DIP) joints

Key Clinical Points:

- Deeper layers are median-innervated (anterior interosseous nerve) to digits 2 and 3.
- Superficial layers are ulnar-innervated to digits 4 and 5.
- Median slips (deep) are difficult to study. The individual muscle slip can be identified by having the patient flex one finger at a time.
- The median FDP may be abnormal in anterior interosseous nerve syndrome or proximal median neuropathies.

Cross-section Anatomy Key Points:

- C*aution*: when placing the needle this deep, the main ulnar nerve is within reach of the needle. To avoid the ulnar nerve, the needle should be angled medially toward the body. Indeed, this muscle is best avoided unless it is needed to establish the diagnosis (e.g., anterior interosseous neuropathy).

Flexor Digitorum Sublimis (FDS) *(Figure 13–7A,B)*

Innervation:

Median nerve, medial–lateral cords, middle–lower trunks, C7–**C8**

Needle Insertion:

With the patient's forearm supinated, insert the needle just medial to the mid-point between the biceps tendon and the mid-wrist

Activation:

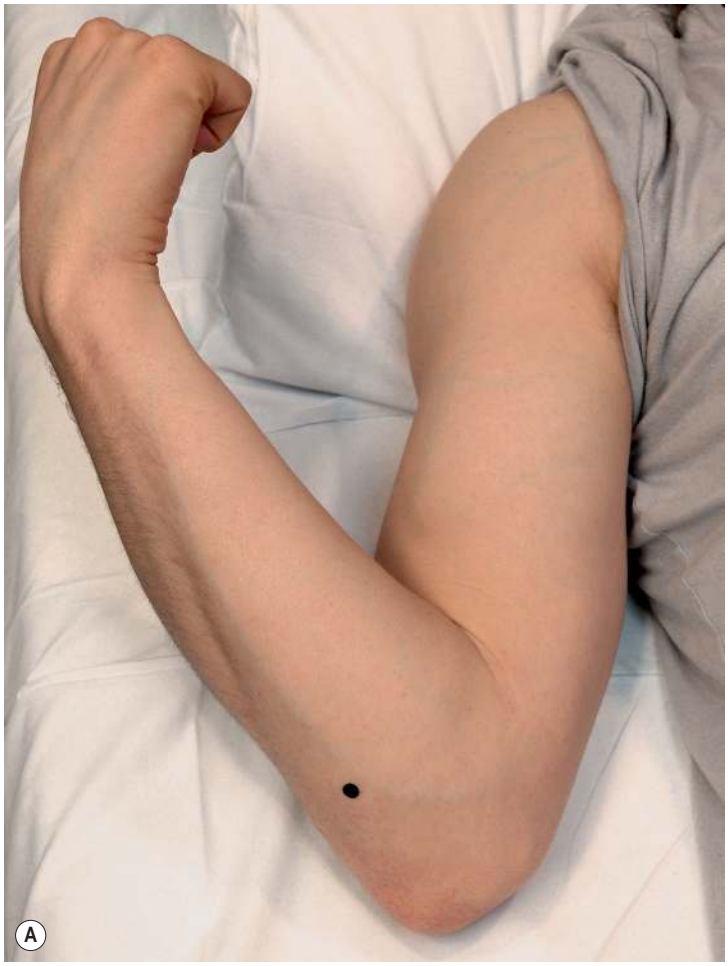
Have the patient flex the digits at the proximal interphalangeal (PIP) joints

Key Clinical Points:

- May be abnormal in proximal median neuropathies.
- Spared in anterior interosseous nerve syndrome.

Cross-section Anatomy Key Points:

- The FDS supplies digits 2–5. The slips to different fingers can be determined by placing the needle slightly lateral or medial to the original location, and having the patient move individual fingers.
- If the needle is too deep, it will be in the FDP.
- C*aution*: if the needle is placed in the midline and too deeply, it may reach the median nerve.
- More difficult muscle to localize than other proximal median muscles (e.g., FCR and PT).



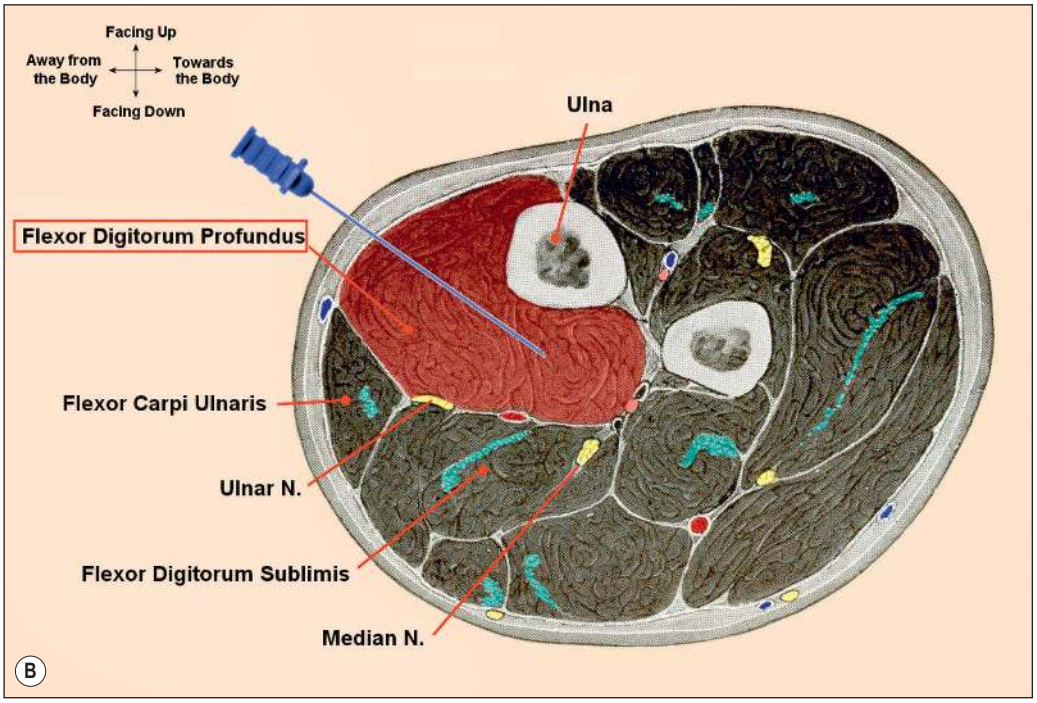


FIGURE 13–6 A. Flexor digitorum profundus to digits 2, 3 insertion point.
B. Cross-section anatomy*.

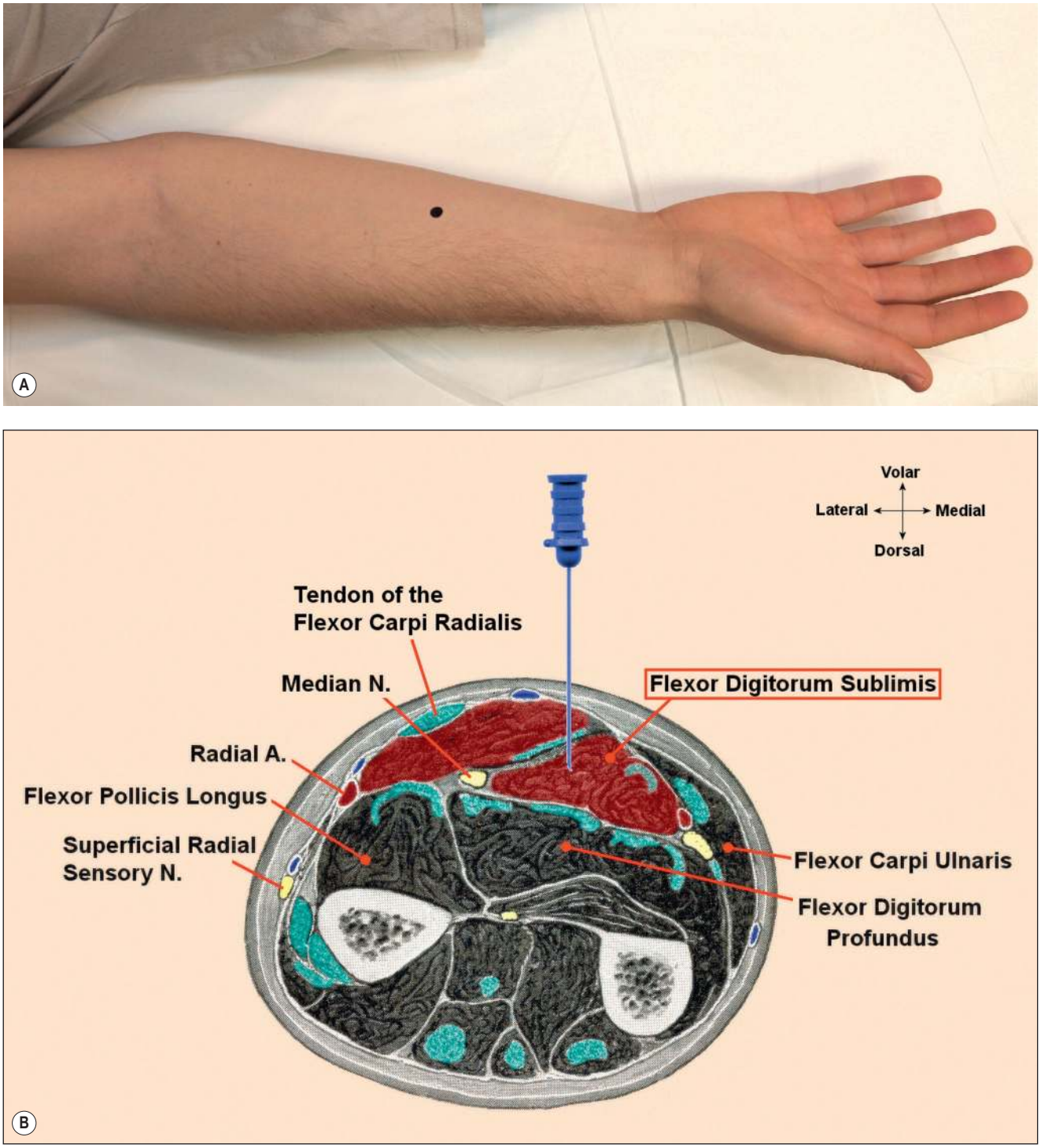


FIGURE 13–7 A. Flexor digitorum sublimis insertion point.
B. Cross-section anatomy*.

Flexor Carpi Radialis (FCR)
(Figure 13–8A,B)

Innervation:
Median nerve, lateral cord, upper–middle trunks, **C6–C7**

Needle Insertion:
With the patient's forearm supinated, insert the needle four fingerbreadths distal to the mid-point between the biceps tendon and medial epicondyle on a line to the center of the wrist

Activation:
Have the patient flex the wrist radially

Key Clinical Points:
- Often abnormal in C6 or C7 radiculopathy.
- Often abnormal in proximal median neuropathies including pronator syndrome.
- Spared in anterior interosseous nerve syndrome.

Cross-section Anatomy Key Points:
- If the needle is too medial, it may be in the FDS.
- If the needle is too lateral and deep, it may be in the PT.
- *Caution*: if the needle is placed too deeply, it may reach the median nerve.

Pronator Teres (PT) *(Figure 13–9A,B)*

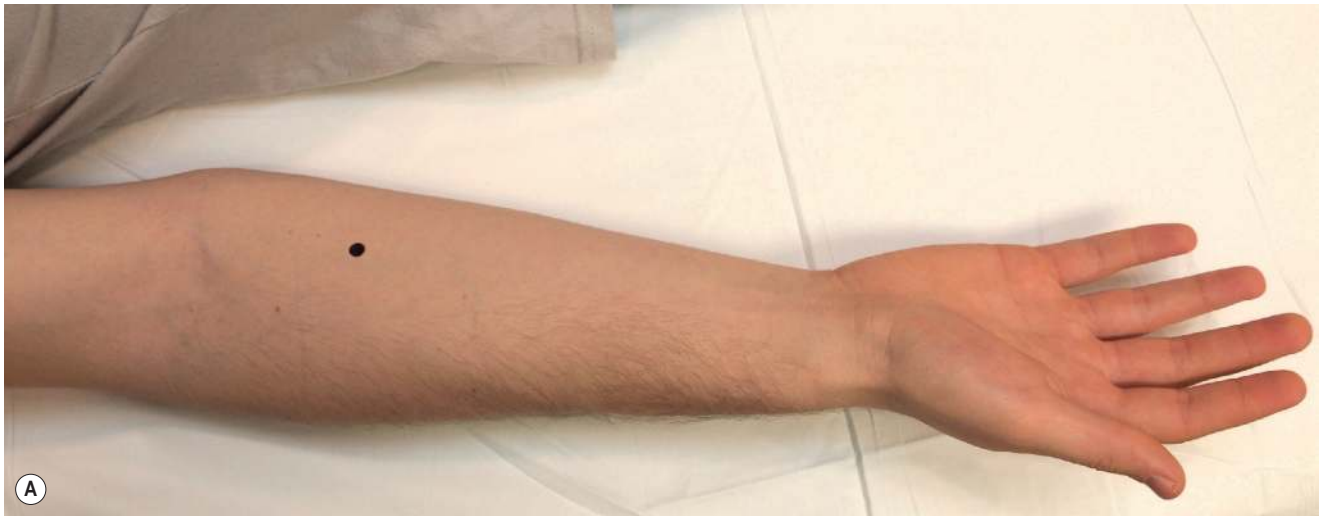
Innervation:
Median nerve, lateral cord, upper–middle trunks, **C6–C7**

Needle Insertion:
With the patient's forearm supinated, insert the needle two fingerbreadths distal to the mid-point between biceps tendon and medial epicondyle

Activation:
Have the patient pronate the hand with the elbow fully extended

Key Clinical Points:
- Often abnormal in C6 or C7 radiculopathy.
- Often abnormal in proximal median neuropathies but may be spared in pronator syndrome.
- Spared in anterior interosseous nerve syndrome.
- It is easily located and activated.

Cross-section Anatomy Key Points:
- The PT is the first muscle medial to the antecubital fossa.
- If the needle is too lateral, it will be in either the FCR or FDS.
- *Caution*: if the needle is placed deeply, it may reach the median nerve.



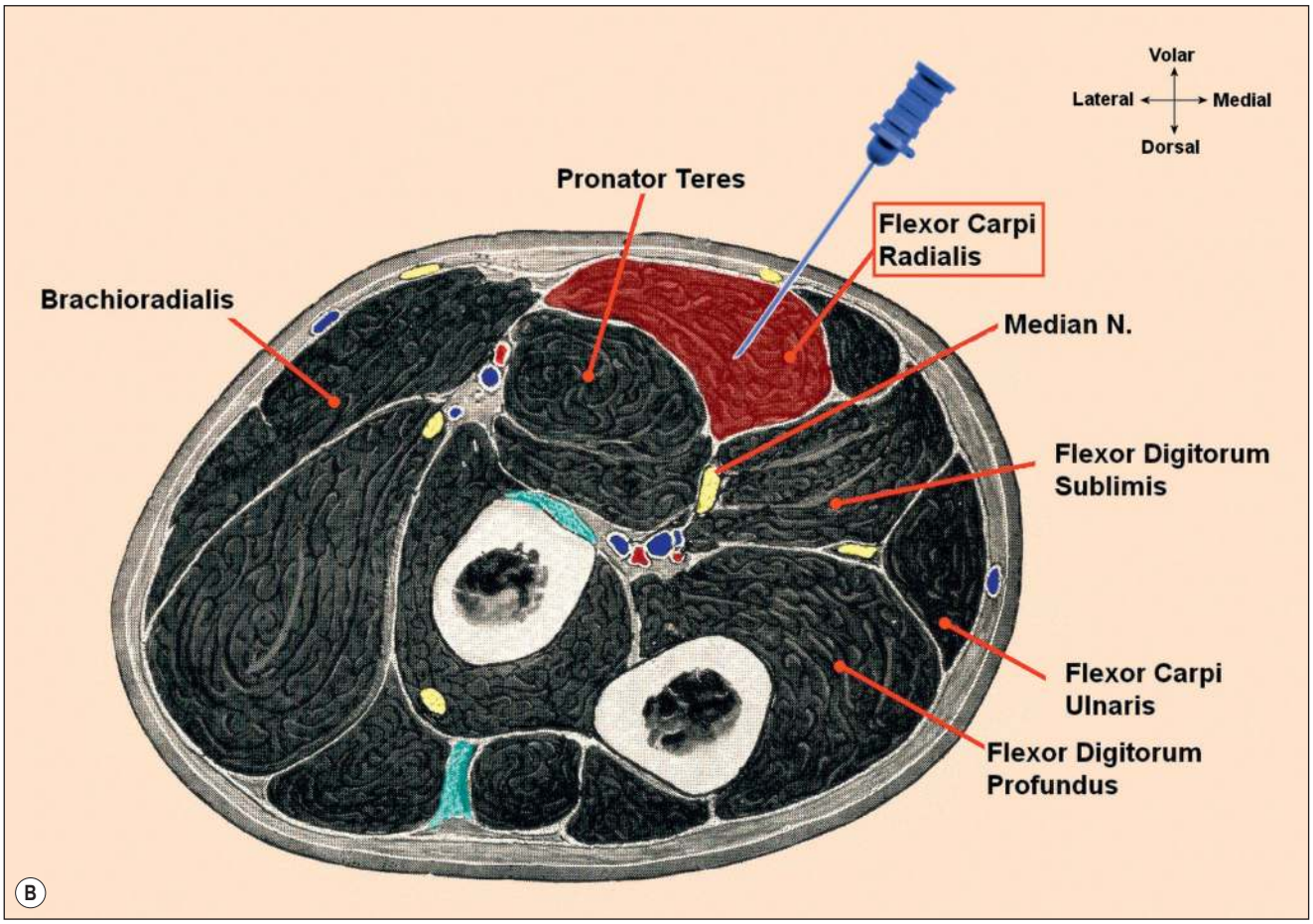
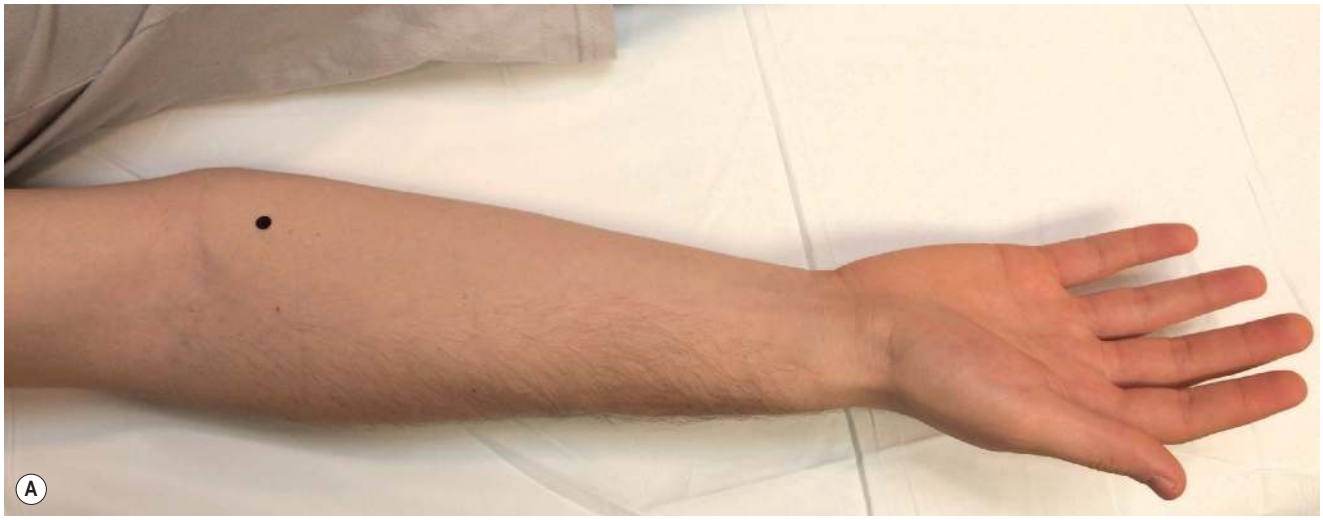


FIGURE 13–8 A. Flexor carpi radialis insertion point.
B. Cross-section anatomy*.



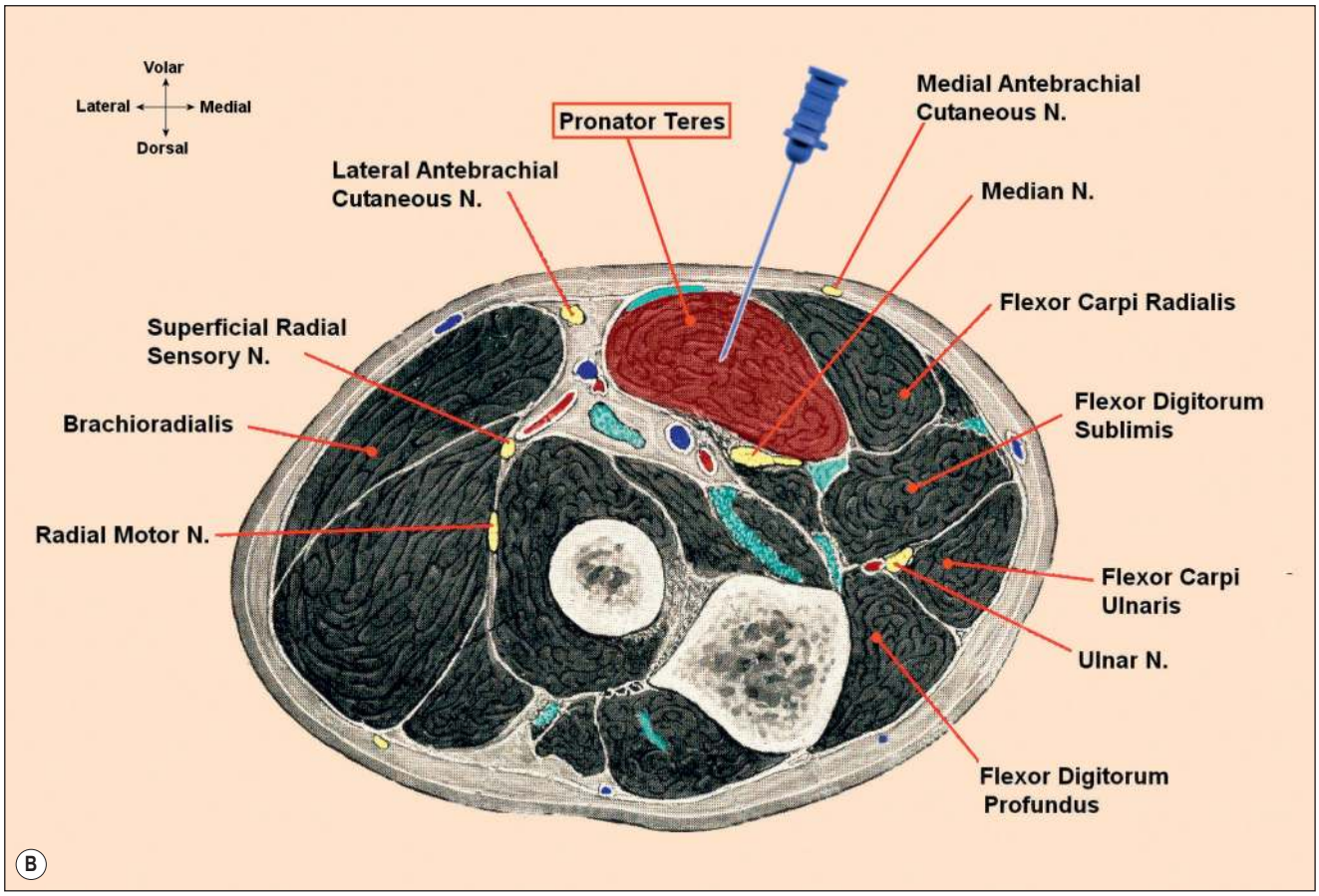


FIGURE 13–9 A. Pronator teres insertion point.
B. Cross-section anatomy*.

ULNAR NERVE

First Dorsal Interosseous (FDI)

(Figure 13–10A,B)

Innervation:

Ulnar nerve, medial cord, lower trunk, **C8–T1**

Needle Insertion:

Insert the needle into the patient's dorsal hand, halfway between the first and second metacarpal–phalangeal joints

Activation:

Have the patient abduct the index finger (spread the fingers)

Key Clinical Points:

- The FDI is easy to study.
- It is the least painful of the intrinsic hand muscles.
- Often abnormal in ulnar lesions at Guyon's canal. May be abnormal in ulnar neuropathy, lower trunk/medial cord plexopathy, thoracic outlet syndrome, C8–T1 radiculopathy, distal polyneuropathy.

Cross-section Anatomy Key Points:

- If the needle is too deep, it will be in the adductor pollicis muscle, which is also supplied by the ulnar nerve.

Abductor Digiti Minimi (ADM)

(Figure 13–11A,B)

Innervation:

Ulnar nerve, medial cord, lower trunk, **C8–T1**

Needle Insertion:

Insert the needle into the medial hand at the mid-point of the fifth metacarpal

Activation:

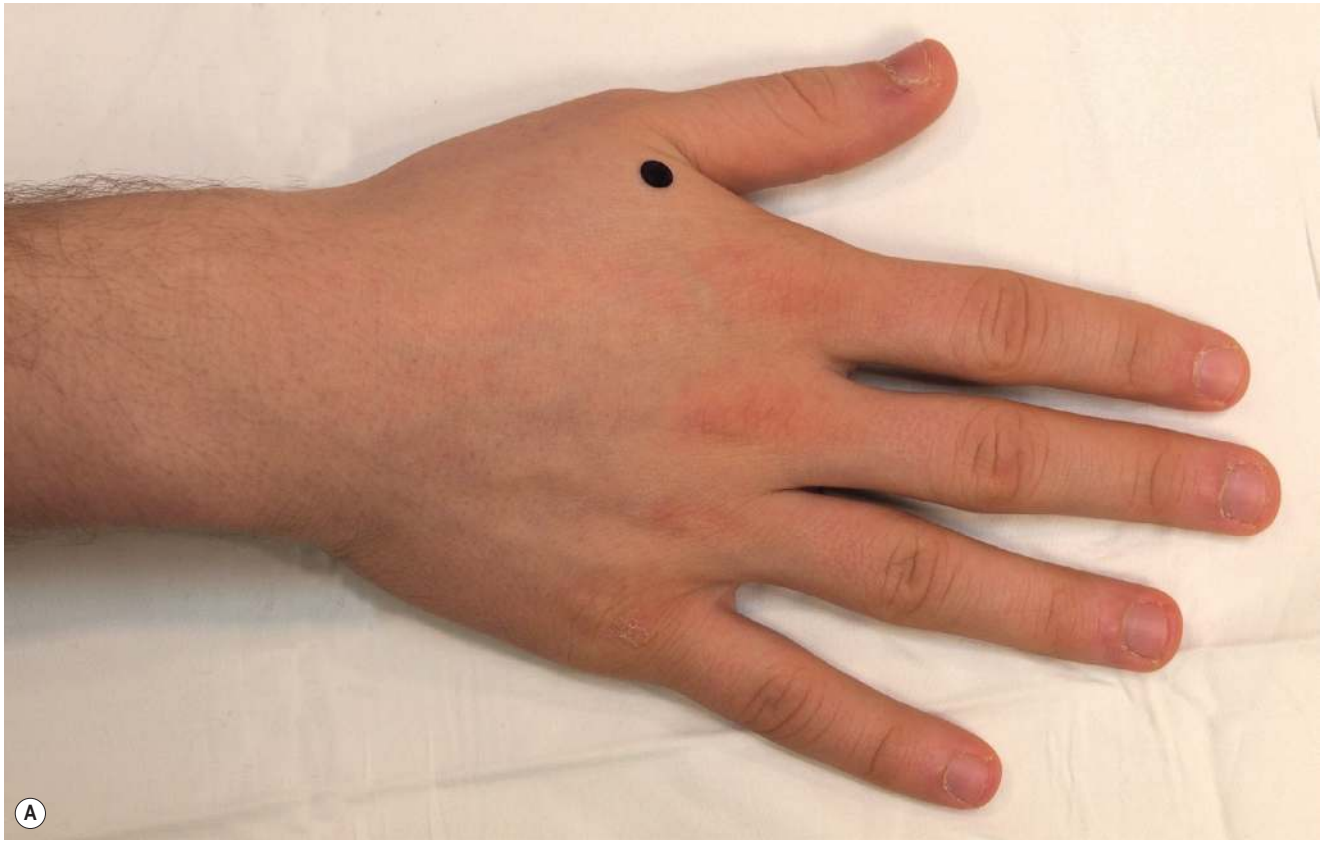
Have the patient abduct the little finger (spread the fingers)

Key Clinical Points:

- The ADM may be spared in some ulnar lesions at Guyon's canal. May be abnormal in ulnar neuropathy, lower trunk/medial cord plexopathy, thoracic outlet syndrome, C8–T1 radiculopathy, distal polyneuropathy.
- This muscle often is perceived as more painful than the FDI.

Cross-section Anatomy Key Points:

- If the needle is inserted too deeply, it will be in the flexor or opponens digiti minimi; however, both of these muscles are also supplied by the ulnar nerve in the hypothenar eminence.



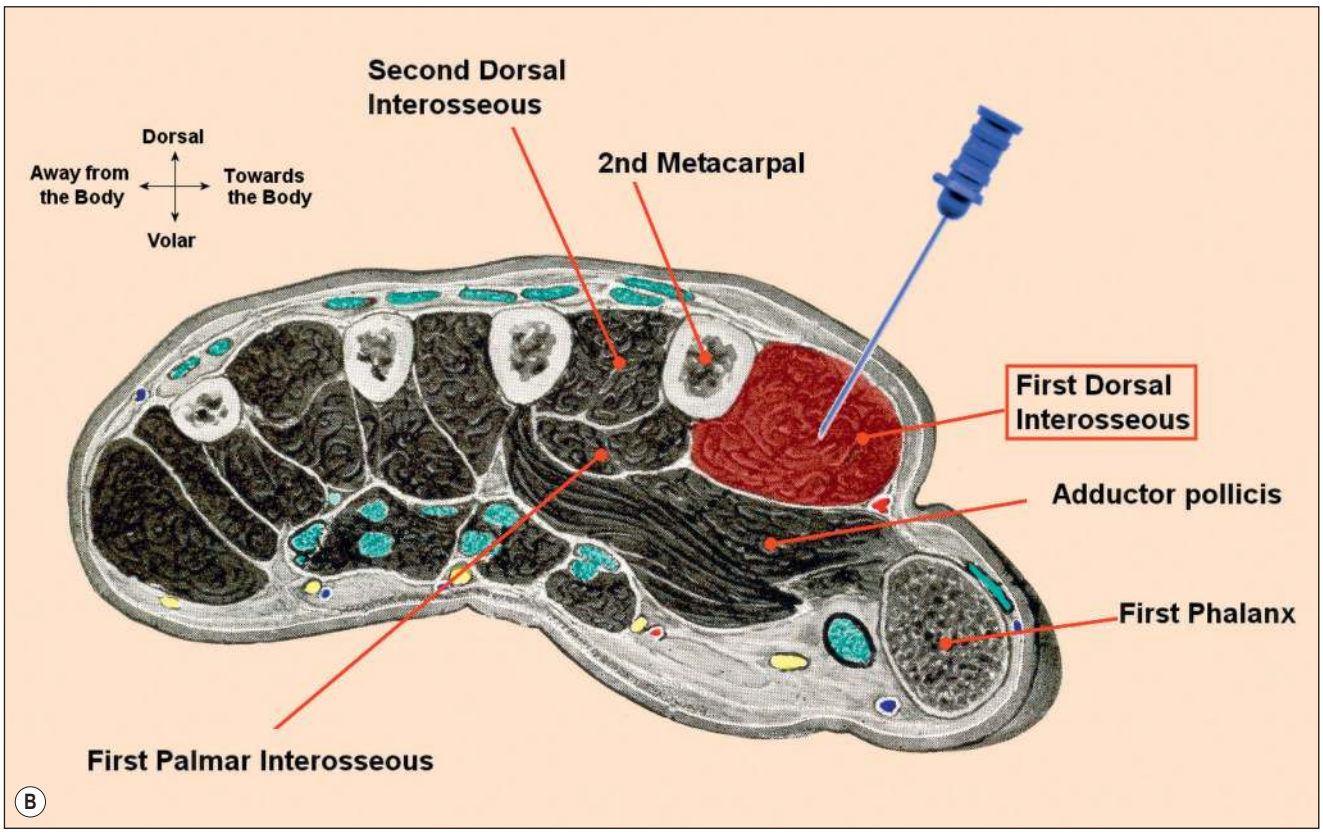


FIGURE 13–10 A. First dorsal interosseous insertion point.
B. Cross-section anatomy*.

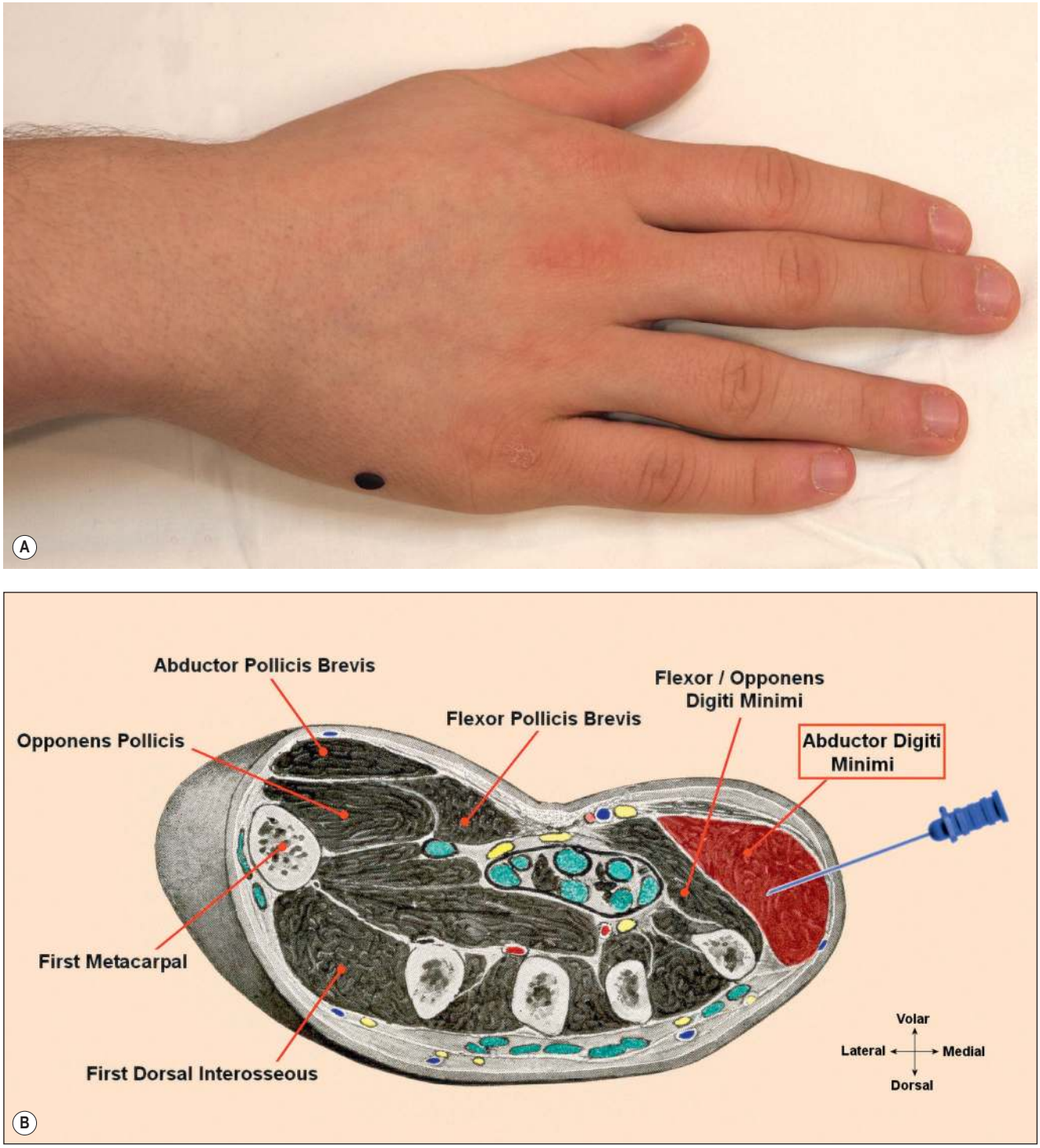


FIGURE 13–11 A. Abductor digiti minimi insertion point.
B. Cross-section anatomy*.

Flexor Digitorum Profundus to Digits 4, 5 (FDP 4, 5) *(Figure 13–12A,B)*

Innervation:

Ulnar nerve, medial cord, lower trunk, C7–C8–T1

Needle Insertion:

With the patient's elbow flexed, hand pointing toward the head and the back of the hand facing down, insert the needle three to four fingerbreadths distal to the olecranon

Activation:

Have the patient flex the fingers at the DIP joints

Key Clinical Points:

- Superficial layers are ulnar-innervated to digits 4 and 5.
- Deeper layers are median-innervated (anterior interosseous nerve) to digits 2 and 3.
- Ulnar slips (superficial) are easy to study. The individual muscle slip can be identified by having the patient flex one finger at a time.
- The ulnar FDP often is involved in ulnar neuropathy at the elbow.

Cross-section Anatomy Key Points:

- C*aution*: the main ulnar nerve is within reach of the needle. To avoid the ulnar nerve, the needle should be angled slightly medially toward the body.

Flexor Carpi Ulnaris (FCU) *(Figure 13–13A,B)*

Innervation:

Ulnar nerve, medial cord, lower trunk, C8–T1

Needle Insertion:

With the patient's forearm supinated, insert the needle into the medial forearm at the mid-point between the elbow and wrist

Activation:

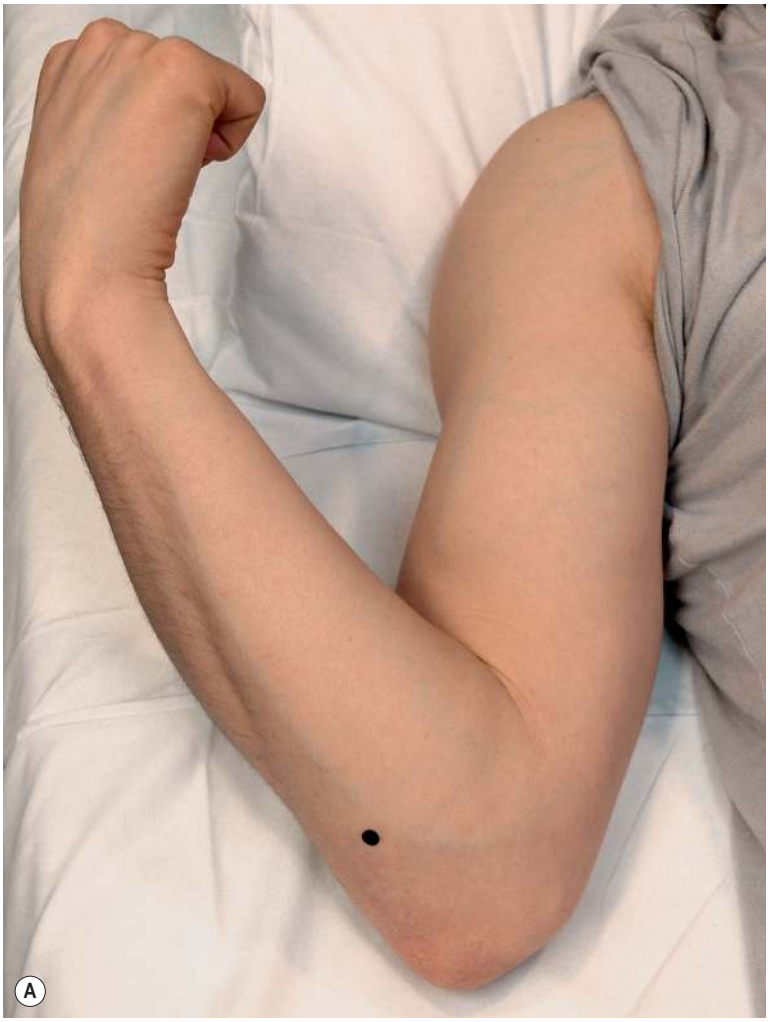
Have the patient flex the wrist in ulnar deviation or abduct the fifth finger

Key Clinical Points:

- To ensure the proper needle location, ask the patient to spread his or her fingers. During fifth-finger abduction, the FCU contracts to fix the pisiform bone, the origin of the ADM.
- The FCU muscle is very superficial and thin.
- The muscle often is spared in ulnar neuropathy at the elbow, especially in mild cases.

Cross-section Anatomy Key Points:

- If the needle is inserted too deeply, it will be in the FDP.



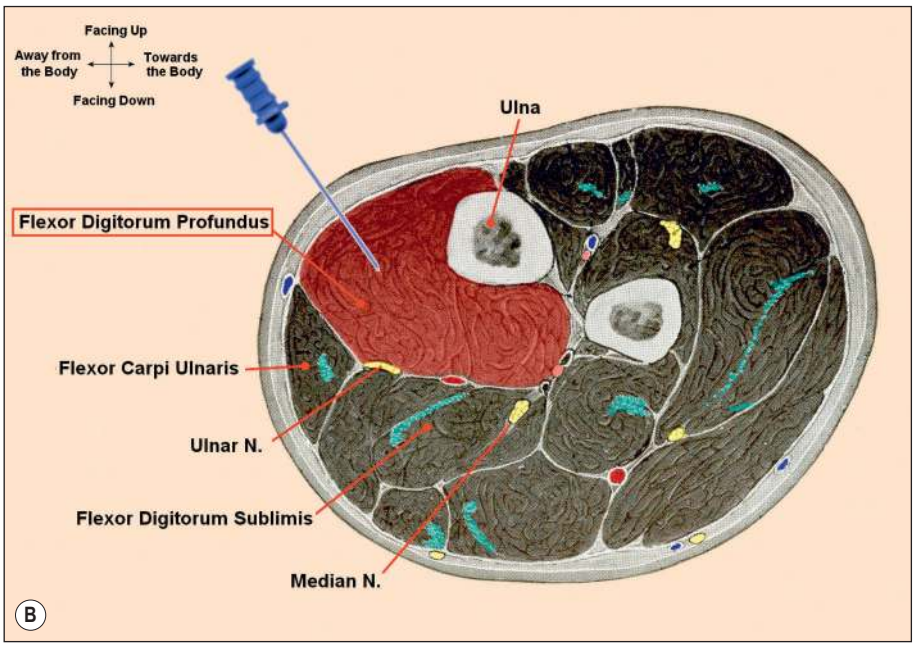
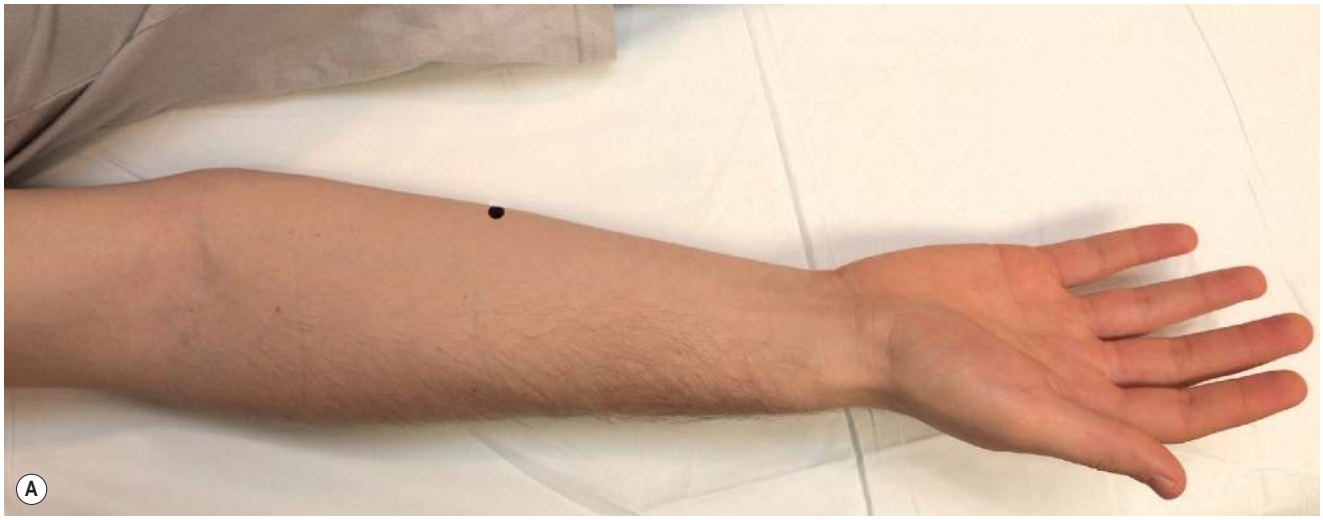


FIGURE 13–12 A. Flexor digitorum profundus to digits 4, 5 insertion point.
B. Cross-section anatomy*.



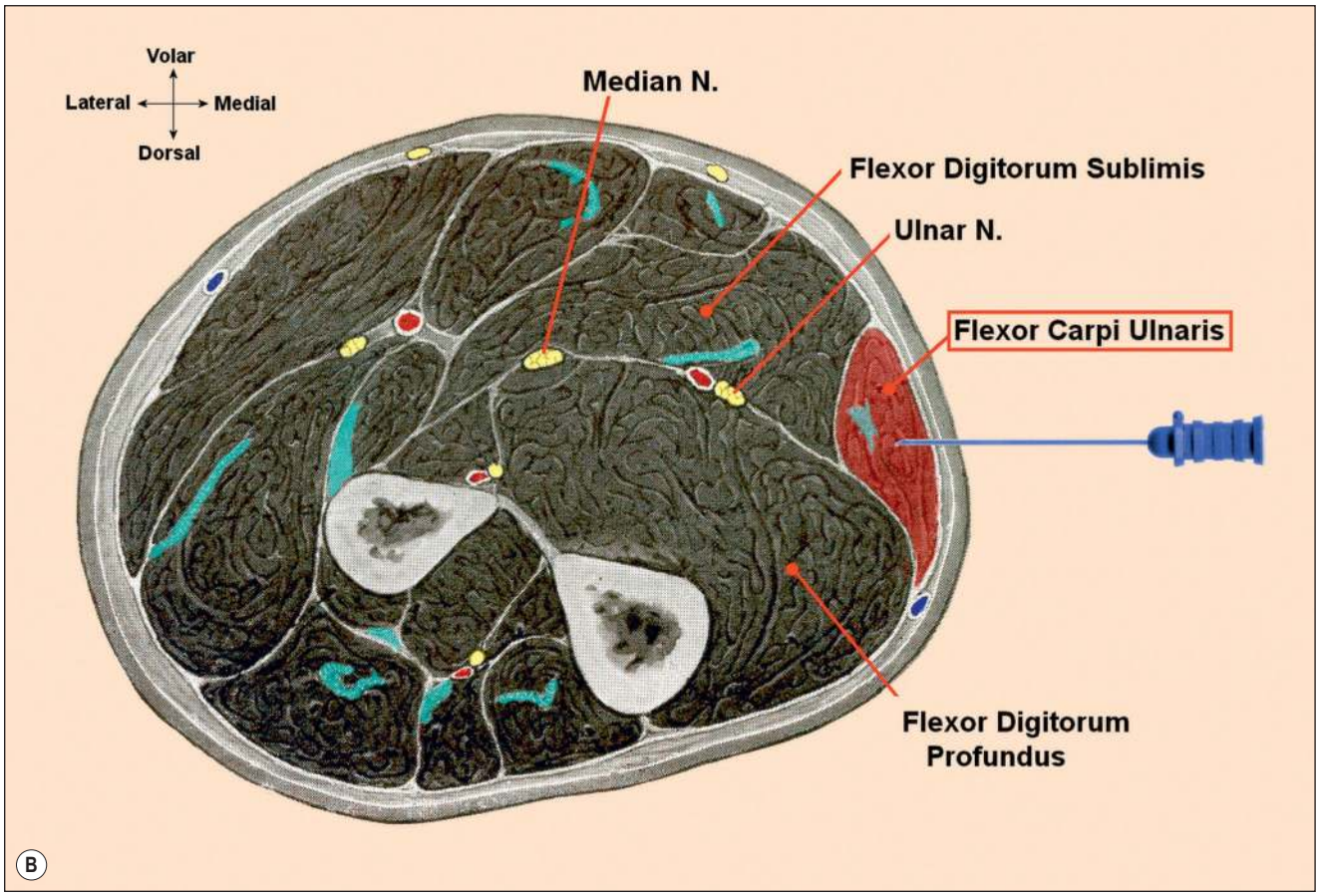


FIGURE 13–13 A. Flexor carpi ulnaris insertion point.
B. Cross-section anatomy*.

RADIAL NERVE

Extensor Indicis Proprius (EIP)

(Figure 13–14A,B)

Innervation:

Posterior interosseous nerve, radial nerve, posterior cord, middle–lower trunks, C7–**C8**

Needle Insertion:

With the patient's hand and forearm pronated, insert the needle straight down slightly medial to the point two fingerbreadths proximal to the ulnar styloid

Activation:

Have the patient extend the index finger

Key Clinical Points:

- Can be abnormal in all radial nerve lesions, including posterior interosseous nerve palsy.
- The EIP is the most distal radial innervated muscle.
- May be abnormal in lower trunk/posterior cord plexopathy, thoracic outlet syndrome, C8 radiculopathy, distal polyneuropathy.

Cross-section Anatomy Key Points:

- If the needle is too superficial, it will be in the extensor carpi ulnaris or extensor digiti quinti.
- The needle passes near several superficial tendons.

Extensor Carpi Ulnaris (ECU)

(Figure 13–15A,B)

Innervation:

Posterior interosseous nerve, radial nerve, posterior cord, middle–lower trunks, C7–**C8**

Needle Insertion:

With the patient's forearm pronated, insert the needle just rostral to the mid-point of the ulna

Activation:

Have the patient extend the wrist in ulnar deviation

Key Clinical Points:

- Can be abnormal in all radial nerve lesions, including posterior interosseous nerve palsy.
- May be abnormal in lower trunk/posterior cord plexopathy, thoracic outlet syndrome, C7–C8 radiculopathy, distal polyneuropathy.

Cross-section Anatomy Key Points:

- If the needle is too medial, it will be in the extensor digiti quinti or extensor digitorum communis.

Extensor Digitorum Communis (EDC)

(Figure 13–16A,B)

Innervation:

Posterior interosseous nerve, radial nerve, posterior cord, middle–lower trunks, **C7**–C8

Needle Insertion:

With the patient's forearm pronated, insert the needle three to four fingerbreadths distal to the olecranon, three fingerbreadths above the ulna

Activation:

Have the patient extend the middle finger

Key Clinical Points:

- The EDC is easily palpated when the patient activates the muscle.
- Can be abnormal in all radial nerve lesions, including posterior interosseous nerve palsy.
- This muscle often is selected for study for single-fiber electromyography (EMG).

Cross-section Anatomy Key Points:

- If the needle is too lateral, it may be in the ECU.
- If the needle is too medial, it may be in the ECR.
- *Caution*: if the needle is placed too deeply, it may reach the radial motor nerve. However, the muscle is very easy to sample just below the surface.

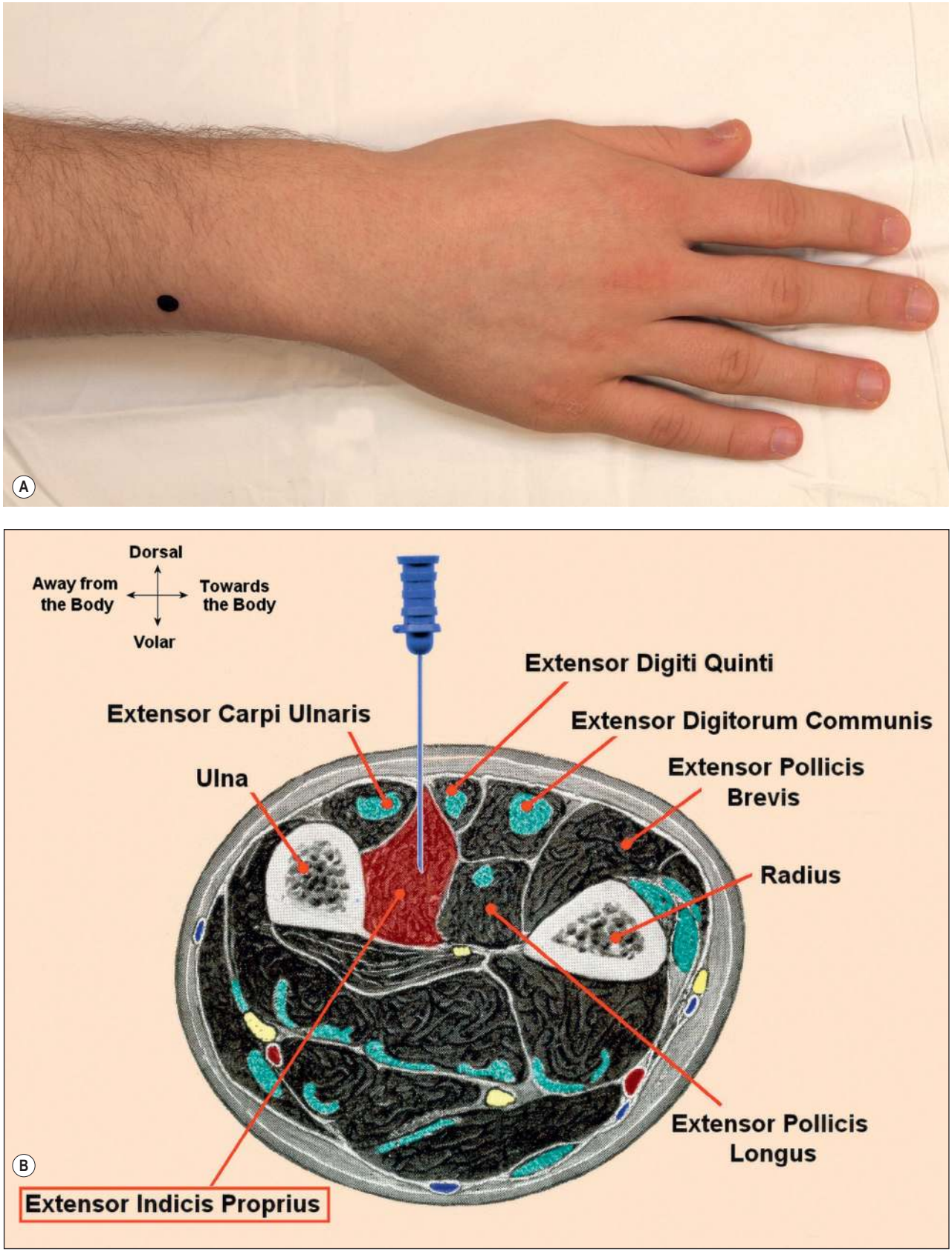
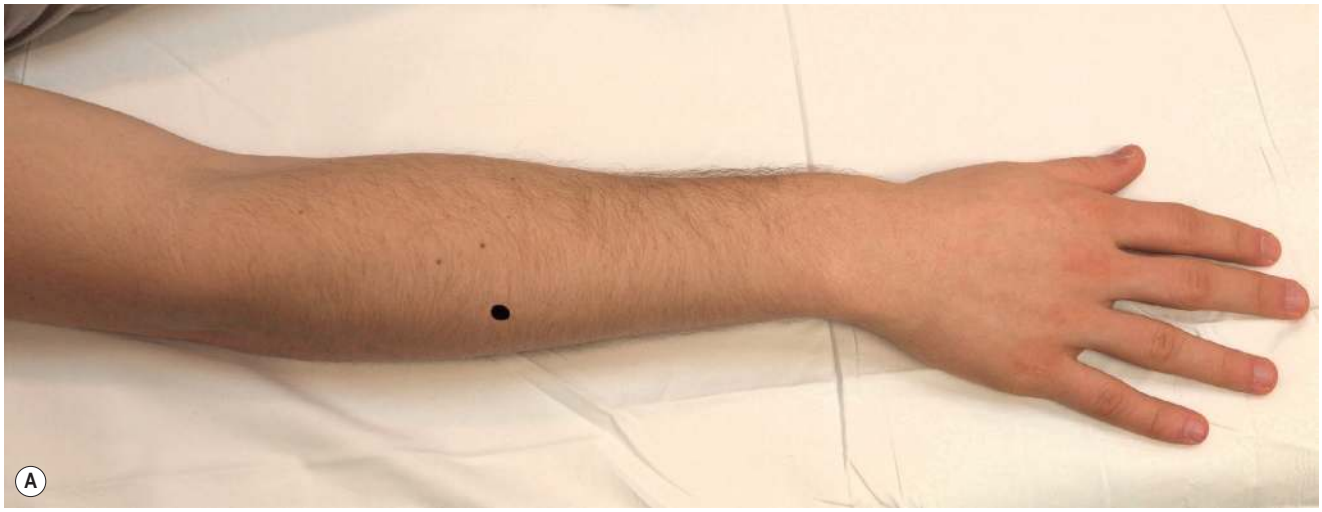


FIGURE 13–14 A. Extensor indicis proprius insertion point.
B. Cross-section anatomy*.



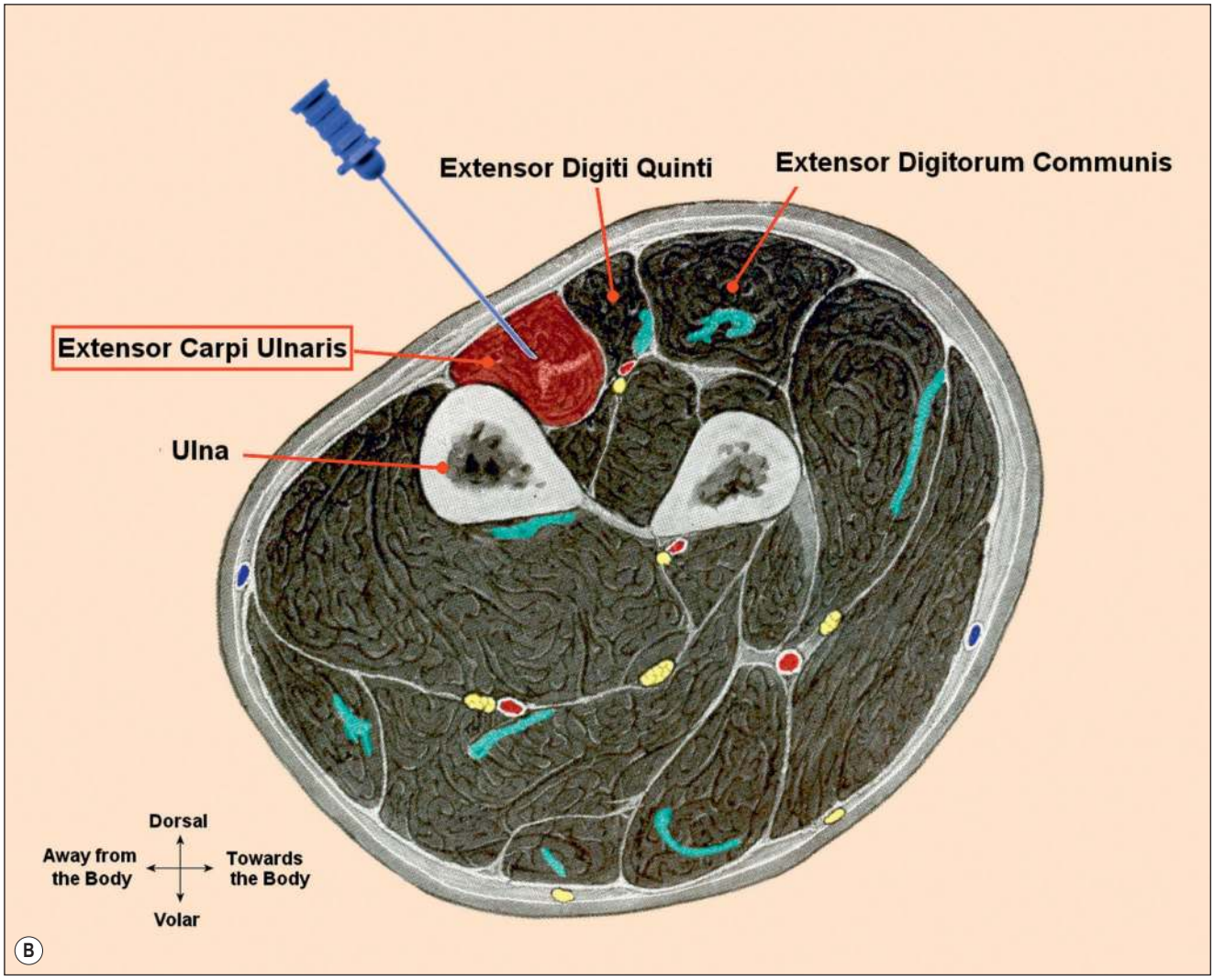


FIGURE 13–15 A. Extensor carpi ulnaris insertion point.
B. Cross-section anatomy*.

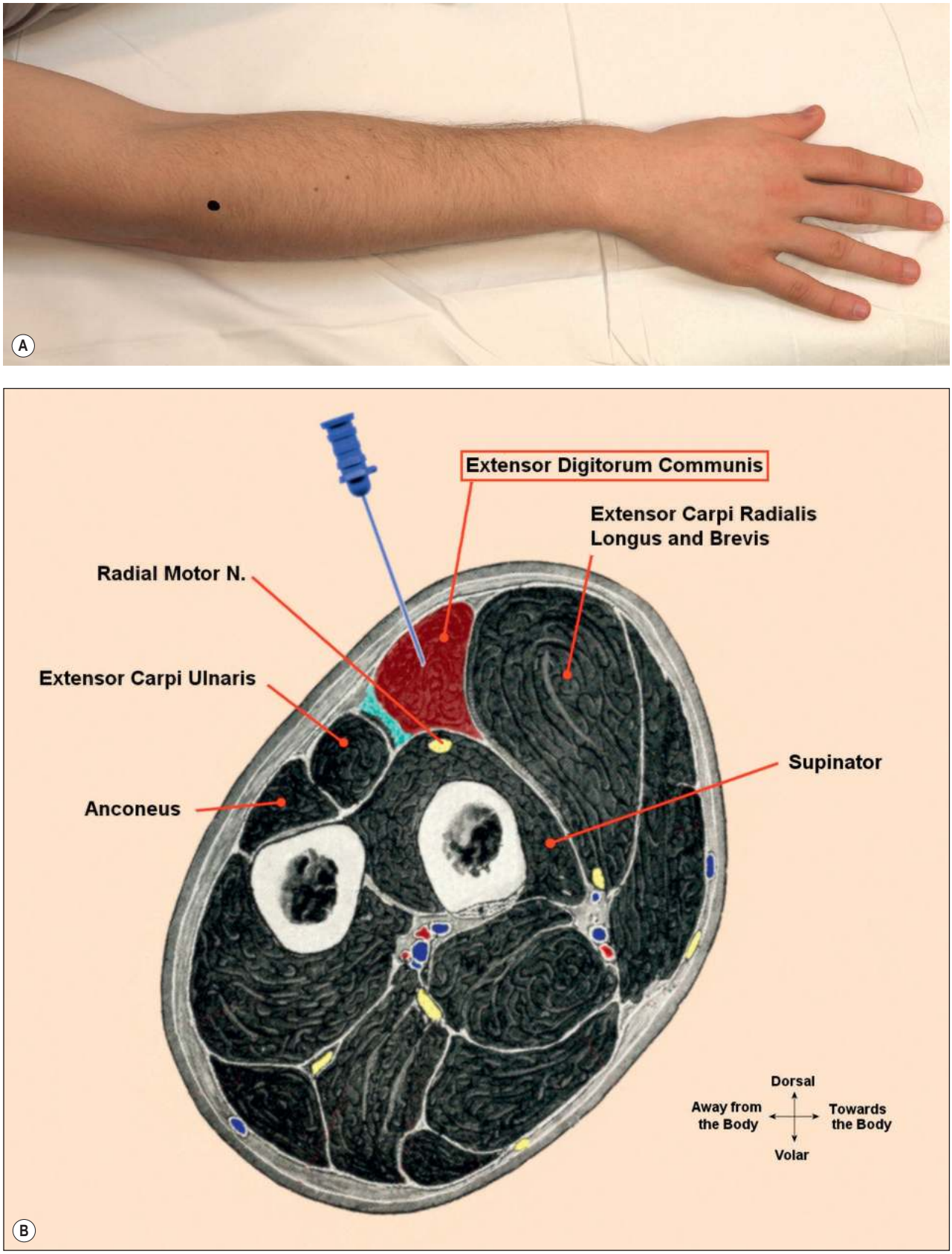


FIGURE 13–16 A. Extensor digitorum communis insertion point.
B. Cross-section anatomy*.

Extensor Carpi Radialis–Long Head (ECR–LH) *(Figure 13–17A,B)*

Innervation:

Radial nerve, posterior cord, upper–middle trunks, **C6–C7**

Needle Insertion:

With the patient's forearm pronated, insert the needle just above the lateral epicondyle

Activation:

Have the patient extend the wrist radially

Key Clinical Points:

- The long head of the ECR is the only forearm extensor spared in posterior interosseous nerve palsy.
- May be abnormal in radial nerve lesions at or proximal to the spiral groove.

Cross-section Anatomy Key Points:

- If the needle is inserted distally into the extensor mass, it is difficult to separate this muscle from other wrist and finger extensors innervated by the posterior interosseous nerve.
- If the needle is inserted too medially, it will be in the brachioradialis.

Brachioradialis (BR) *(Figure 13–18A,B)*

Innervation:

Radial nerve, posterior cord, upper trunk, **C5–C6**

Needle Insertion:

Insert the needle three to four fingerbreadths distal to the mid-point between the biceps tendon and lateral epicondyle

Activation:

Have the patient flex the elbow with the wrist in the mid-position between supination and pronation

Key Clinical Points:

- May be abnormal in lesions of the radial nerve at or proximal to the spiral groove.
- Spared in posterior interosseous nerve palsy.
- May be abnormal in upper trunk plexopathy or C5 or C6 radiculopathy.

Cross-section Anatomy Key Points:

- The BR is the first muscle lateral to the antecubital fossa.
- If the needle is too lateral and deep, it will be in the ECR.

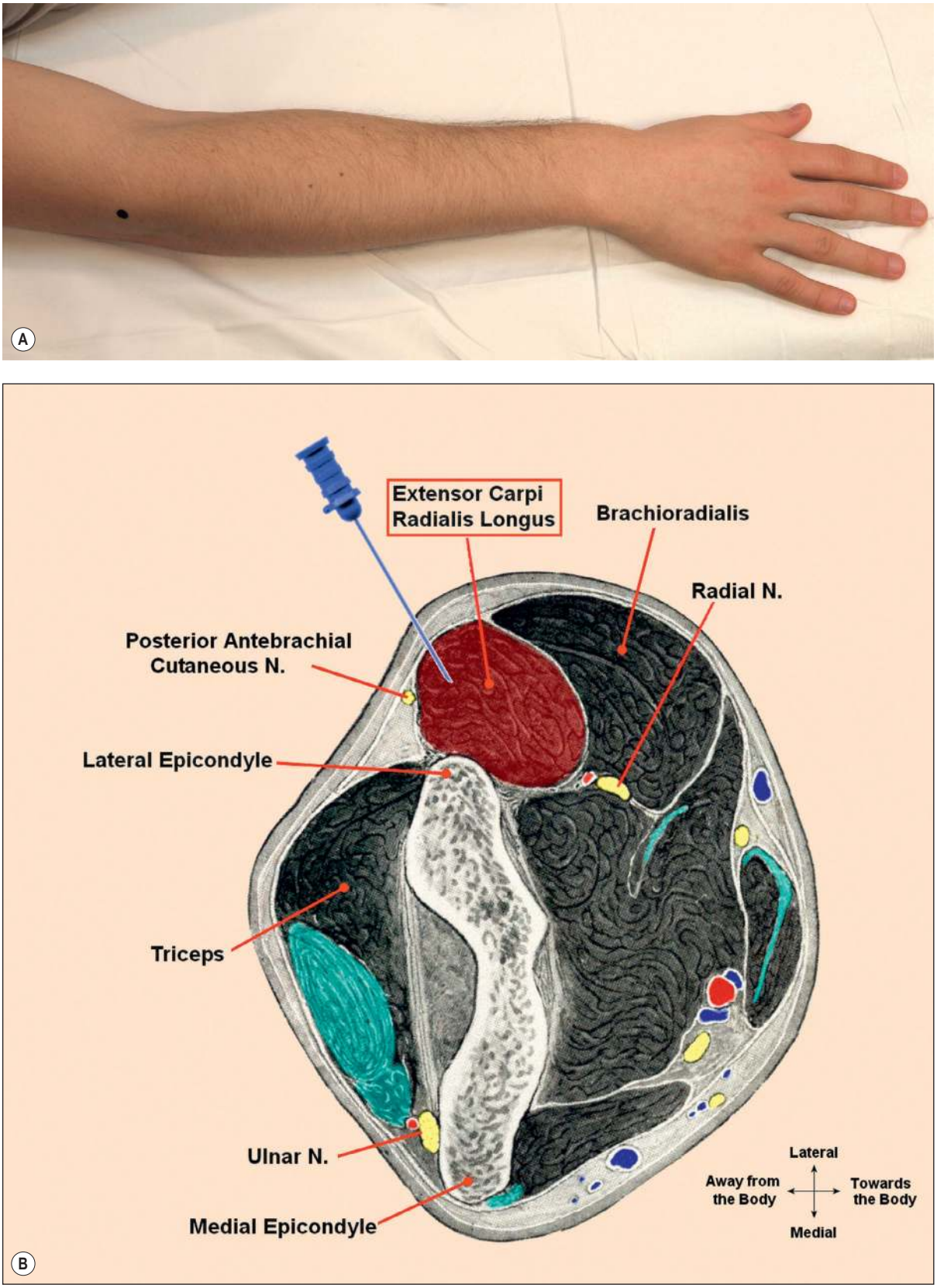


FIGURE 13–17 A. Extensor carpi radialis (long head) insertion point. B. Cross-section anatomy*.

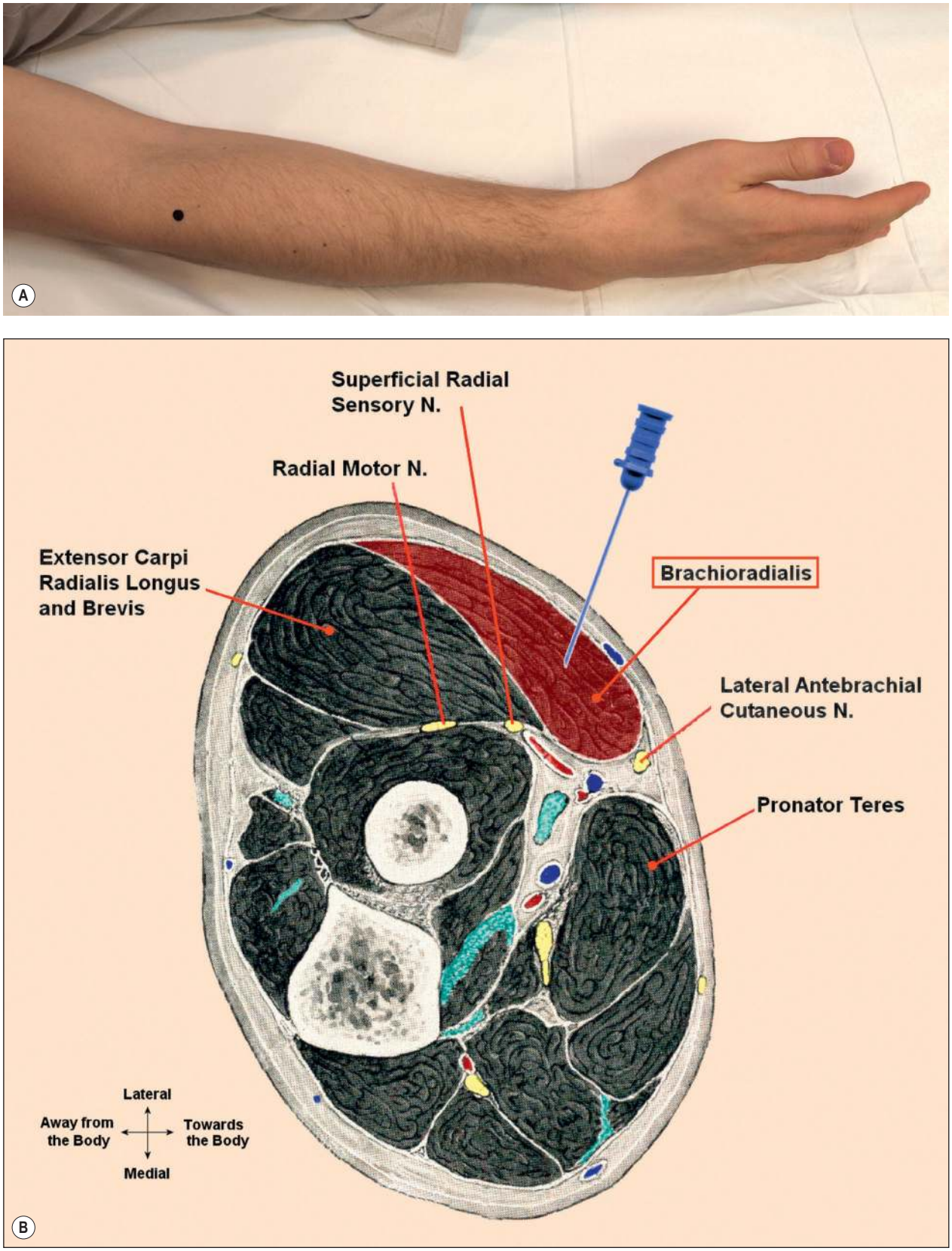


FIGURE 13–18 A. Brachioradialis insertion point.
B. Cross-section anatomy*.

Anconeus (ANC) *(Figure 13–19A,B)*

Innervation:

Radial nerve, posterior cord, upper–middle–lower trunks, C6–**C7**–C8

Needle Insertion:

With the patient's forearm pronated, insert the needle one to two fingerbreadths distal to the olecranon slightly above the ulna

Activation:

Have the patient extend the elbow

Key Clinical Points:

- The ANC is effectively an extension of the medial head of the triceps.
- It is the only radial muscle in the forearm innervated from above the spinal groove.
- Spared in radial neuropathy at the spiral groove.

Cross-section Anatomy Key Points:

- If the needle is too anterior, it will be in the ECU or EDC.

Triceps Brachii–Lateral Head (TB) *(Figure 13–20A,B)*

Innervation:

Radial nerve, posterior cord, upper–middle–lower trunks, C6–**C7**–C8

Needle Insertion:

With the patient's forearm pronated and the elbow flexed, insert the needle just below the mid-point between the lateral epicondyle and shoulder

Activation:

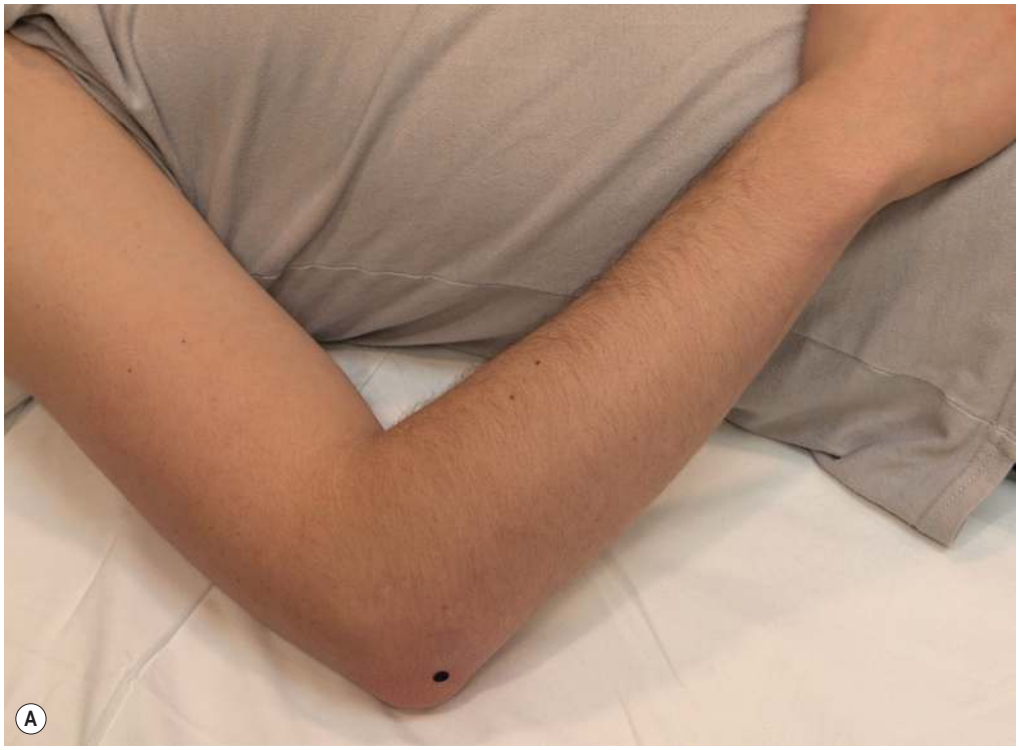
Have the patient extend the elbow

Key Clinical Points:

- The lateral head is the easiest of the three heads of the triceps to study.
- Often abnormal in C7 radiculopathy.
- Spared in radial neuropathy at the spiral groove.

Cross-section Anatomy Key Points:

- As long as this muscle is sampled from the lateral approach, there are no other nearby vascular structures or major nerves.



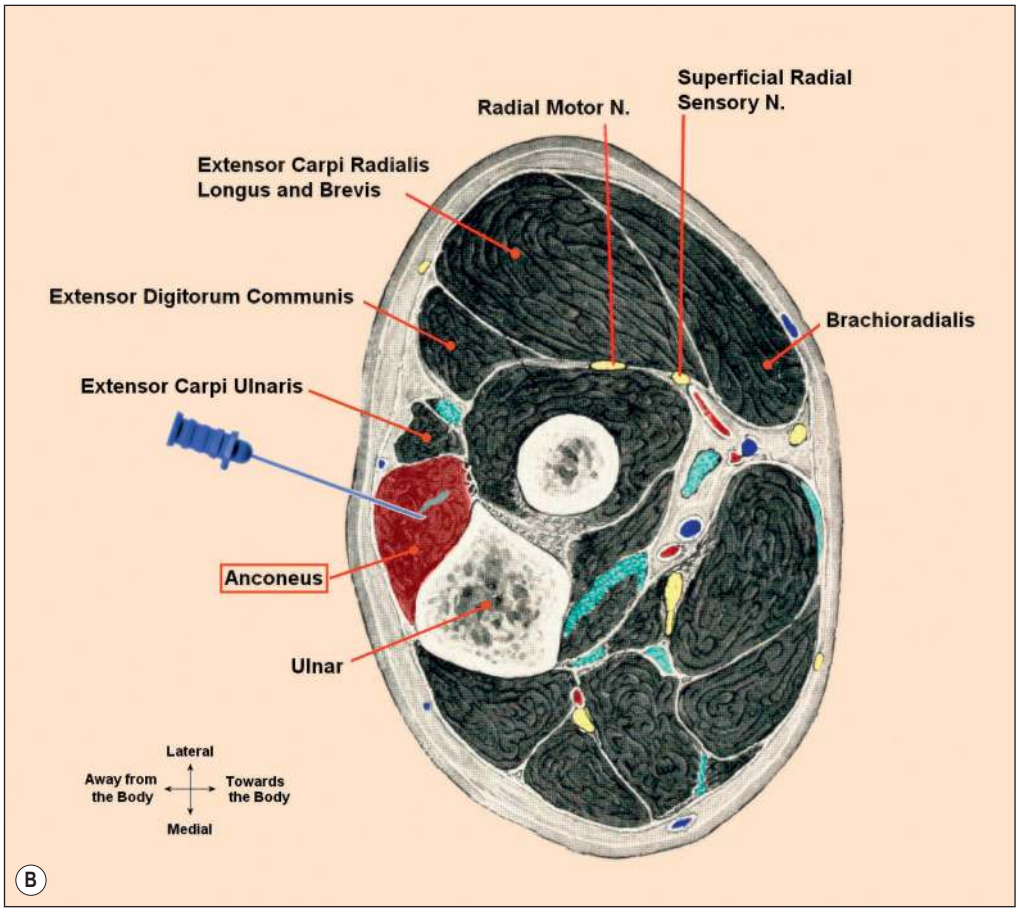
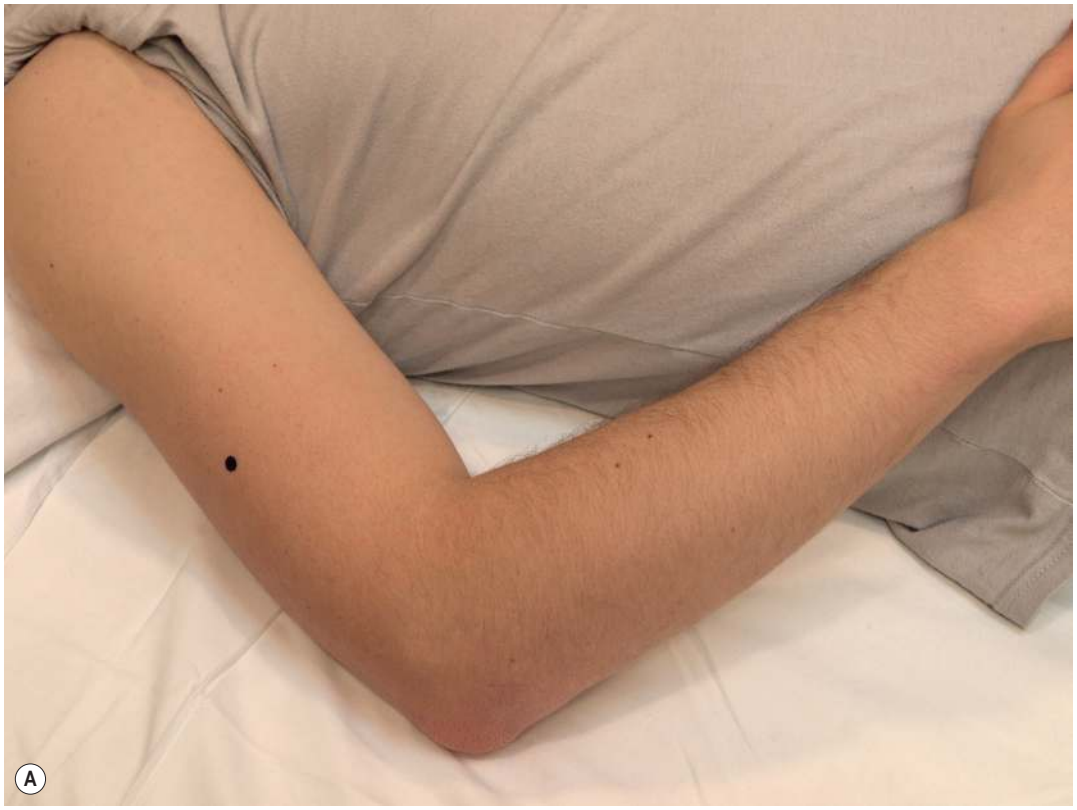


FIGURE 13–19 A. Anconeus insertion point.
B. Cross-section anatomy*.



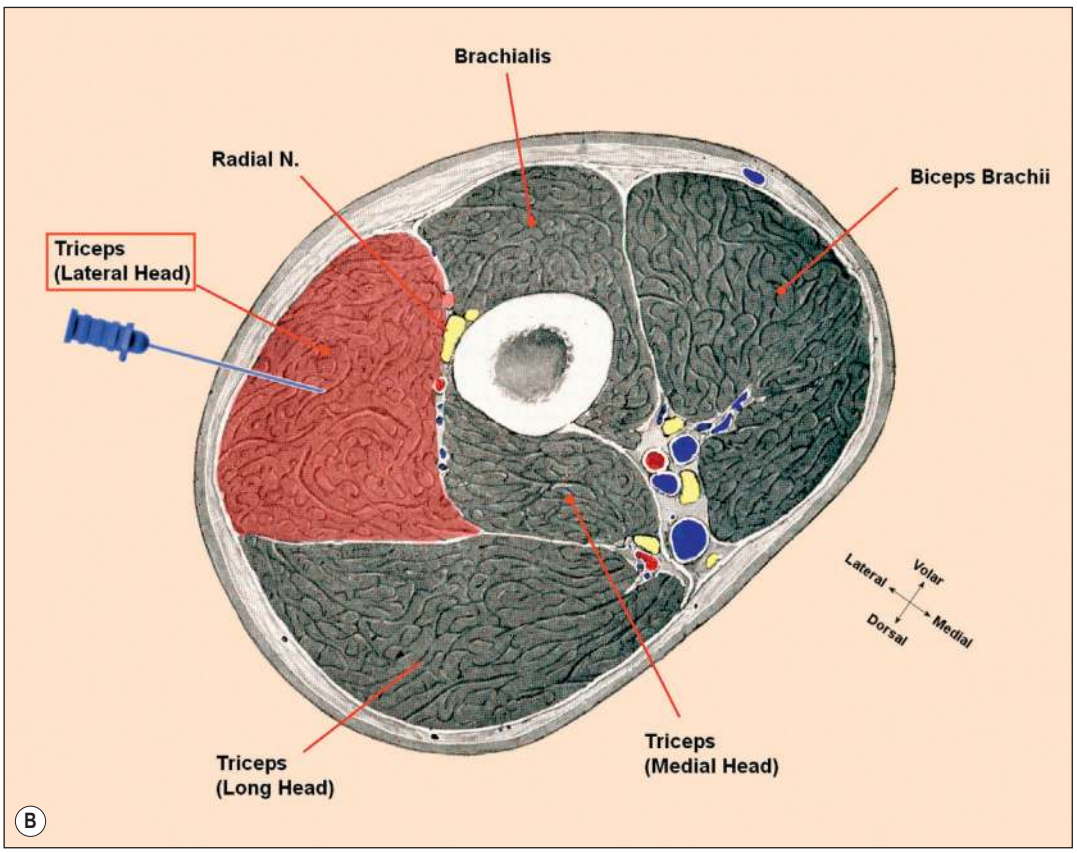


FIGURE 13–20 A. Triceps brachii (lateral head) insertion point.
B. Cross-section anatomy*.

MUSCULOCUTANEOUS NERVE

Biceps Brachii (BB) *(Figure 13–21A,B)*

Innervation:

Musculocutaneous nerve, lateral cord, upper trunk, **C5–C6**

Needle Insertion:

With the patient's forearm supinated, insert the needle at the mid-point between biceps tendon and anterior shoulder

Activation:

Have the patient flex the elbow with the hand supinated

Key Clinical Points:

- The BB is the most accessible muscle innervated by the musculocutaneous nerve.
- Often abnormal in upper trunk/lateral cord plexopathy and C5 or C6 radiculopathy.

Cross-section Anatomy Key Points:

- As long as this muscle is sampled from the anterior approach, there are no other nearby vascular structures or major nerves.
- If this muscle is sampled from the medial side (which is not recommended), the brachial artery, the median nerve and other large veins would be vulnerable to injury.

PECTORAL NERVES

Pectoralis Major (PM) *(Figure 13–22A,B)*

Innervation:

Medial–lateral pectoral nerves, medial–lateral cords, upper–middle–lower trunks, C5–**C6–C7–C8**–T1

Needle Insertion:

Insert the needle into the anterior inferior shoulder at the anterior axillary line

Activation:

Have the patient adduct the shoulder

Key Clinical Points:

- The pectoralis inserts into the clavicle (superior) and sternum (inferior).
- The clavicular portion is innervated by the lateral pectoral nerve (lateral cord, C5–C6–C7).
- The sternal portion is innervated by medial pectoral nerve (medial cord, C8–T1).

Cross-section Anatomy Key Points:

- If the needle is too lateral, it will be in the deltoid.
- If the needle is too lateral and too deep, it could come close to the coracobrachialis, brachial plexus and major bloods vessels to and from the upper extremity.

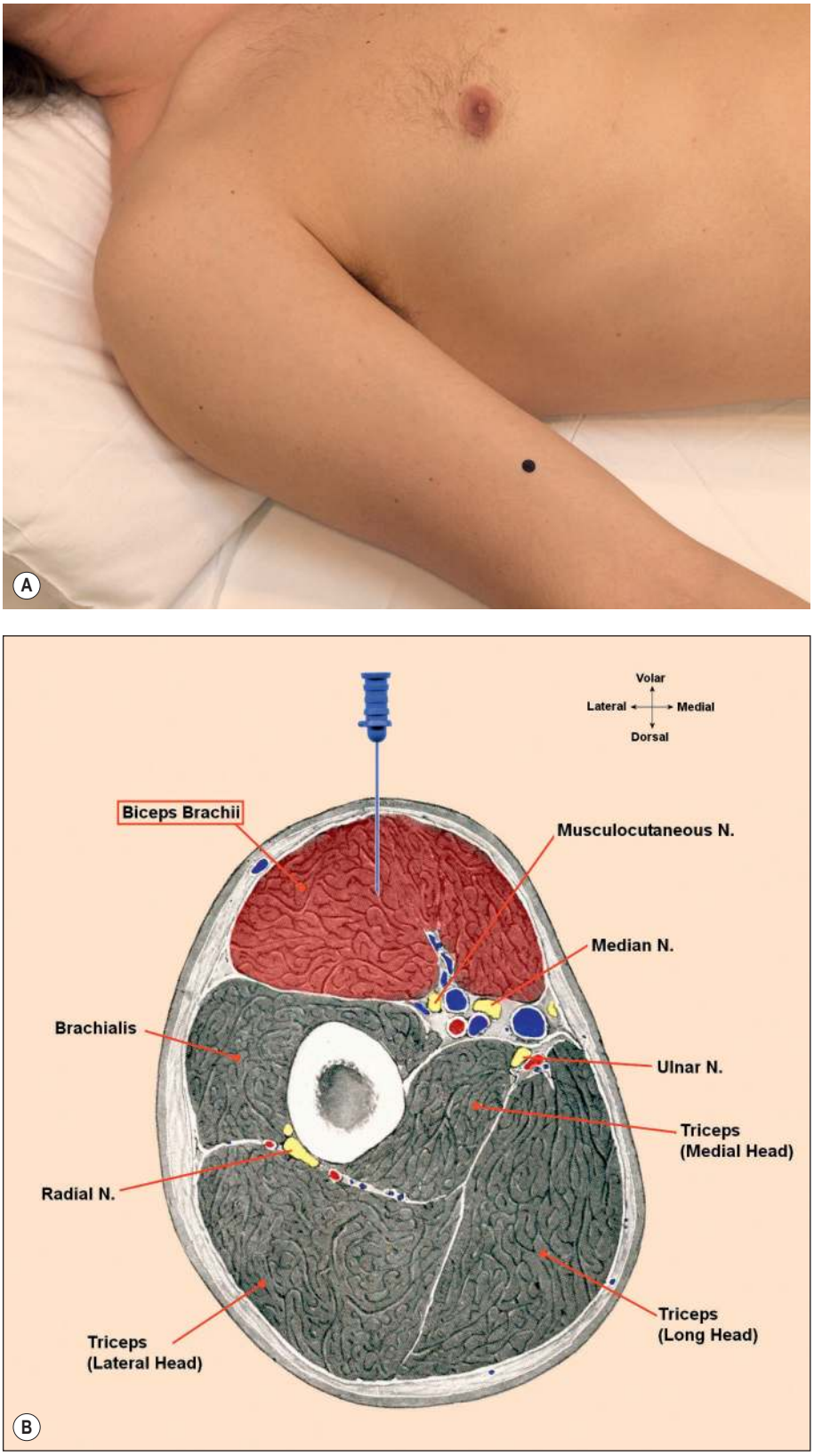


FIGURE 13–21 A. Biceps brachii insertion point.
B. Cross-section anatomy*.

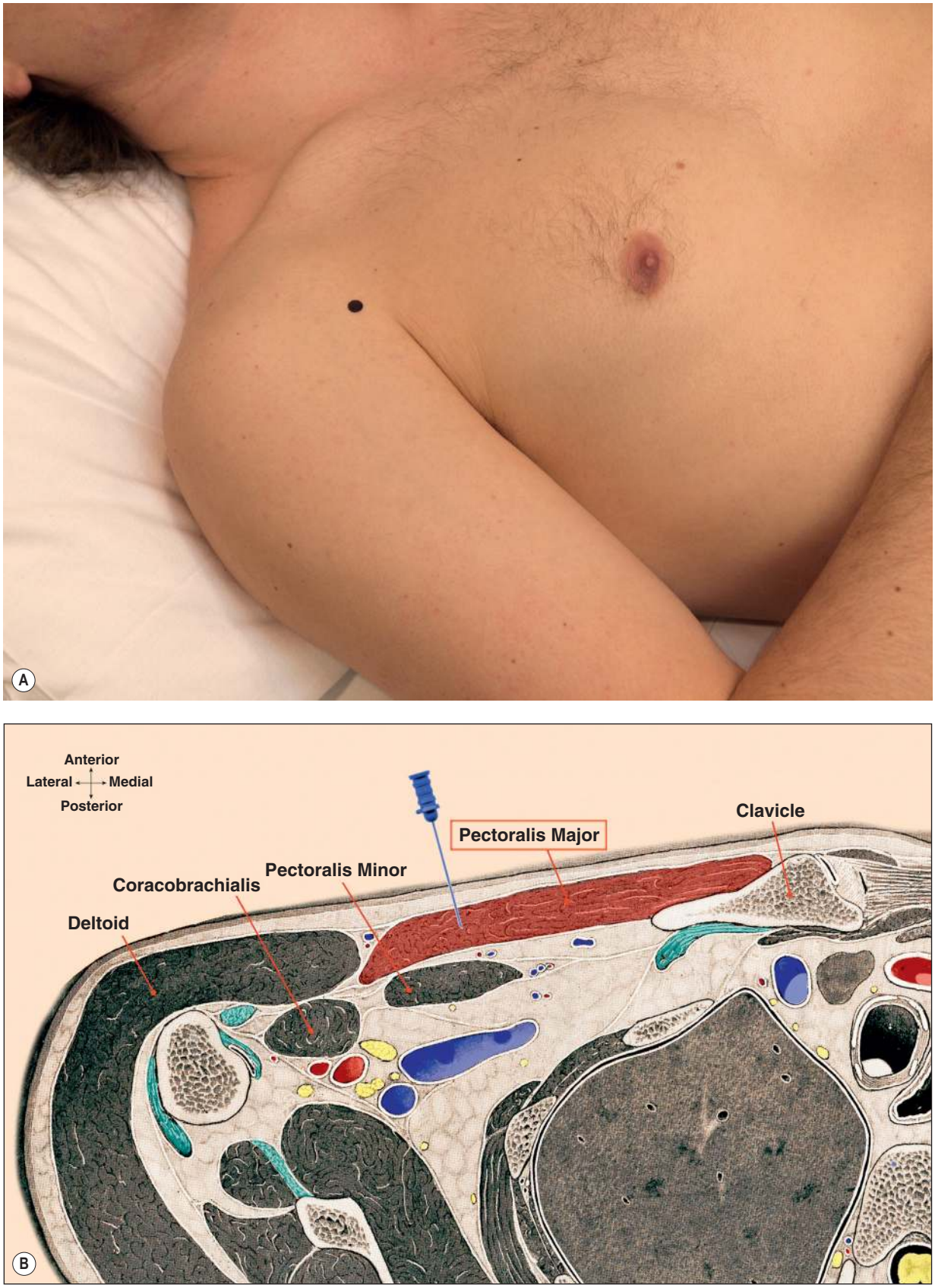


FIGURE 13–22 A. Pectoralis major insertion point.
B. Cross-section anatomy*.

AXILLARY NERVE

Deltoid–Medial Head (MD)

(Figure 13–23A,B)

Innervation:

Axillary nerve, posterior cord, upper trunk, **C5–C6**

Needle Insertion:

Insert the needle into the medial shoulder

Activation:

Have the patient abduct the shoulder

Key Clinical Points:

- The medial head is the easiest of the three heads to study.
- Motor unit action potentials may have increased polyphasia in normal subjects.
- Most accessible axillary-innervated muscle.
- Often involved in axillary neuropathy, upper trunk/posterior cord plexopathy and C5 or C6 radiculopathy.

Cross-section Anatomy Key Points:

- As long as this muscle is sampled from the lateral approach, there are no other nearby vascular structures or major nerves.

Teres Minor *(Figure 13–24A,B)*

Innervation:

Axillary nerve, posterior cord, upper trunk, **C5–C6**

Needle Insertion:

Insert the needle into a point two-thirds the distance from the inferior tip of the scapula to the acromion

Activation:

Have the patient externally rotate arm

Key Clinical Points:

- More difficult to localize than the deltoid; thus, the deltoid is preferred when screening for an axillary neuropathy.
- Often involved in axillary neuropathy, upper trunk/posterior cord plexopathy and C5 or C6 radiculopathy.

Cross-section Anatomy Key Points:

- If the needle is too medial, it will be in the infraspinatus.
- If the needle is too superficial and/or too lateral, it will be in the posterior head of the deltoid.

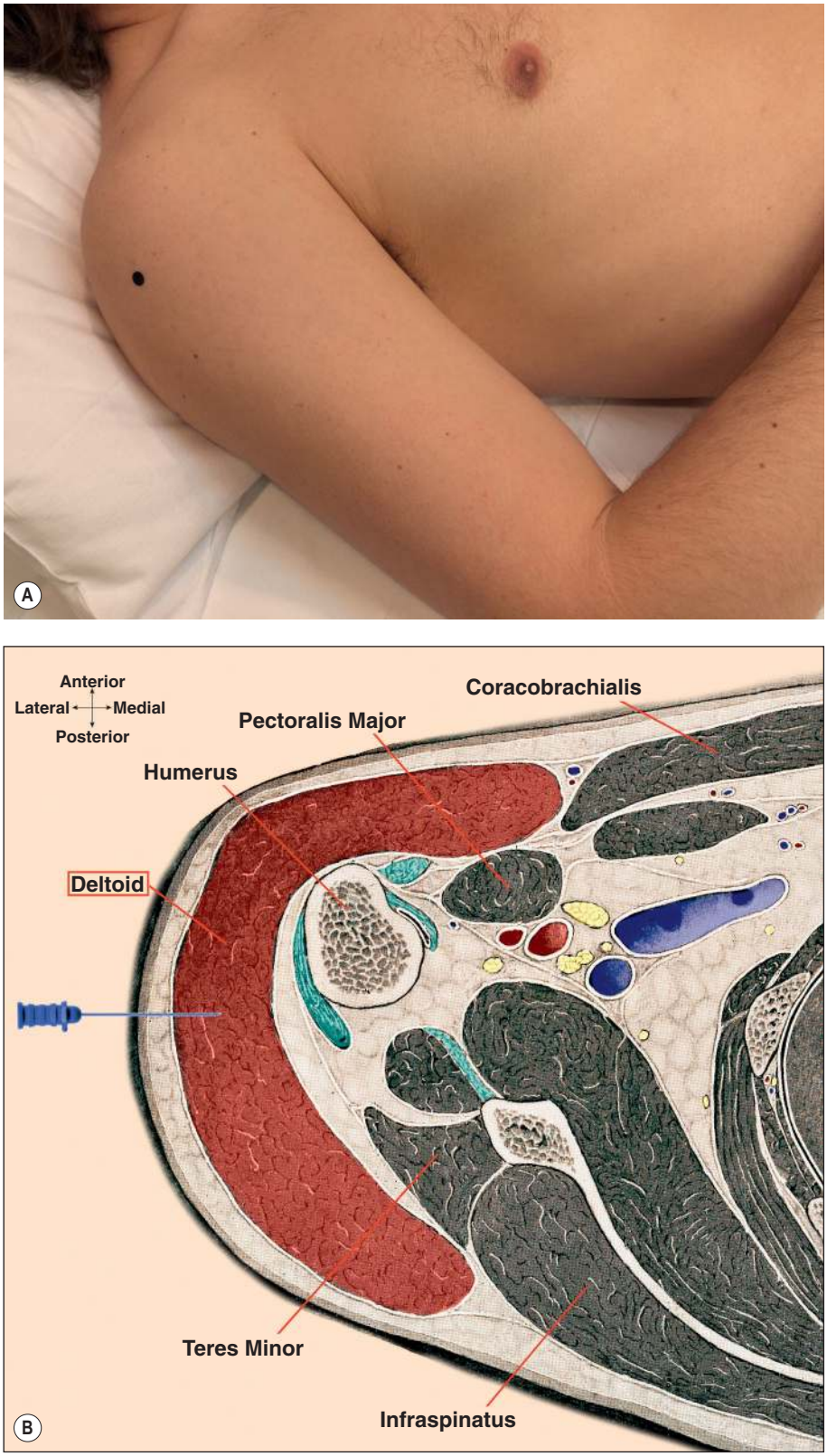


FIGURE 13–23 A. Deltoid (medial head) insertion point.
B. Cross-section anatomy*.

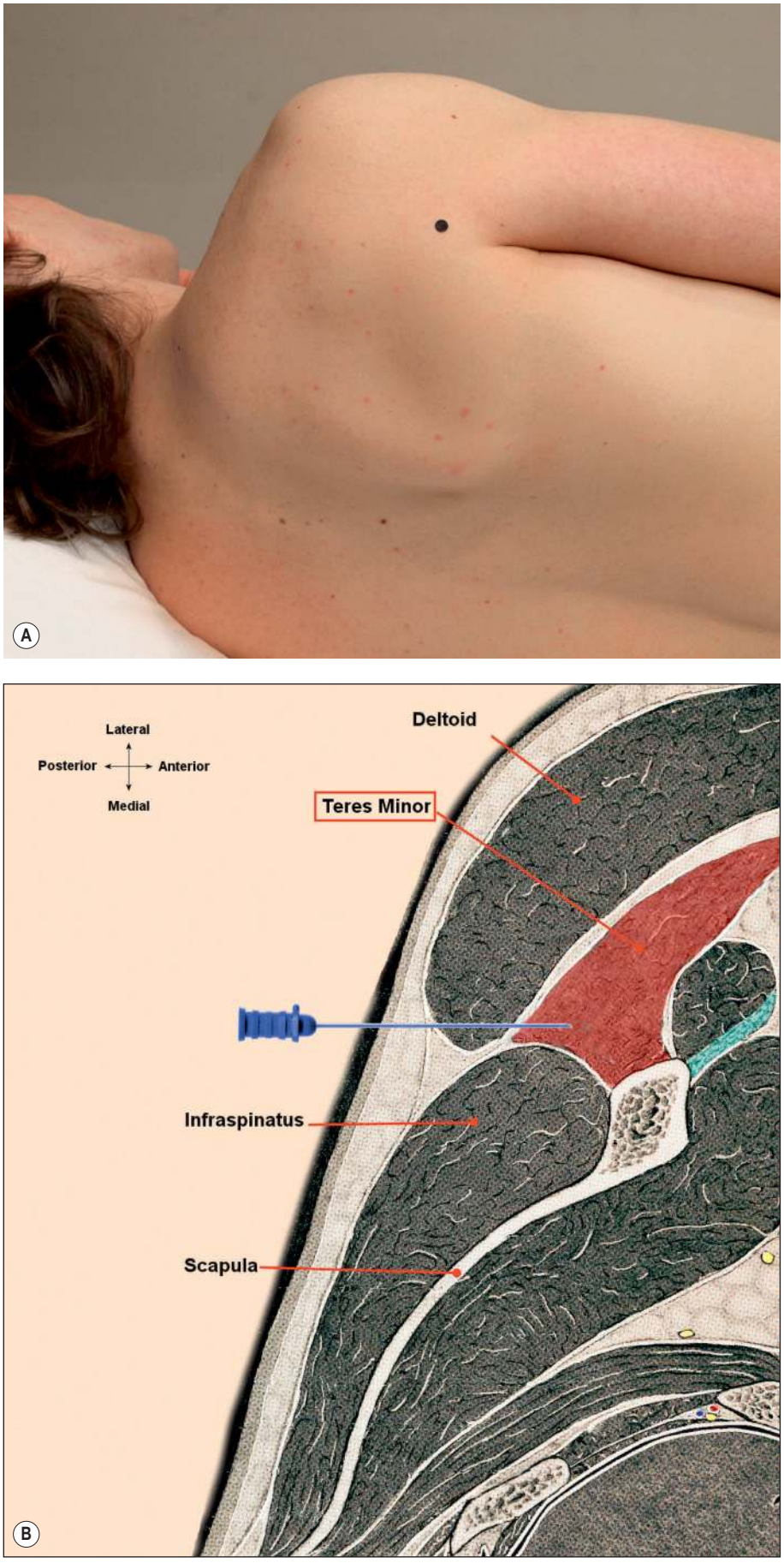


FIGURE 13–24 A. Teres minor insertion point.
B. Cross-section anatomy*.

SPINAL ACCESSORY NERVE

Upper Trapezius (TRAP) *(Figure 13–25A,B)*

Innervation:

Spinal accessory nerve, **C3–C4**

Needle Insertion:

With the patient lying on his or her side and the shoulder to be studied placed upward, insert the needle where the posterior shoulder meets the neck

Activation:

Have the patient shrug the shoulder

Key Clinical Points:

- Most often abnormal in spinal accessory nerve lesions caused by local surgery, with sparing of the sternocleidomastoid muscle.

Cross-section Anatomy Key Points:

- The muscle is superficial.
- If the needle is too medial and too deep, it could enter the rhomboids, levator scapulae and/or paraspinal muscles.

Sternocleidomastoid (SCM) *(Figure 13–26A,B)*

Innervation:

Spinal accessory nerve, upper cervical cord

Needle Insertion:

With the muscle palpated and held between the fingers, insert the needle near the mid-point of the muscle

Activation:

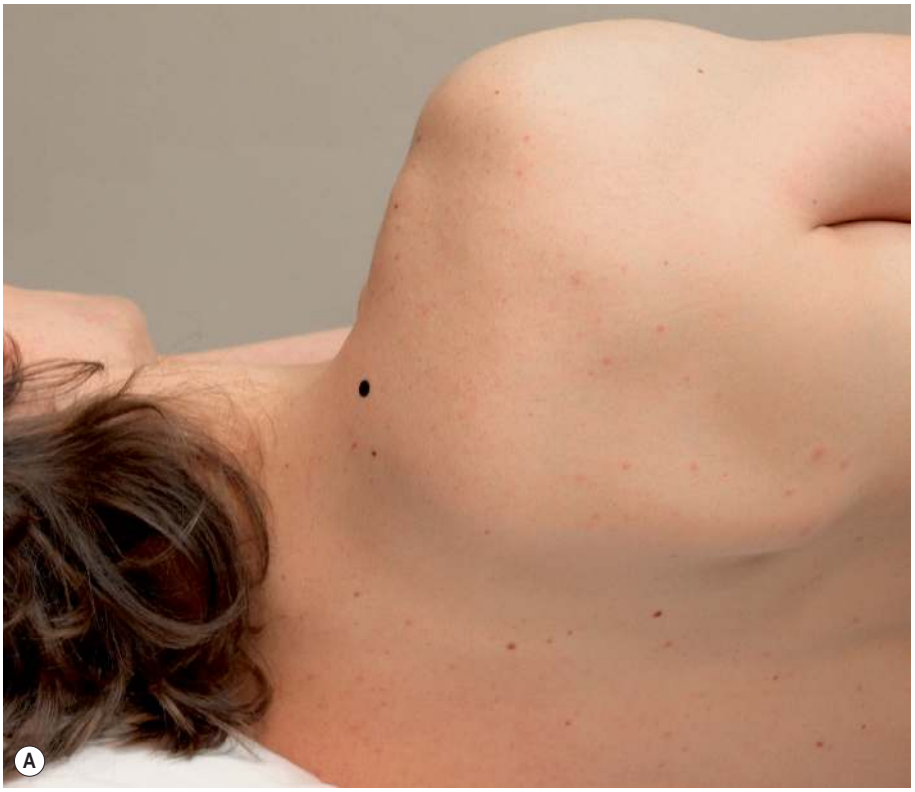
Have the patient turn his or her head and neck to the contralateral side

Key Clinical Points:

- The sternocleidomastoid often is involved in spasmodic torticollis.

Cross-section Anatomy Key Points:

- C*aution*: The needle must remain superficial at all times to avoid injury to the carotid artery or jugular vein.



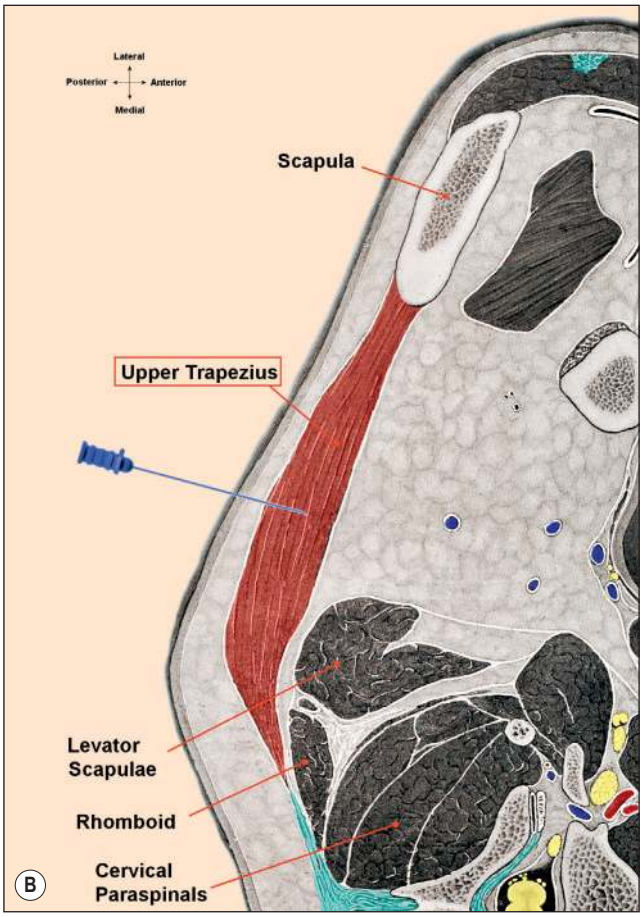
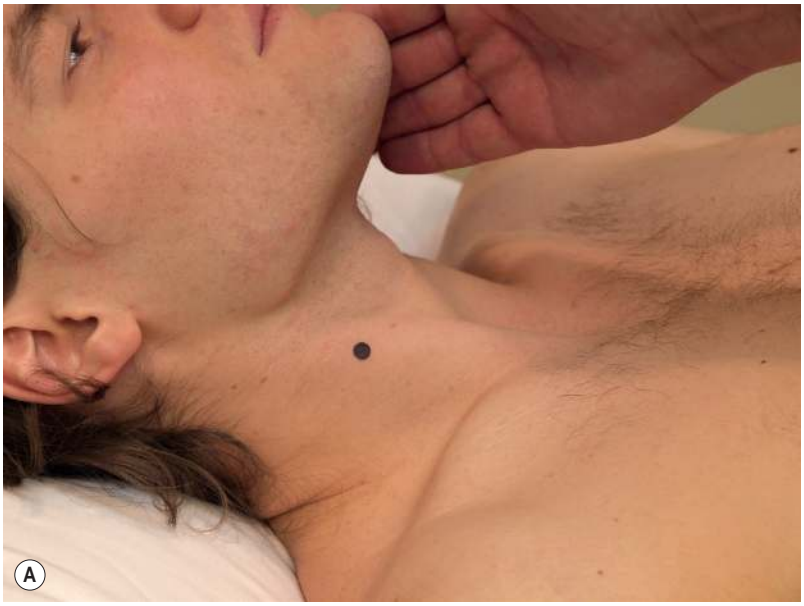


FIGURE 13–25 A. Upper trapezius insertion point.
B. Cross-section anatomy*.



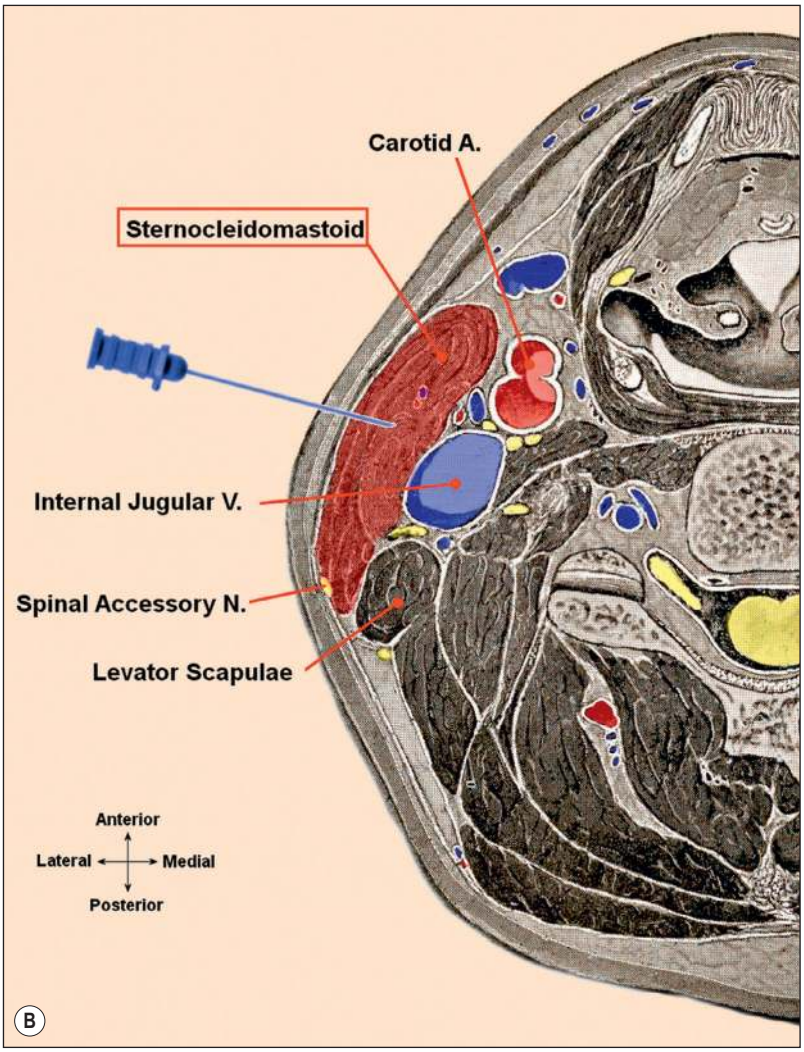


FIGURE 13–26 A. Sternocleidomastoid insertion point.
B. Cross-section anatomy*.

SUPRASCAPULAR NERVE

Supraspinatus (SS) *(Figure 13–27A,B)*

Innervation:

Suprascapular nerve, upper trunk, **C5–C6**

Needle Insertion:

With the patient lying on his or her side, the shoulder to be studied placed upward, and the elbow at the side, insert the needle just rostral and medial to the mid-point of the scapular spine

Activation:

Have the patient abduct the shoulder

Key Clinical Points:

- If the needle is inserted too superficially, it will be in the trapezius.
- The SS may be spared in suprascapular neuropathy at the spinoglenoid notch.
- The muscle is more difficult to study than the infraspinatus.
- It may be abnormal in upper trunk plexopathy and C5–C6 radiculopathy.

Cross-section Anatomy Key Points:

- If the needle is too superficial, it will be in the upper trapezius.
- C*aution*: Rare cases of pneumothorax have been reported with improper needle placement too rostral and deep.

Infraspinatus (IS) *(Figure 13–28A,B)*

Innervation:

Suprascapular nerve, upper trunk, **C5–C6**

Needle Insertion:

With the patient lying on his or her side, shoulder to be studied placed upward, and the elbow at the side, insert the needle one to two fingerbreadths below the mid-point of the scapular spine

Activation:

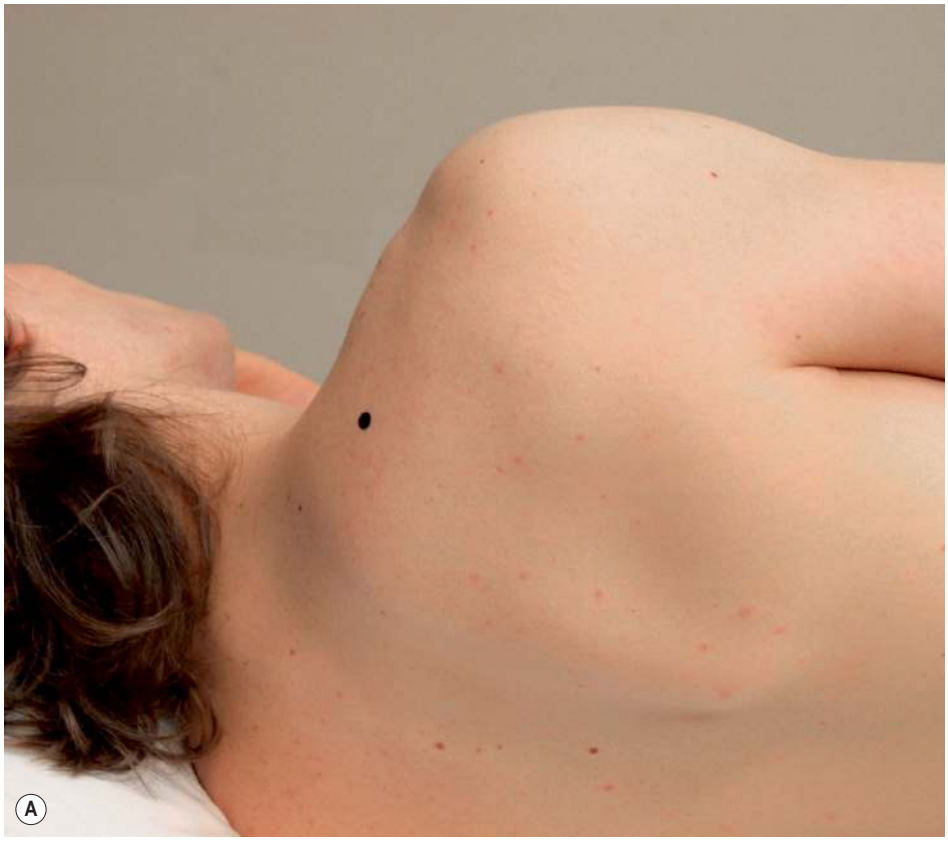
Have the patient externally rotate the shoulder

Key Clinical Points:

- Often abnormal in suprascapular neuropathy, upper trunk plexopathy, and C5 or C6 radiculopathy.
- The scapula (infrascapular fossa) is deep to the muscle (thus, there is no risk of pneumothorax if the needle is correctly placed).

Cross-section Anatomy Key Points:

- Much of the muscle is superficial. However, if the needle is inserted too superficially near the scapular spine, it may be in the posterior deltoid. Hence, if the needle is inserted down to the scapula, then withdrawn slightly, one can be assured that the needle is in the correct muscle.



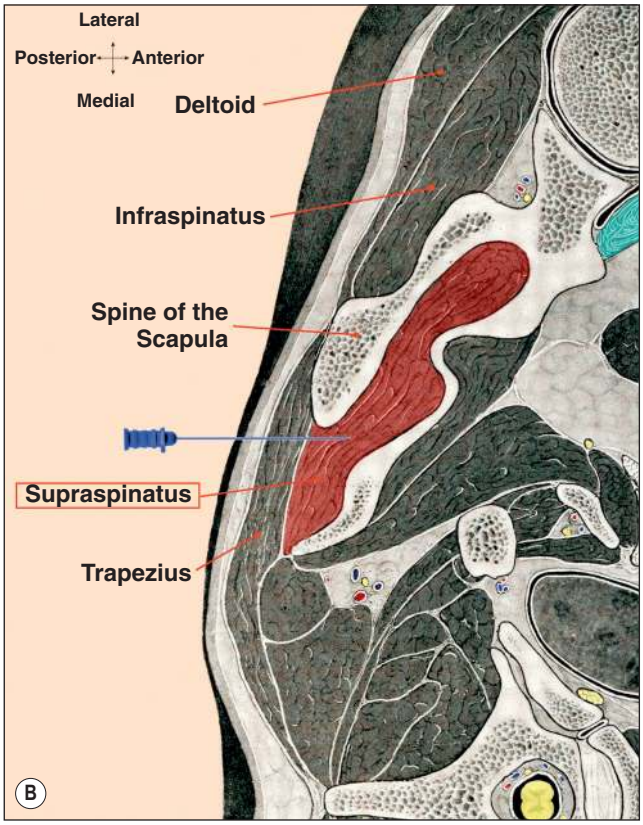


FIGURE 13–27 A. Supraspinatus insertion point.
B. Cross-section anatomy*.

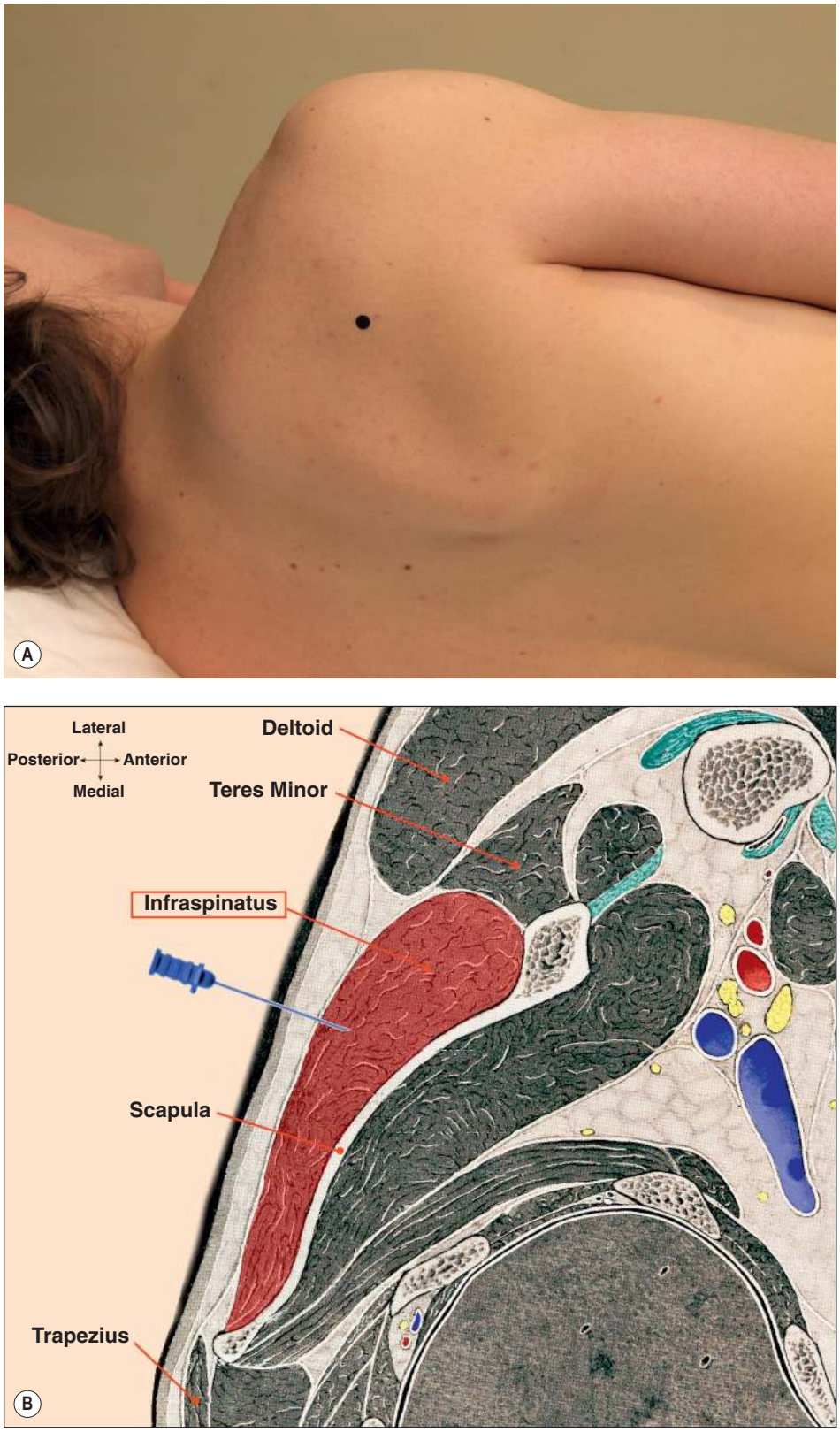


FIGURE 13–28 A. Infraspinatus insertion point.
B. Cross-section anatomy*.

DORSAL SCAPULAR NERVE

Rhomboids *(Figure 13–29A,B)*

Innervation:

Dorsal scapular nerve, C4–**C5**

Needle Insertion:

With the patient lying on his or her side, the side to be studied placed upward, and the arm internally rotated and flexed at the elbow with the dorsum of the hand on the midback, insert needle at the mid-point between the medial border of the scapula and midback

Activation:

Raise hand from the back

Key Clinical Points:

- May be abnormal in C5 radiculopathy.
- Because the dorsal scapular nerve arises proximal to the brachial plexus, the rhomboids are spared in upper trunk brachial plexopathy.

Cross-section Anatomy Key Points:

- If the needle is inserted too superficially, it will be in the trapezius.
- If the needle is inserted too deeply, it will be in the paraspinal muscles.
- *Caution*: Rare cases of pneumothorax have been reported with improper needle placement too deep.

THORACODORSAL NERVE

Latissimus Dorsi (LD) *(Figure 13–30A,B)*

Innervation:

Thoracodorsal nerve, posterior cord, upper–middle–lower trunks, C6–**C7**–C8

Needle Insertion:

With the patient lying on his or her side and the side to be studied placed upward, insert the needle lateral to the tip of the scapula at the posterior axillary line

Activation:

With the patient's shoulder internally rotated and adducted, and the arm above the horizontal, have the patient extend the shoulder (i.e., bring the hand down toward the foot)

Key Clinical Points:

- The LD is more difficult to study than the triceps and other radial-innervated muscles that have similar cord, trunk, and root innervation.

Cross-section Anatomy Key Points:

- If the needle is too deep, it may be in the serratus anterior.

LONG THORACIC NERVE

Serratus Anterior (SA) *(Figure 13–31A,B)*

Innervation:

Long thoracic nerve, **C5–C6–C7**

Needle Insertion:

With the patient lying on his or her side and the shoulder to be studied placed upward, carefully insert the needle over the sixth rib at the mid-axillary line

Activation:

Have the patient push his or her hand forward with the arm straight

Key Clinical Points:

- Because the long thoracic nerve arises proximal to the brachial plexus, the serratus anterior is spared in brachial plexopathy.
- Often abnormal in "brachial plexitis" (also known as brachial amyotrophy or more properly, neuralgic amyotrophy).
- The SA muscle is difficult to study because most of the muscle lies between the rib cage and scapula.

Cross-section Anatomy Key Points:

- Use caution with needle insertion. If the needle is inserted between the ribs, there is a risk of neurovascular bundle injury or pneumothorax.

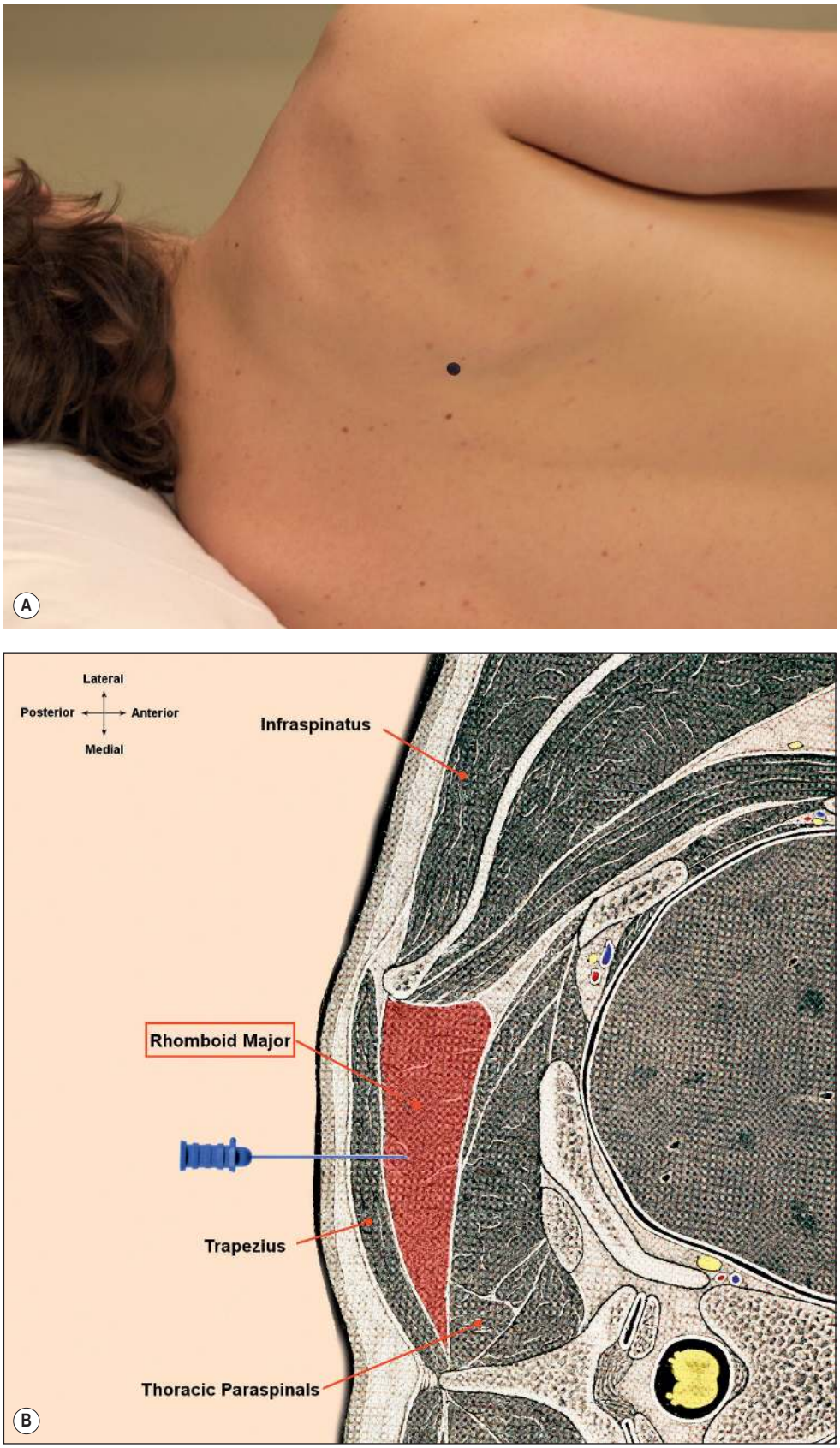
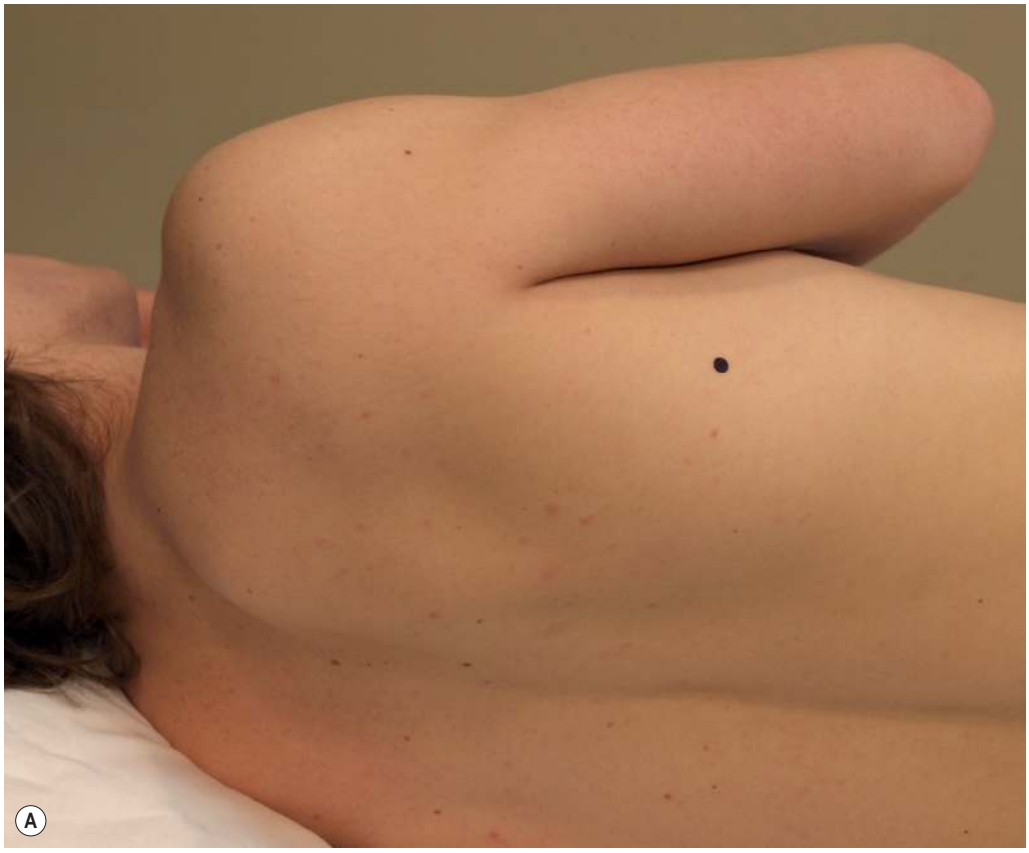


FIGURE 13–29 A. Rhomboids insertion point.
B. Cross-section anatomy*.



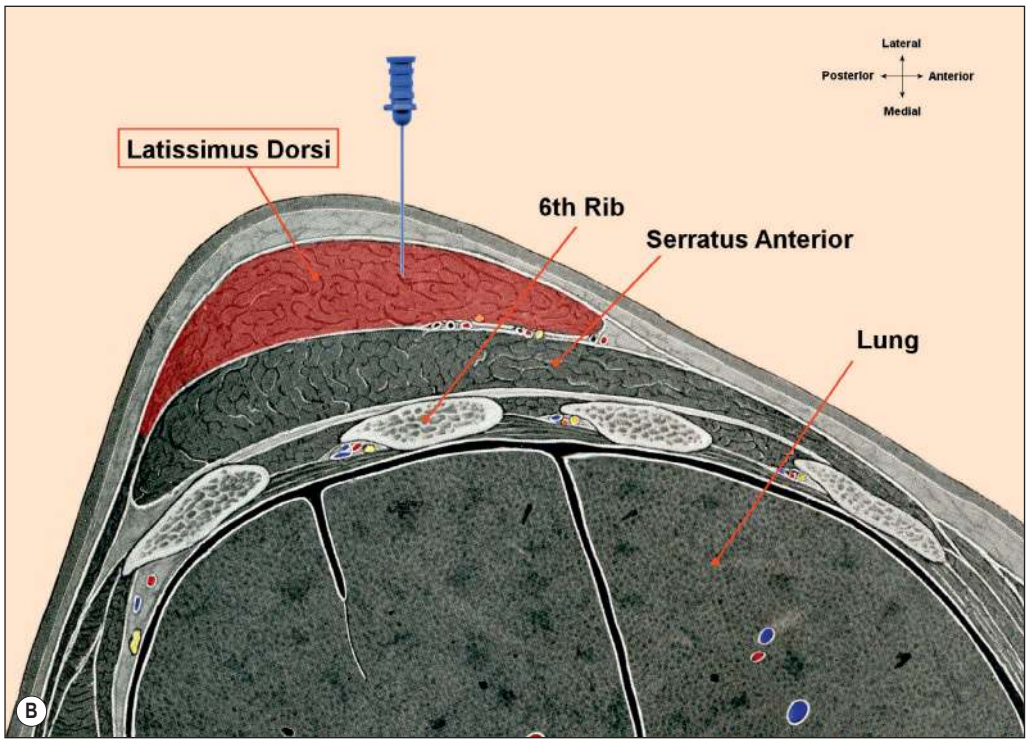


FIGURE 13–30 A. Latissimus dorsi insertion point.
B. Cross-section anatomy*.

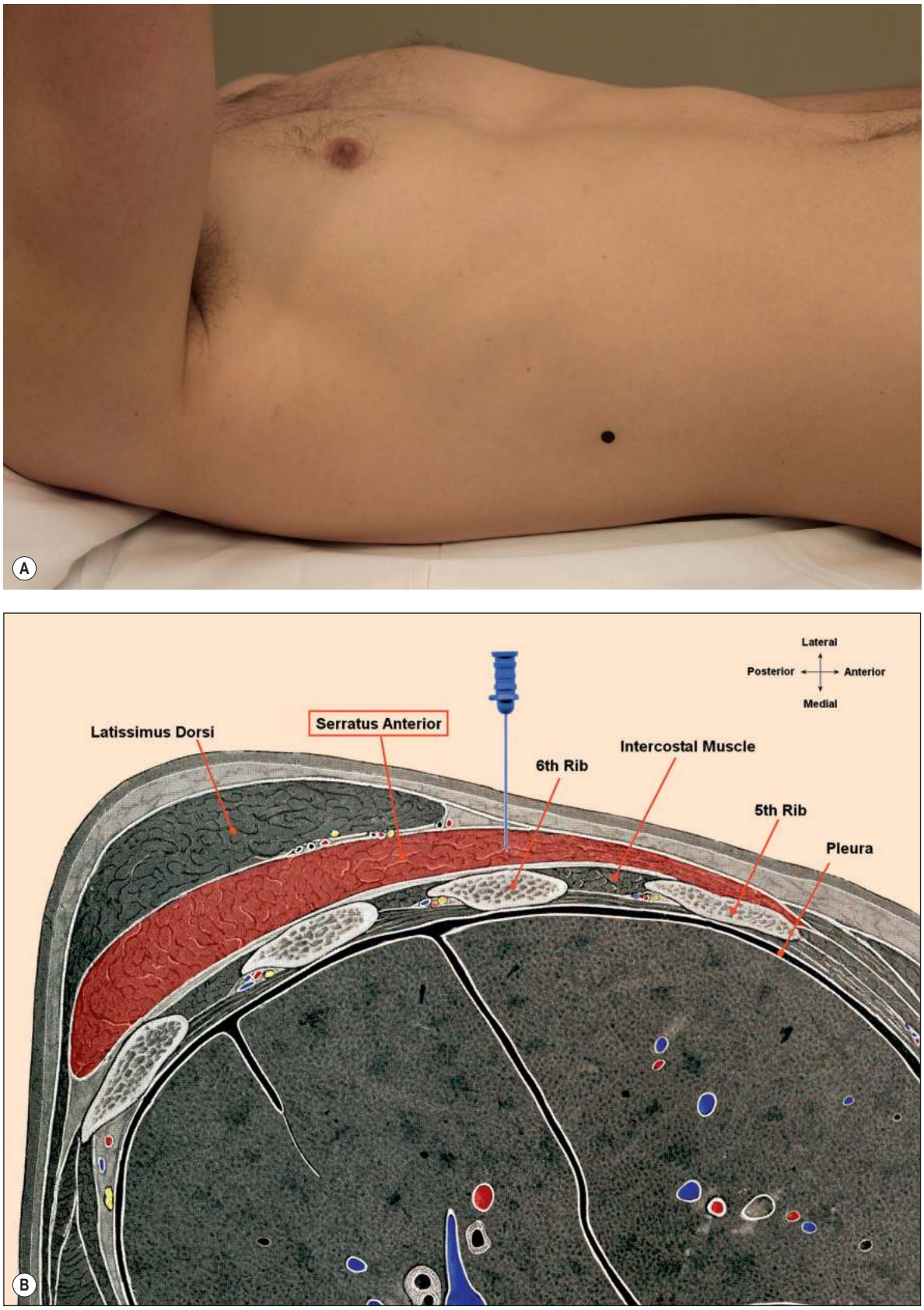


FIGURE 13–31 A. Serratus anterior insertion point.
B. Cross-section anatomy*.

LOWER EXTREMITY

PERONEAL NERVE

Extensor Digitorum Brevis (EDB)

(Figure 13–32A,B)

Innervation:

Deep peroneal nerve, common peroneal nerve, sciatic nerve, lumbosacral plexus, L4–**L5**–S1

Needle Insertion:

Insert the needle tangentially into the dorsum of the foot two to three fingerbreadths distal to the lateral malleolus. The muscle can often be easily felt by having the patient extend all theirs toes

Activation:

Have the patient extend the toes

Key Clinical Points:

- May be involved in anterior tarsal tunnel syndrome.
- Use caution with the interpretation of abnormalities. Some denervation and reinnervation is common in normal subjects without symptoms. Side-to-side comparison can be useful.

Cross-section Anatomy Key Points:

- Muscle is extremely superficial and very thin.
- Tendons from the EDL run over the muscle

Extensor Hallucis Longus (EHL)

(Figure 13–33A,B)

Innervation:

Deep peroneal nerve, common peroneal nerve, sciatic nerve, lumbosacral plexus, L4–**L5**–S1

Needle Insertion:

Insert the needle three to four fingerbreadths above the ankle, just lateral to the tibialis anterior tendon

Activation:

Have the patient extend the great toe

Key Clinical Points:

- The EHL is a strongly L5-innervated distal muscle.
- The muscle often is perceived as painful; several tendons are close by.
- It often is abnormal in lesions of the deep or common peroneal nerves.
- The EHL is one of the most distal muscles in the leg and often is abnormal in polyneuropathy.

Cross-section Anatomy Key Points:

- Note that the EHL is just lateral to the TA tendon.
- If the needle is inserted too deep, it could come close to the deep peroneal nerve and nearby vascular structures.
- As the needle is inserted, it may be perceived as painful if it passes near or through nearby tendons.

Extensor Digitorum Longus (EDL)

(Figure 13–34A,B)

Innervation:

Deep peroneal nerve, common peroneal nerve, sciatic nerve, lumbosacral plexus, L4–**L5**

Needle Insertion:

Insert the needle three to four fingerbreadths lateral to the tibial crest, between the tibialis anterior and peroneus longus muscles

Activation:

Have the patient extend the toes

Key Clinical Points:

- The EDL is more difficult to locate than the tibialis anterior muscle.

Cross-section Anatomy Key Points:

- If the needle is too medial, it will be in the TA.
- If the needle is too lateral, it will be in the PL.

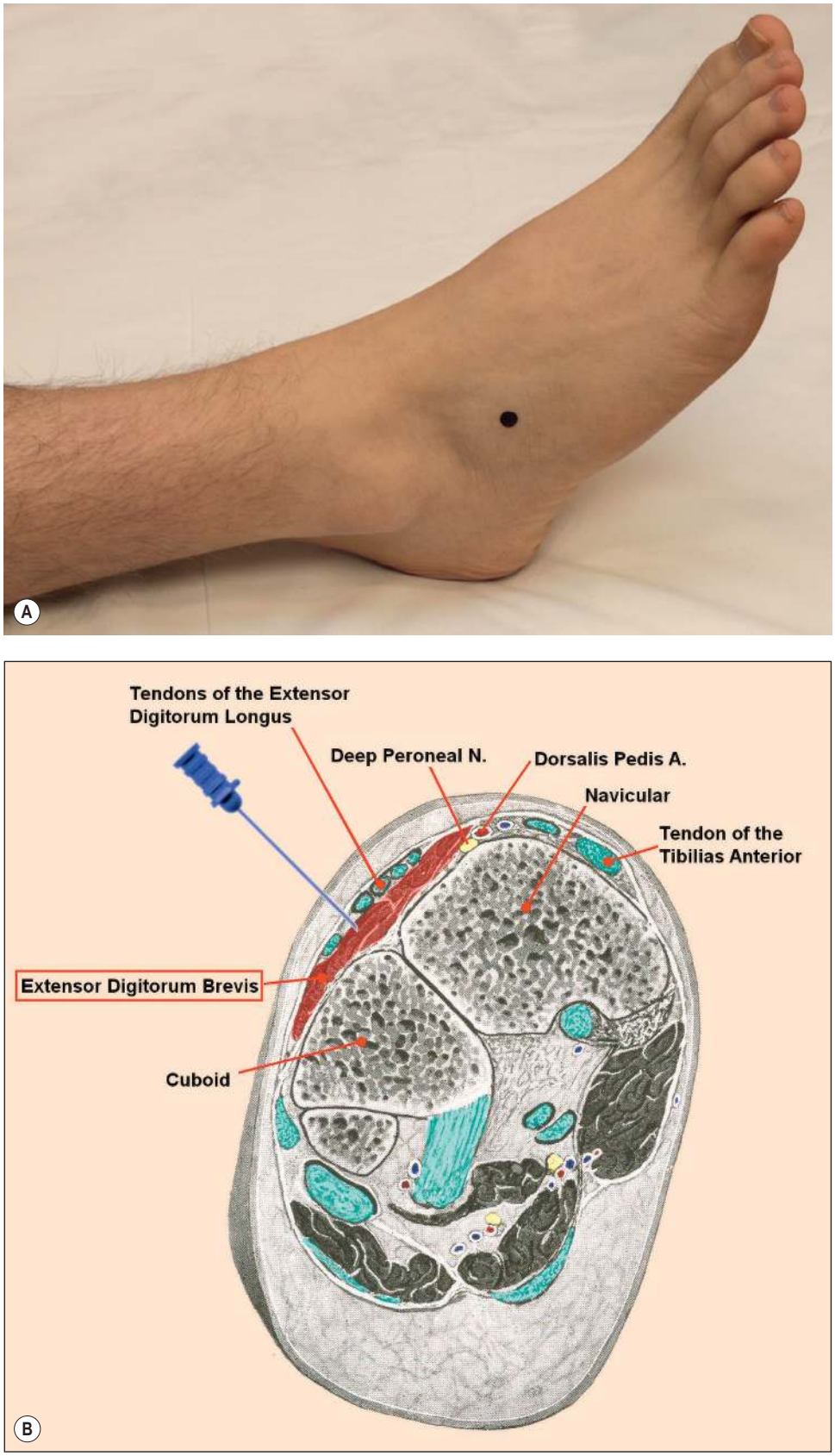
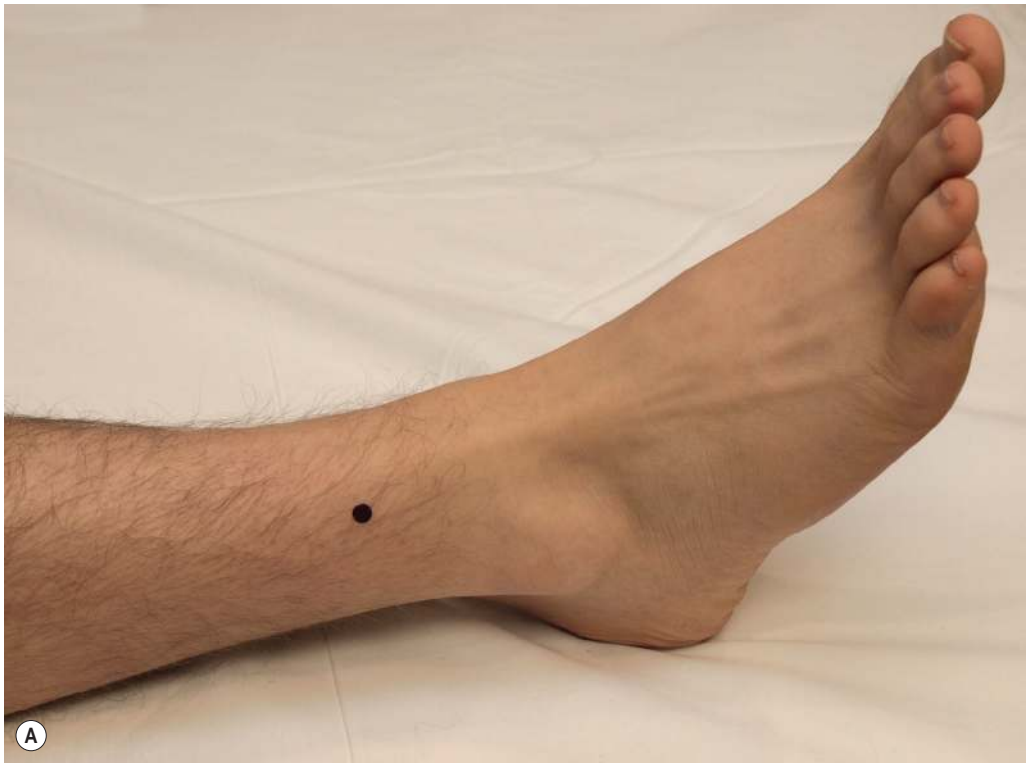


FIGURE 13–32 A. Extensor digitorum brevis insertion point.
B. Cross-section anatomy*.



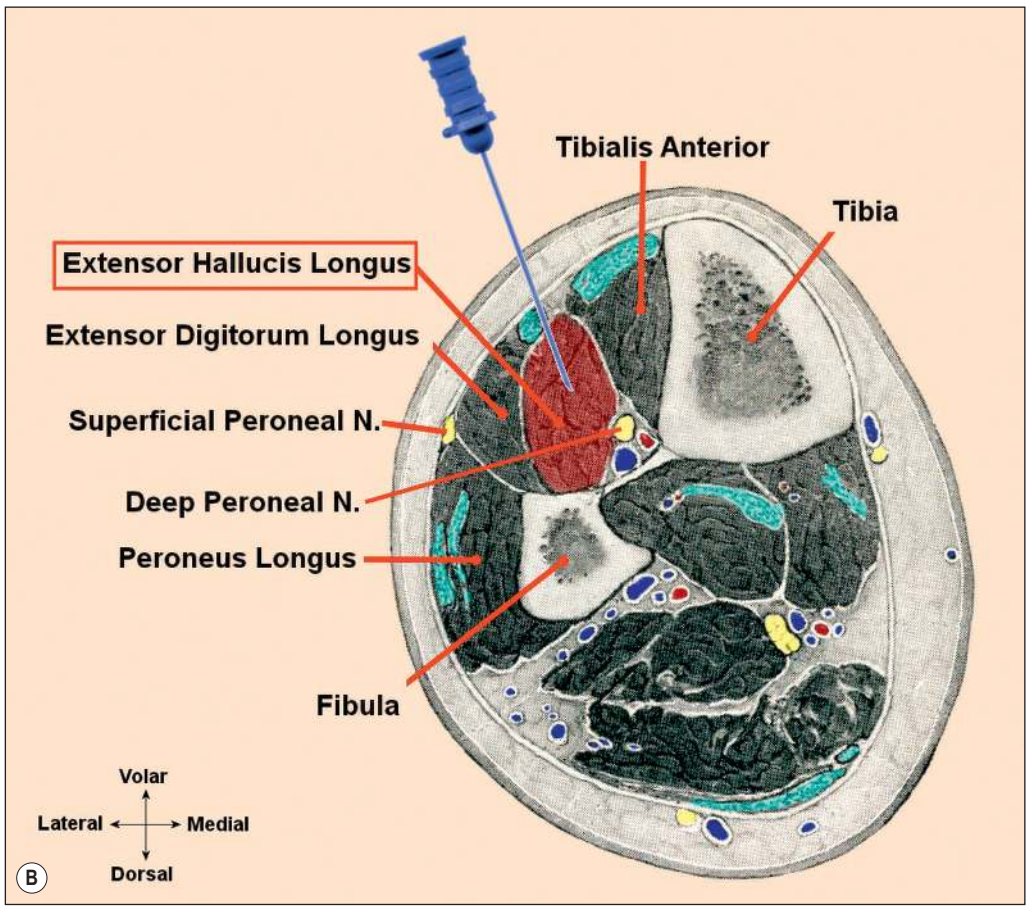
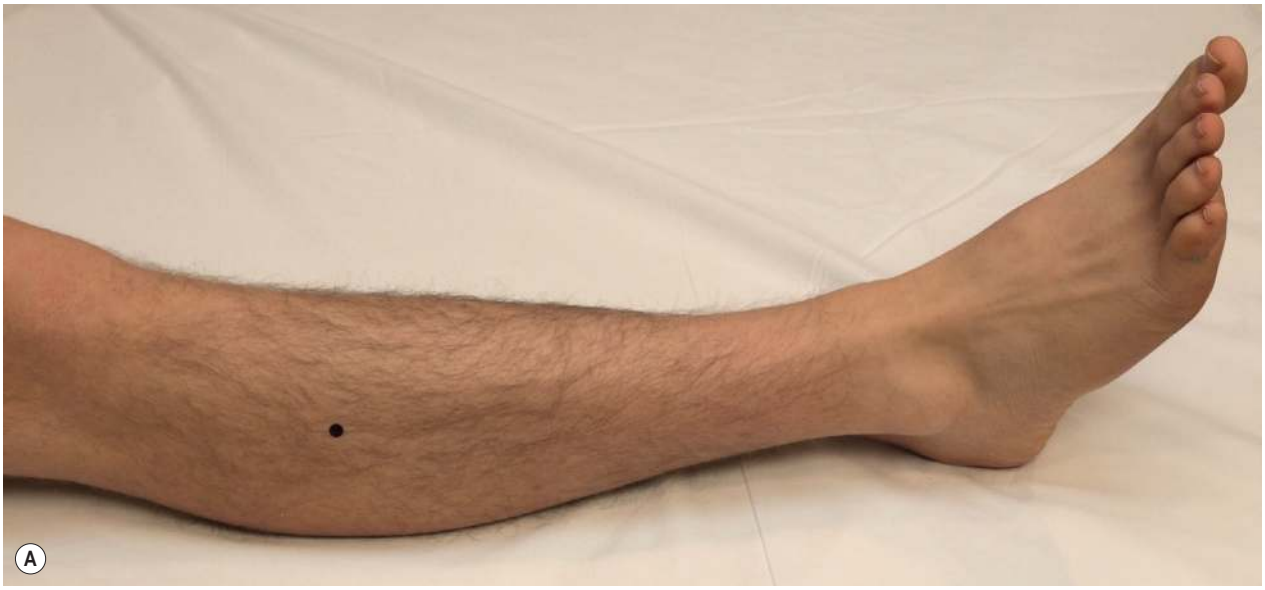


FIGURE 13–33 A. Extensor hallucis longus insertion point.
B. Cross-section anatomy*.



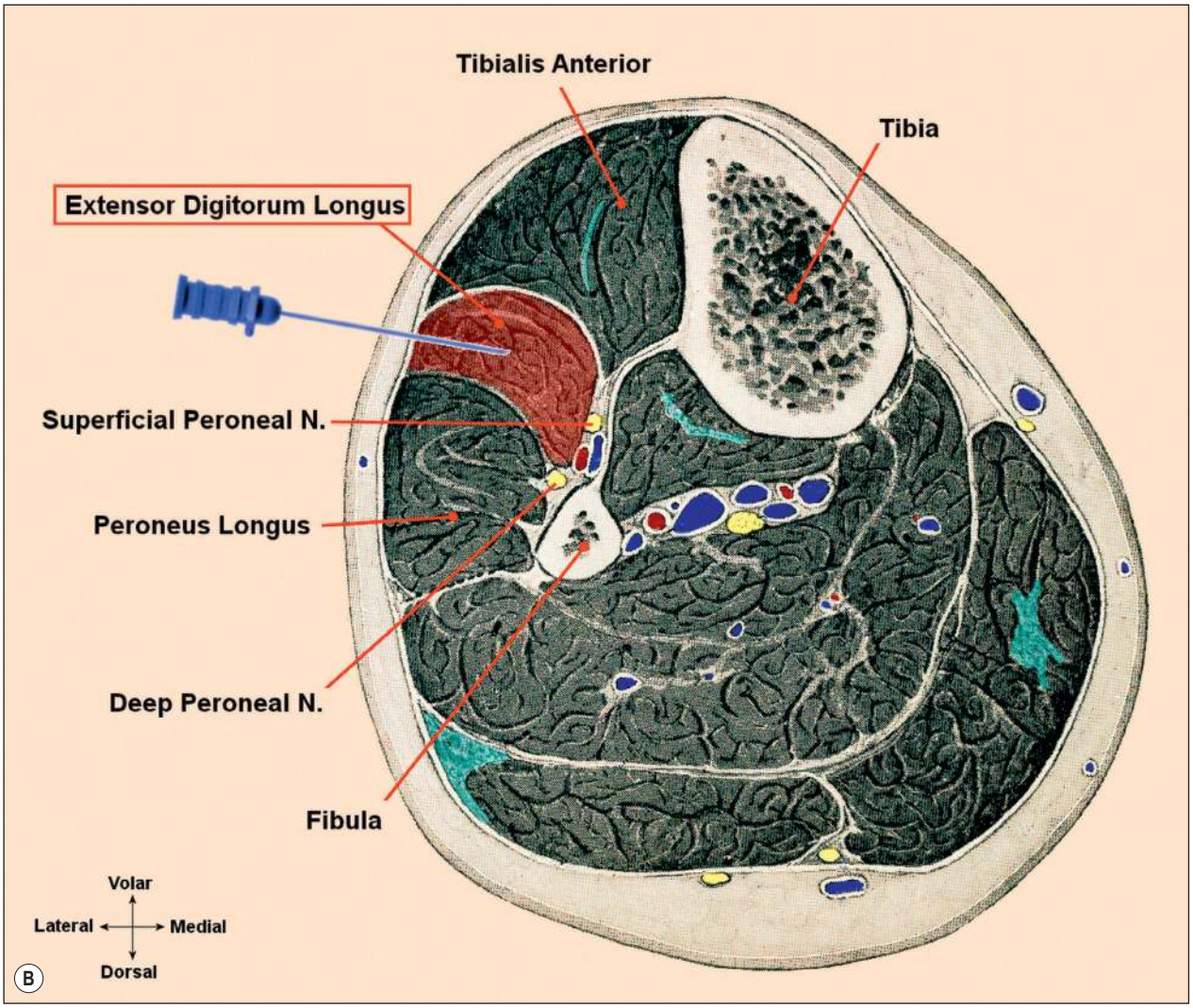


FIGURE 13–34 A. Extensor digitorum longus insertion point.
B. Cross-section anatomy*.

Tibialis Anterior (TA) *(Figure 13–35A,B)*

Innervation:

Deep peroneal nerve, common peroneal nerve, sciatic nerve, lumbosacral plexus, **L4–L5**

Needle Insertion:

Insert the needle just lateral to the tibial crest, two thirds the distance up from the ankle toward the knee

Activation:

Have the patient dorsiflex the ankle

Key Clinical Points:

- Often abnormal in L4 or L5 radiculopathy and lesions of the deep or common peroneal nerves.
- The TA is the simplest to localize and activate, of the deep peroneal nerve innervated muscles.

Cross-section Anatomy Key Points:

- As long as this muscle is sampled from the anterior lateral approach, there are no other nearby vascular structures or major nerves.

Peroneus Longus (PL) *(Figure 13–36A,B)*

Innervation:

Superficial peroneal nerve, common peroneal nerve, sciatic nerve, lumbosacral plexus, **L5**–S1

Needle Insertion:

Insert the needle into the lateral calf, three to four fingerbreadths distal to the fibular head

Activation:

Have the patient evert the ankle

Key Clinical Points:

- The PL is the most accessible muscle innervated by the superficial peroneal nerve.
- Often abnormal in lesions of the superficial or common peroneal nerves.

Cross-section Anatomy Key Points:

- If the needle is too anterior, it will be in the EHL.
- If the needle is too posterior, it will be in the soleus.
- C*aution*: if the needle is placed too deeply, the deep peroneal nerve is vulnerable to injury.

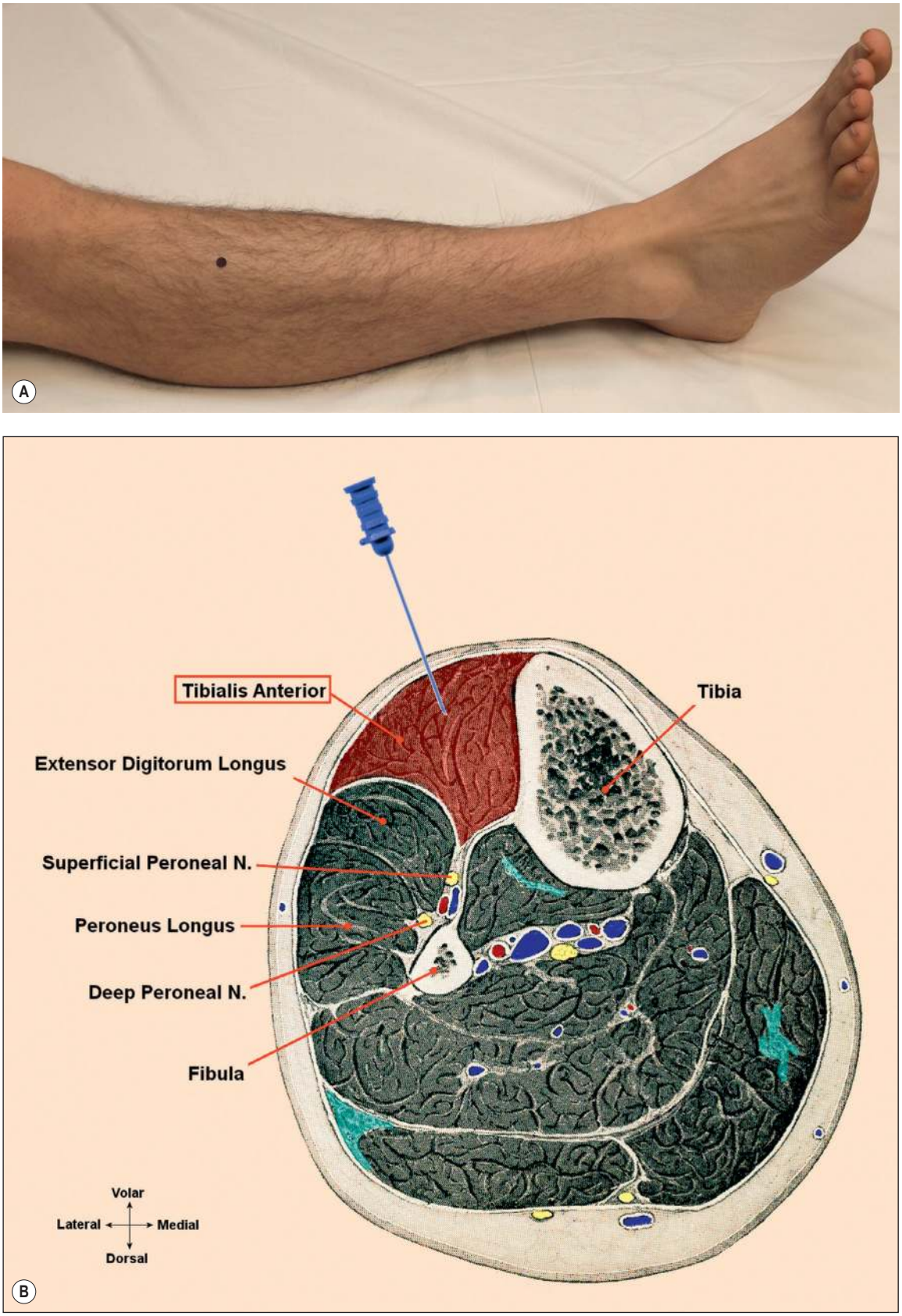


FIGURE 13–35 A. Tibialis anterior insertion point.
B. Cross-section anatomy*.

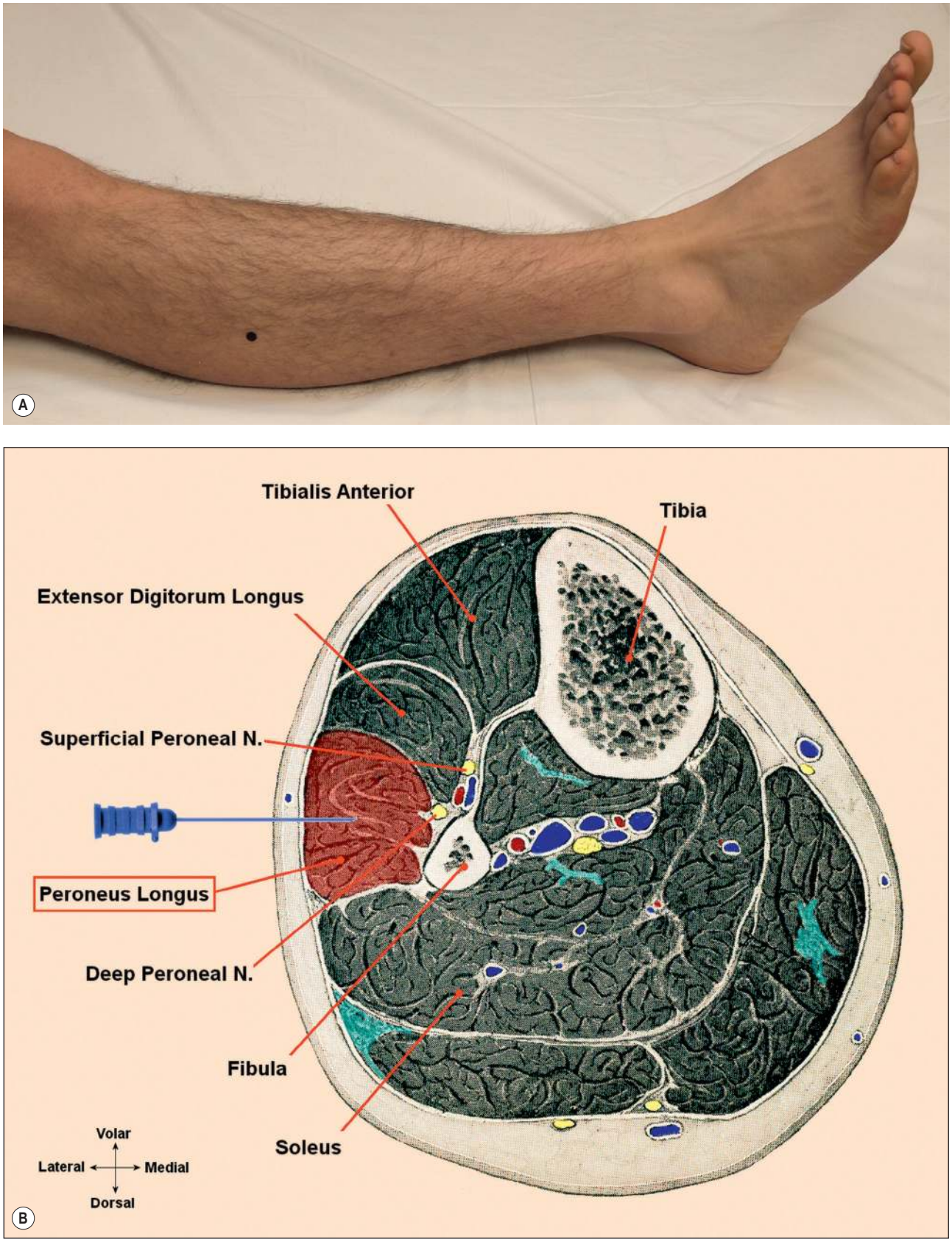


FIGURE 13–36 A. Peroneus longus insertion point.
B. Cross-section anatomy*.

TIBIAL NERVE

Abductor Hallucis Brevis (AHB)

(Figure 13–37A,B)

Innervation:

Medial plantar nerve, tibial nerve, sciatic nerve, lumbosacral plexus, **S1**–S2

Needle Insertion:

Insert the needle tangentially into the medial foot at the mid-point between the heel and the ball of the foot

Activation:

Have the patient spread the toes

Key Clinical Points:

- The AHB often is difficult to activate.
- The muscle often is perceived as painful.
- May be abnormal in tarsal tunnel syndrome.
- Use caution with the interpretation of abnormalities. Some denervation and reinnervation is common in normal subjects without symptoms. Side-to-side comparison can be useful.

Cross-section Anatomy Key Points:

- The muscle is very superficial.
- If the needle is placed too deeply, the medial plantar nerve is vulnerable to injury.

Flexor Hallucis Brevis (FHB) *(Figure 13–38A,B)*

Innervation:

Medial plantar nerve, tibial nerve, sciatic nerve, lumbosacral plexus, **S1**–S2

Needle Insertion:

Insert the needle into the medial sole, just below the ball of the foot, medial to the tendon of the flexor hallucis longus (FHL)

Activation:

Have the patient flex the great toe

Key Clinical Points:

- The FHB often is difficult to activate.
- It often is perceived as painful.
- May be abnormal in tarsal tunnel syndrome.
- It is not recommended to sample this muscle in patients with peripheral vascular insufficiency, especially associated with diabetes.
- Use caution with the interpretation of abnormalities. Some denervation and reinnervation is common in normal subjects without symptoms. Side-to-side comparison can be useful.

Cross-section Anatomy Key Points:

- If the needle is too medial, it will be in the AHB.
- Note how the tendon of the FHL runs superficial to the muscle.

Abductor Digiti Quinti Pedis (ADQP)

(Figure 13–39A,B)

Innervation:

Lateral plantar nerve, tibial nerve, sciatic nerve, lumbosacral plexus, **S1**–S2

Needle Insertion:

Insert the needle tangentially into the lateral foot two to three fingerbreadths proximal to the fifth metatarsal–phalangeal joint

Activation:

Have the patient spread the toes

Key Clinical Points:

- The ADQP often is difficult to activate.
- It often is perceived as painful.
- May be abnormal in tarsal tunnel syndrome.
- Use caution with the interpretation of abnormalities. Some denervation and reinnervation is common in normal subjects without symptoms. Side-to-side comparison can be useful.

Cross-section Anatomy Key Points:

- Note that the muscle is very superficial.
- Note that the tendon to the PL is just anterior.

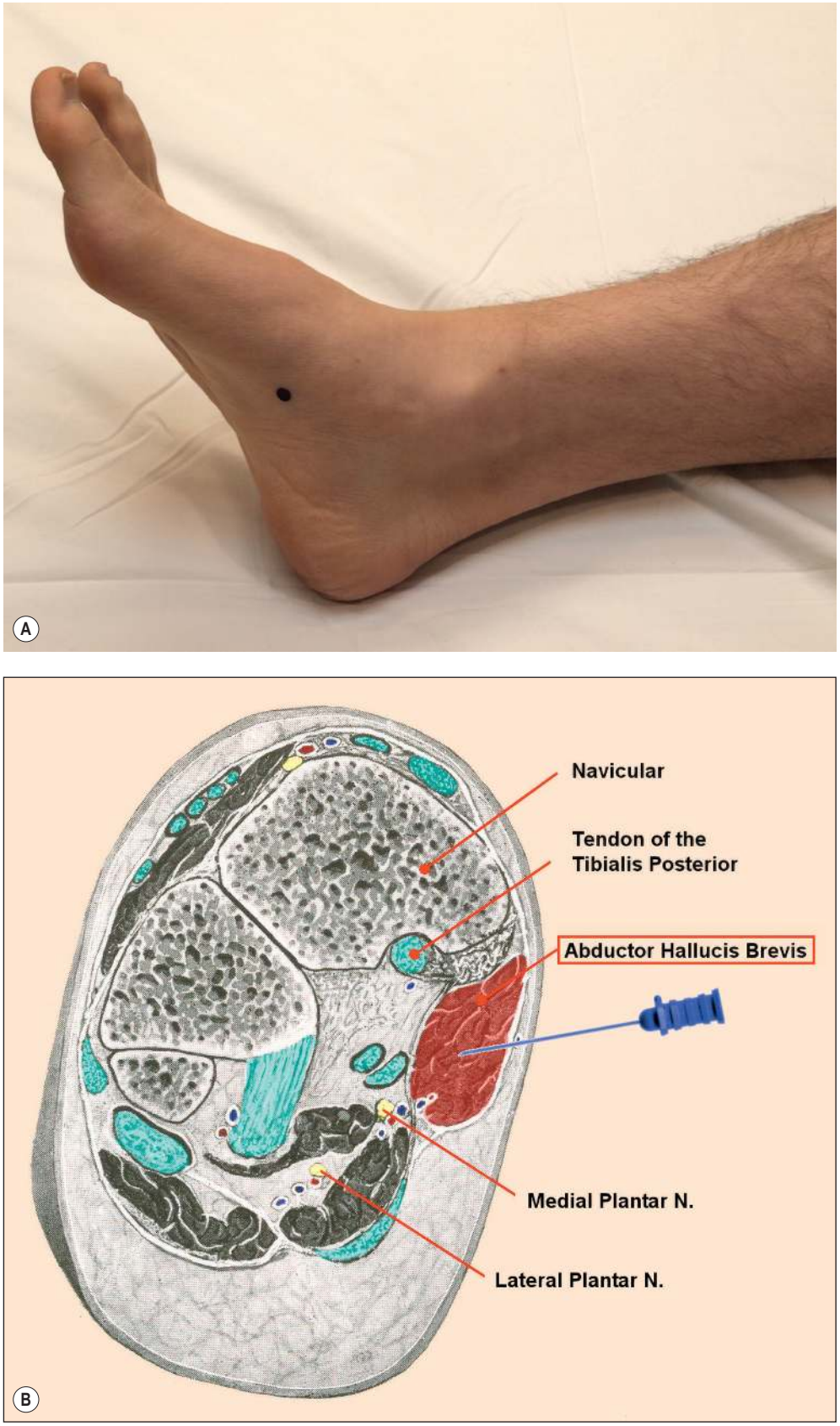


FIGURE 13–37 A. Abductor hallucis brevis insertion point.
B. Cross-section anatomy*.

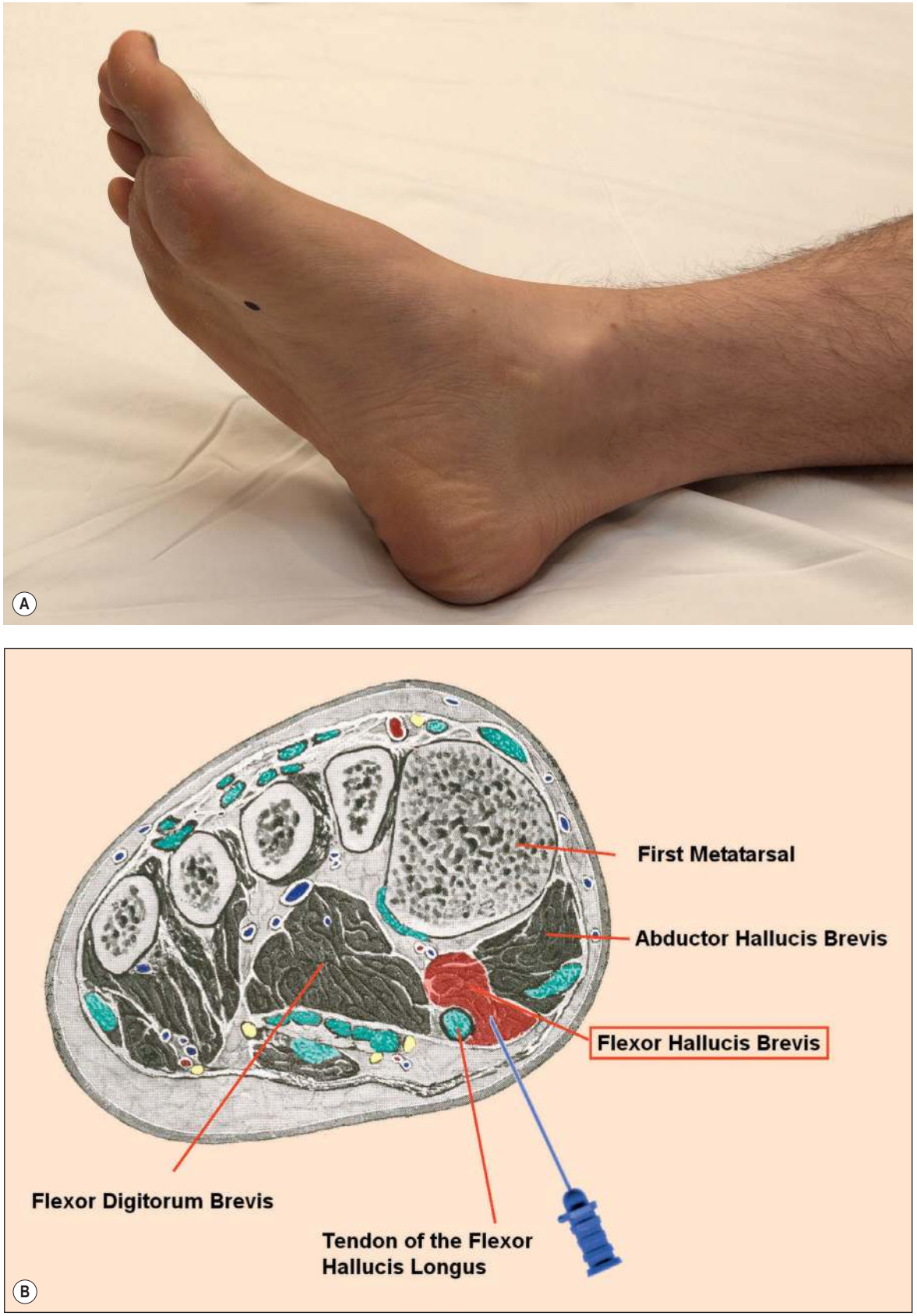
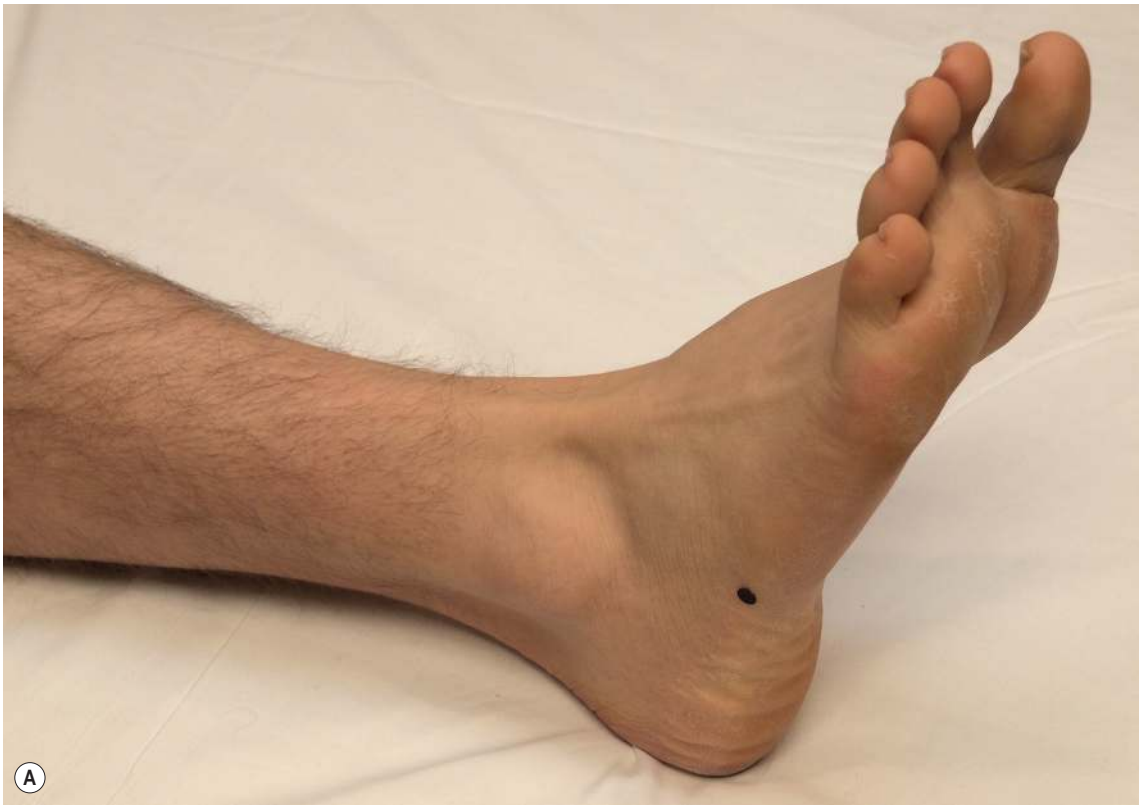


FIGURE 13–38 A. Flexor hallucis brevis insertion point. B. Cross-section anatomy*.



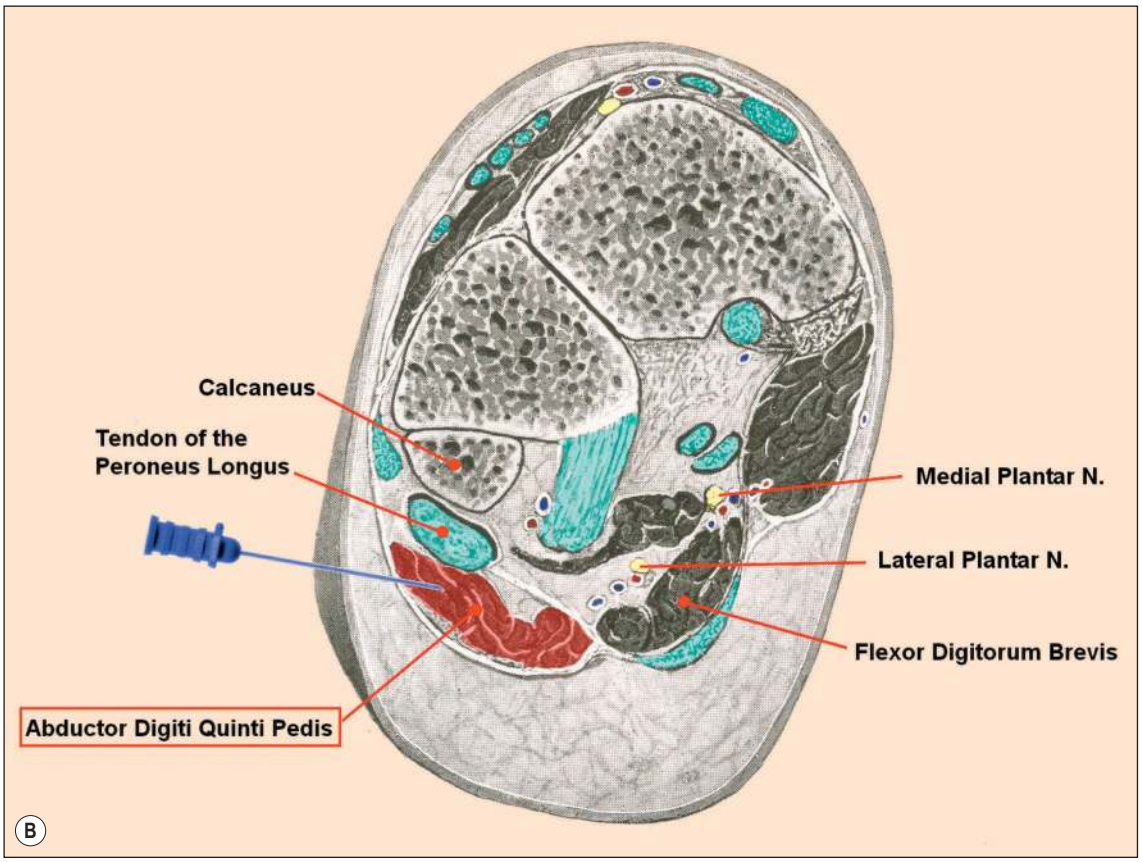


FIGURE 13–39 A. Abductor digiti quinti pedis insertion point.
B. Cross-section anatomy*.

Gastrocnemius–Medial Head (MG) *(Figure 13–40A,B)*

Innervation:

Tibial nerve, sciatic nerve, lumbosacral plexus, **S1**–S2

Needle Insertion:

Insert the needle into the rostral, medial posterior calf

Activation:

Have the patient plantar flex the ankle

Key Clinical Points:

- The MG often is difficult to activate. In some patients, activation can be more easily accomplished by flexing the knee first, and then having the patient plantar flex the ankle.
- It is a distal S1-innervated muscle and often is abnormal in S1 radiculopathy.
- For the assessment of S1 involvement, the MG is preferred over the lateral gastrocnemius (LG) as L5 does not innervate the MG, whereas some L5 fibers may be present in the LG.

Cross-section Anatomy Key Points:

- If the needle is too deep, it will be in the soleus. However, the soleus is supplied by the same nerve (tibial) and same myotomes (**S1**–S2).

Soleus (SOL) *(Figure 13–41A,B)*

Innervation:

Tibial nerve, sciatic nerve, lumbosacral plexus, **S1**–S2

Needle Insertion:

Insert the needle medial to the tibia, slightly distal to the mid-point between the ankle and knee

Activation:

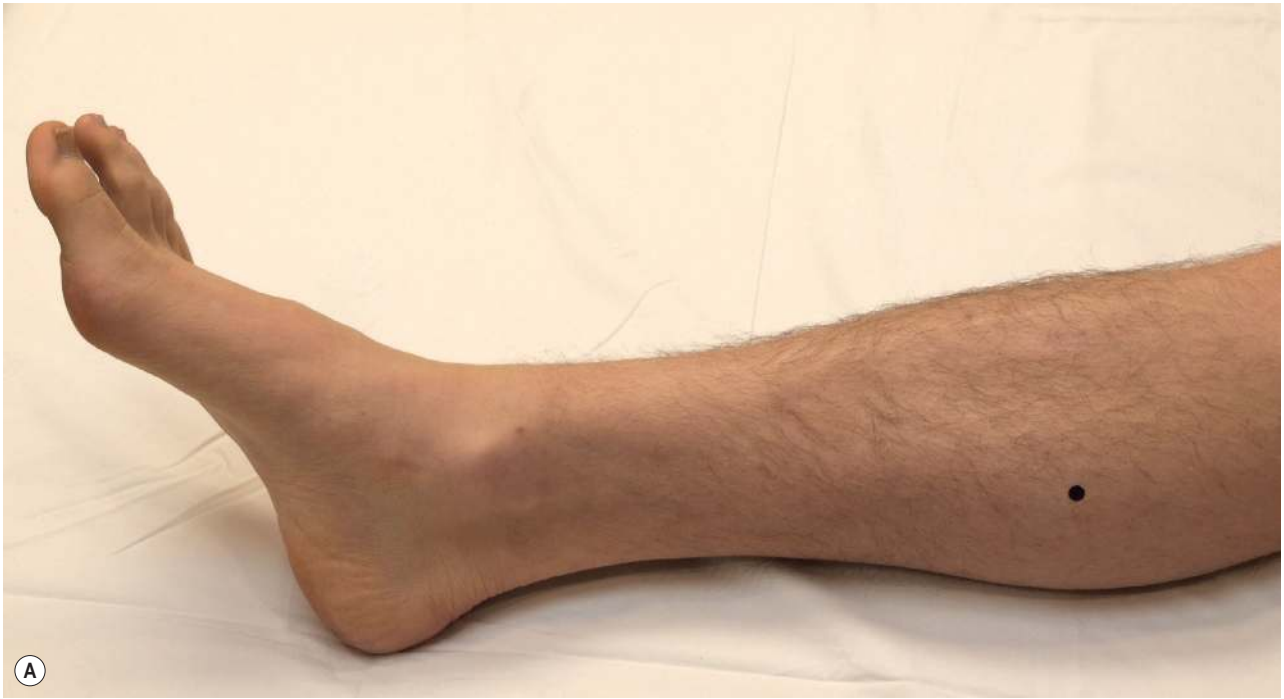
Have the patient plantar flex the ankle

Key Clinical Points:

- The SOL is difficult to activate.
- It is a distal S1-innervated muscle.

Cross-section Anatomy Key Points:

- If the needle is inserted with the needle pointing too anteriorly toward the tibia, it will be in the flexor digitorum longus.



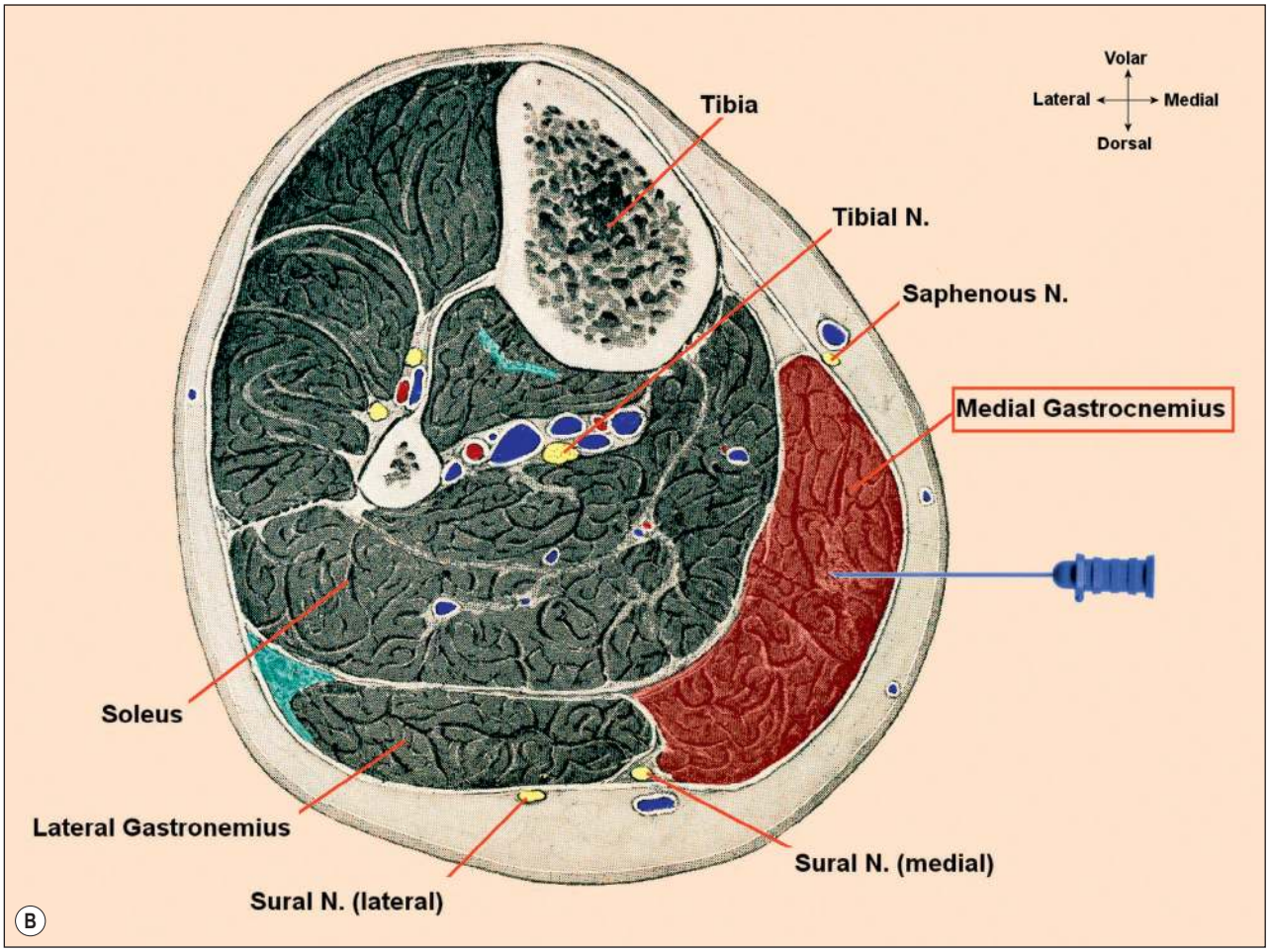
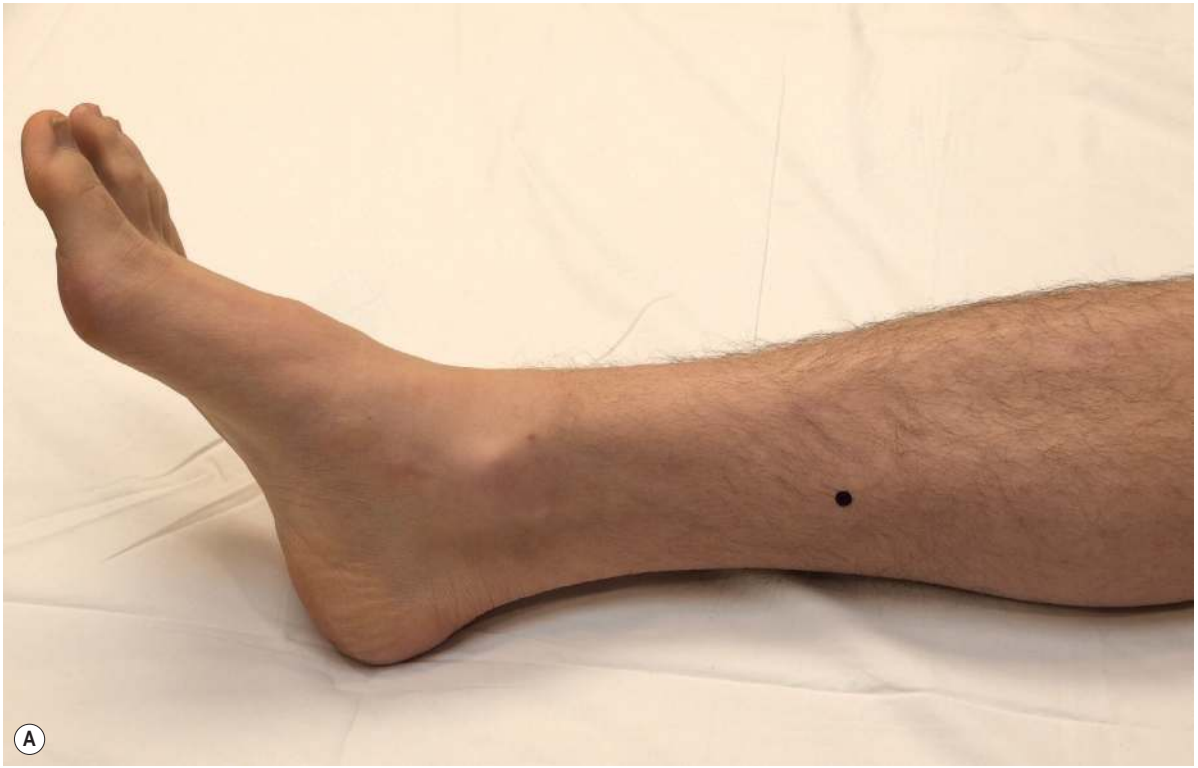


FIGURE 13–40 A. Gastrocnemius (medial head) insertion point.
B. Cross-section anatomy*.



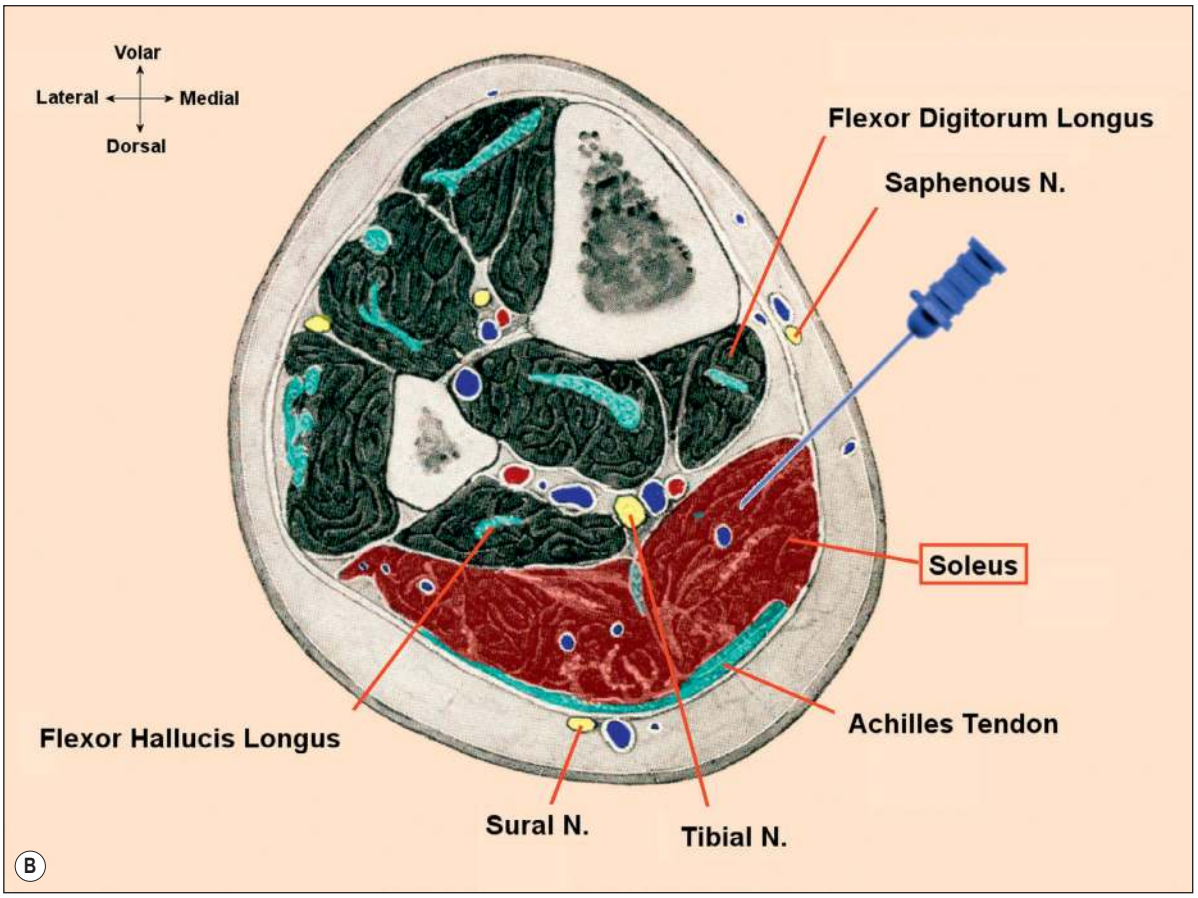


FIGURE 13–41 A. Soleus insertion points
B. Cross-section anatomy*.

Tibialis Posterior (TP) *(Figure 13–42A,B)*

Innervation:

Tibial nerve, sciatic nerve, lumbosacral plexus, **L5**–S1

Needle Insertion:

Insert the needle medial to the tibia, slightly distal to the mid-point between the ankle and knee, deep to the flexor digitorum longus

Activation:

Have the patient invert the ankle

Key Clinical Points:

- The TP is a predominantly L5-innervated tibial muscle.
- Extremely useful in the evaluation of foot drop in differentiating peroneal neuropathy from sciatic nerve lesion, lumbosacral plexopathy, or L5 radiculopathy.
- A deep muscle, the TP often requires a longer needle (37 mm).

Cross-section Anatomy Key Points:

- If the needle is inserted too superficially, it will be in the flexor digitorum longus.
- *Caution*: if the needle is inserted pointing too posterior, the tibial nerve and nearby vascular structures are vulnerable to injury.

Flexor Digitorum Longus (FDL) *(Figure 13–43A,B)*

Innervation:

Tibial nerve, sciatic nerve, lumbosacral plexus, **L5**–S1

Needle Insertion:

Insert the needle medial to the tibia, slightly distal to the mid-point between the ankle and knee, deep to the soleus

Activation:

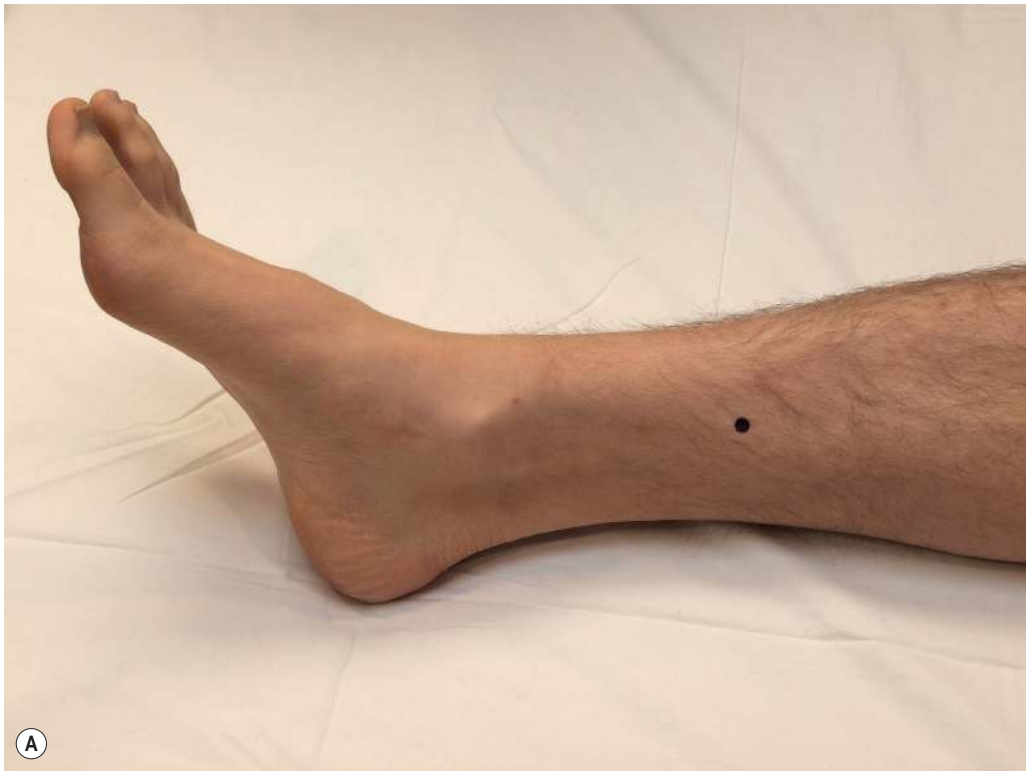
Have the patient flex the toes

Key Clinical Points:

- The FDL is a predominantly L5-innervated muscle.
- Useful in the evaluation of foot drop in differentiating peroneal neuropathy from sciatic nerve lesion, lumbosacral plexopathy, or L5 radiculopathy.

Cross-section Anatomy Key Points:

- *Caution*: the saphenous nerve is just anterior to the needle insertion site.
- *Caution*: if the needle is inserted at the correct location but directed too posteriorly, the tibial nerve and nearby vascular structures are vulnerable to injury.
- If the needle is inserted too posteriorly, or directed posteriorly, it will be in the soleus.
- If the needle is too deep, it will be in the tibialis posterior.



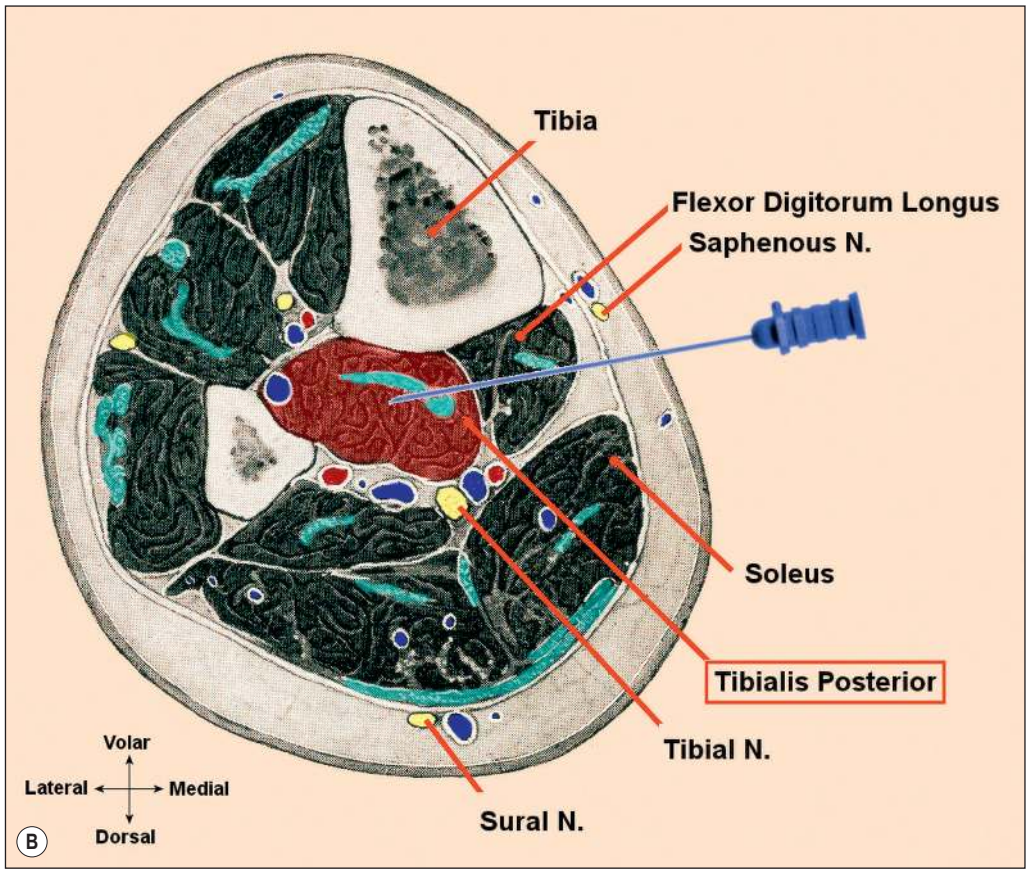


FIGURE 13–42 A. Tibialis posterior insertion point.
B. Cross-section anatomy*.

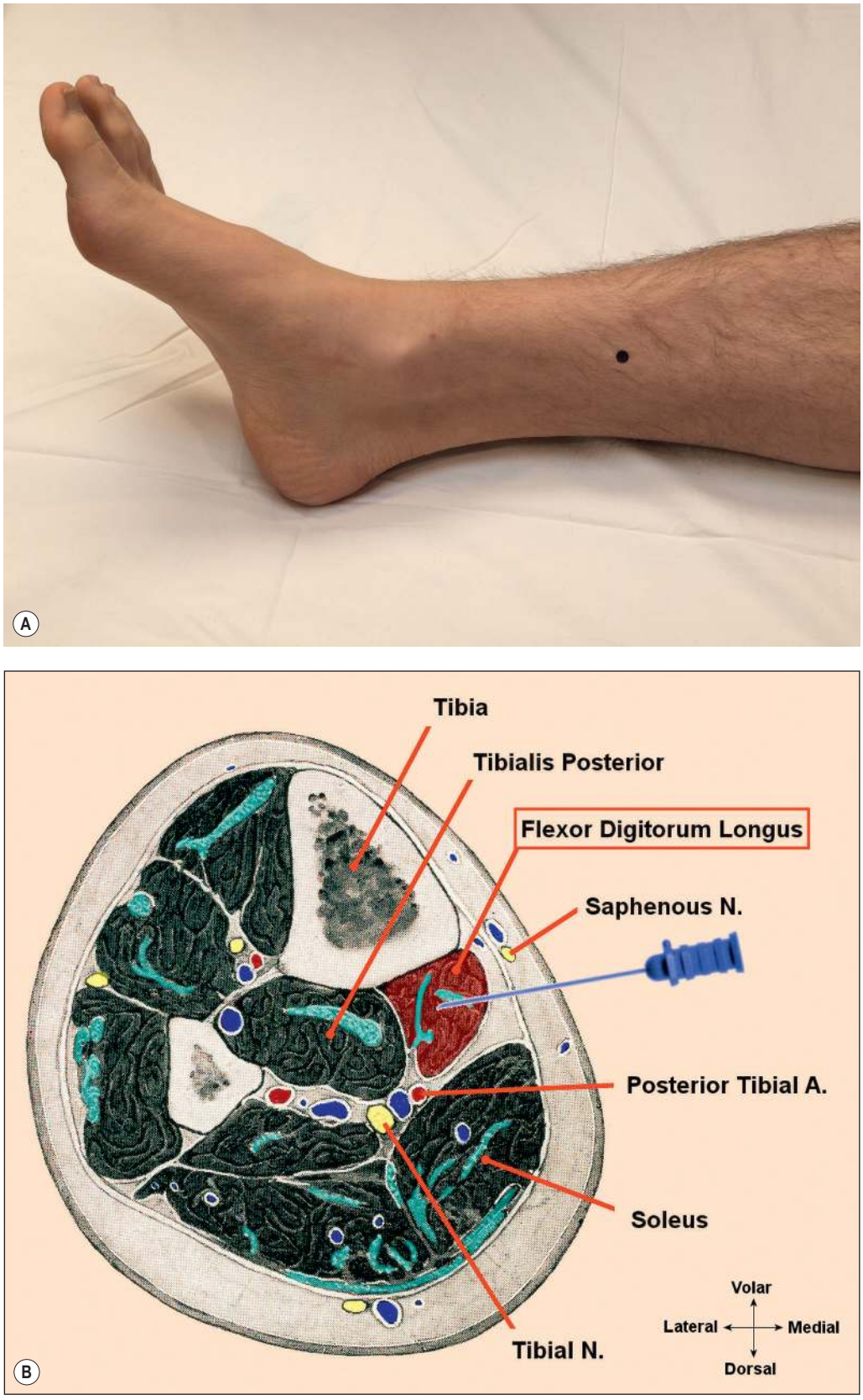


FIGURE 13–43 A. Flexor digitorum longus insertion point.
B. Cross-section anatomy*.

SCIATIC NERVE (NOTE THAT ALL PERONEAL- AND TIBIAL-INNERVATED MUSCLES ALSO ARE SCIATIC INNERVATED)

Biceps Femoris–Short Head (BF–SH)

(Figure 13–44A,B)

Innervation:

Sciatic nerve (peroneal division), lumbosacral plexus, L5–**S1**

Needle Insertion:

Insert the needle three to four fingerbreadths proximal to the lateral knee, medial to the tendon to the long head of the biceps femoris

Activation:

Have the patient flex the knee

Key Clinical Points:

- The BF–SH is the only muscle innervated by the peroneal division of the sciatic nerve above the fibular neck.
- Important to check in suspected lesions of the peroneal nerve at the fibular neck. In peroneal lesions at the fibular neck, it will be normal. In sciatic lesions or higher that mimic clinically a peroneal neuropathy at the fibular neck, this muscle may be abnormal.

Cross-section Anatomy Key Points:

- *Caution*: if the needle is directly too medially and too deep, the sciatic nerve is vulnerable to injury. The muscle is very superficial.
- The muscle can also be sampled by inserting the needle anterior to the tendon of the long head of the biceps femoris – however, there the needle must be directed downward.

Biceps Femoris–Long Head (BF–LH)

(Figure 13–45A,B)

Innervation:

Sciatic nerve (tibial division), lumbosacral plexus, L5–**S1**

Needle Insertion:

Insert the needle at the mid-point between the lateral knee and the ischial tuberosity

Activation:

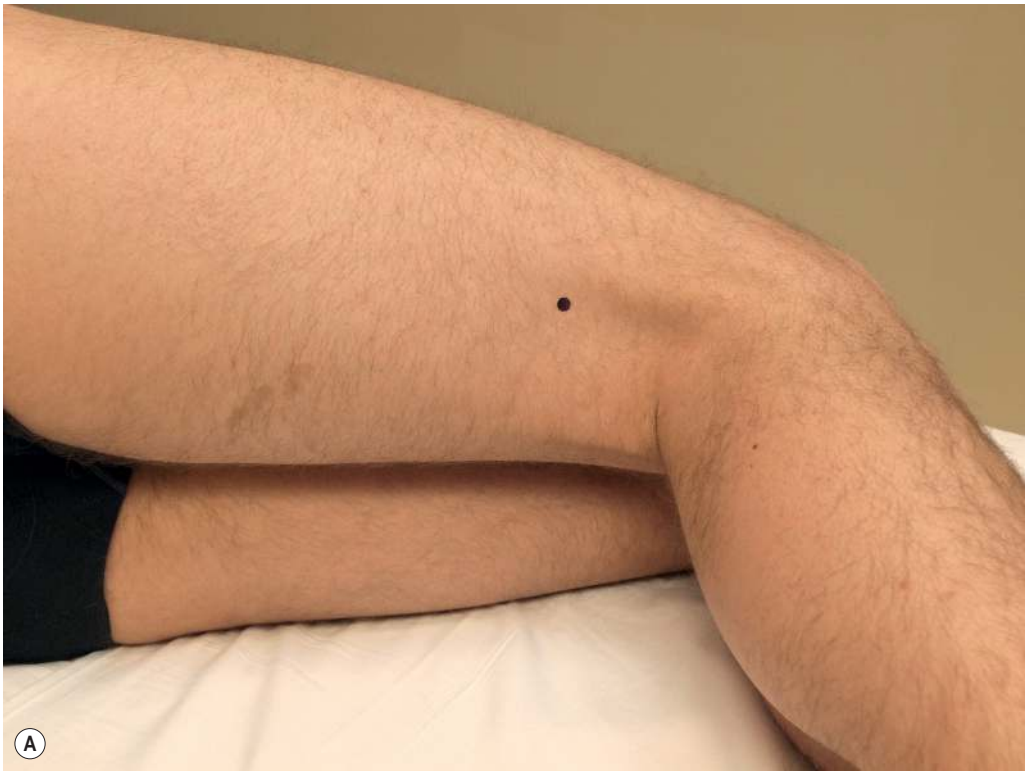
Have the patient flex the knee

Key Clinical Points:

- The BF–LH may be abnormal in sciatic nerve lesions, lumbosacral plexopathy, or S1 radiculopathy. In general the lateral hamstrings are predominantly S1 whereas the medial hamstrings are L5.

Cross-section Anatomy Key Points:

- At this location more proximal in the thigh, only the long head of the biceps femoris is present on needle EMG in the lateral posterior thigh (the short head is more distal in the thigh).
- If the needle is too posterior, it will be in the semitendinosus.



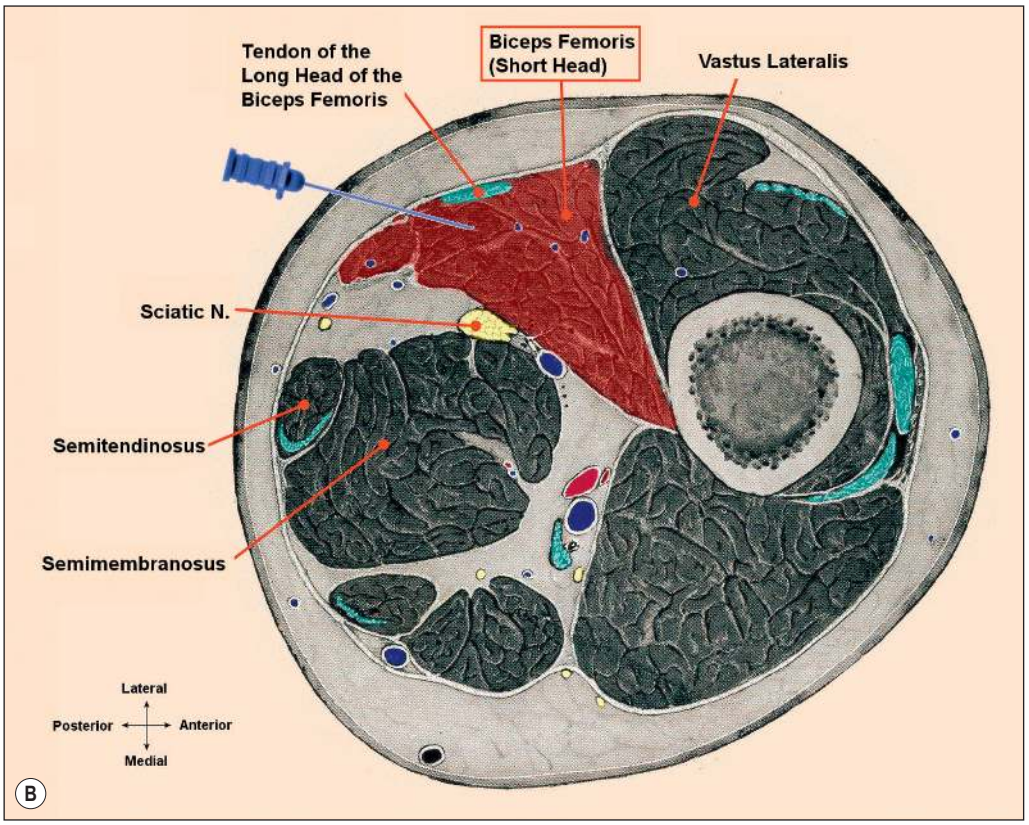
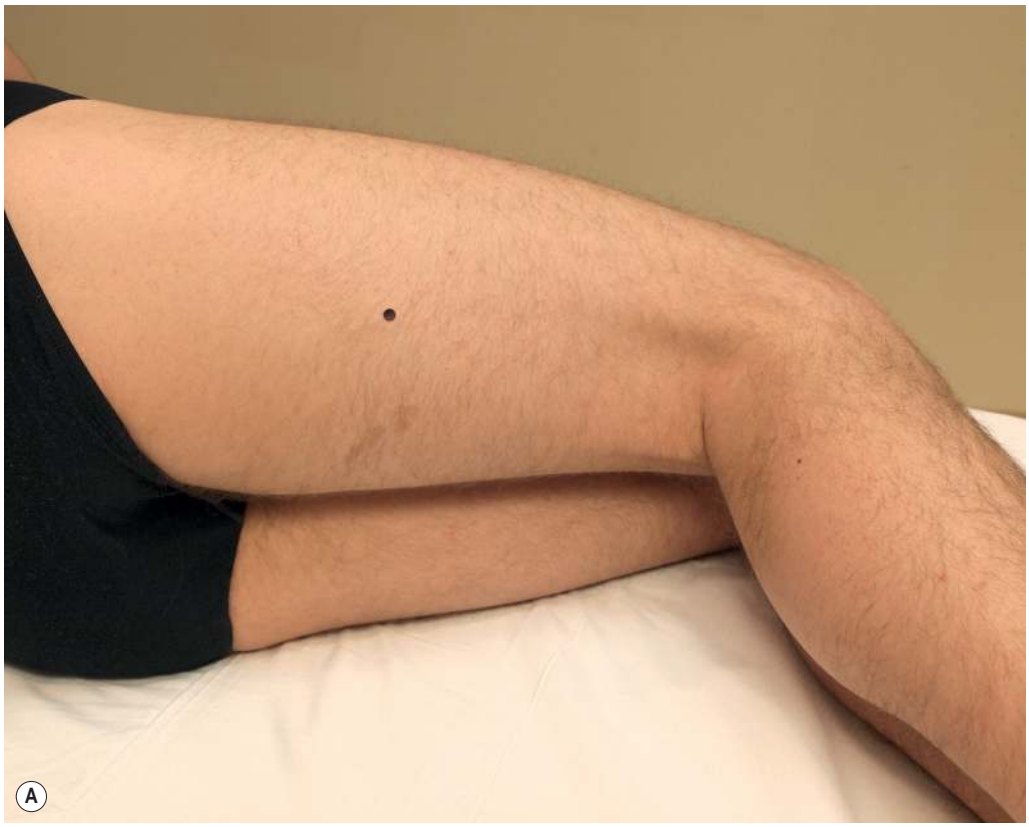


FIGURE 13–44 A. Biceps femoris (short head) insertion point.
B. Cross-section anatomy*.



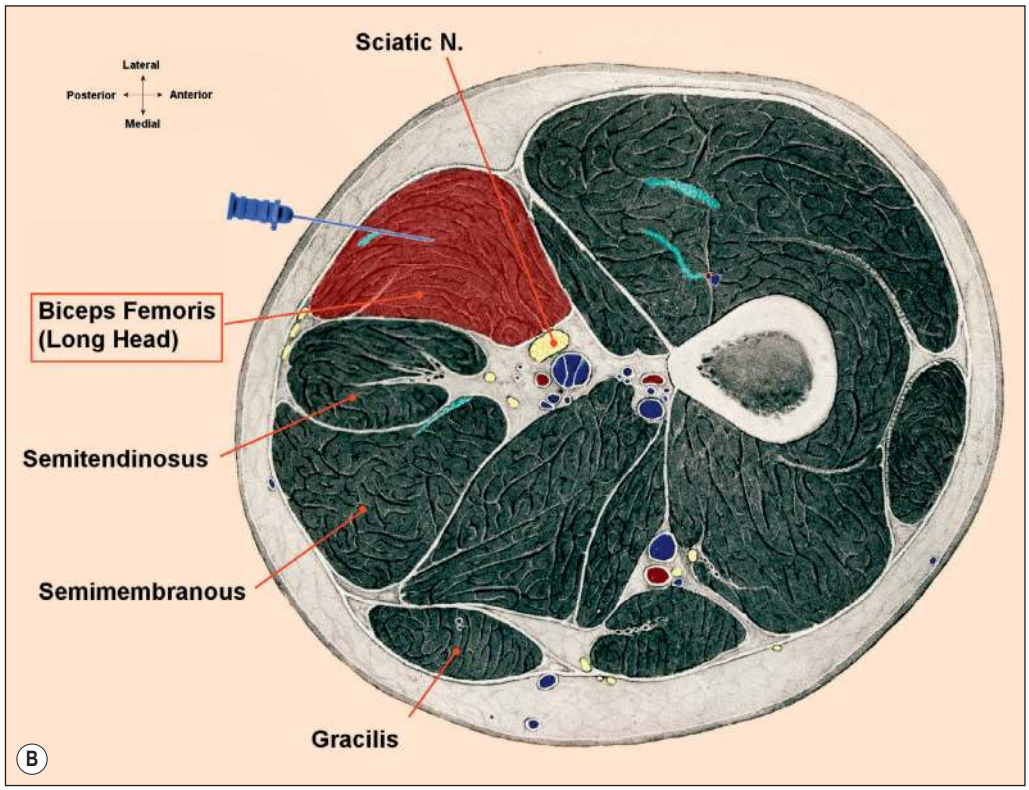


FIGURE 13–45 A. Biceps femoris (long head) insertion point.
B. Cross-section anatomy*.

Semimembranosus (SM) *(Figure 13–46A,B)*

Innervation:

Sciatic nerve (tibial division), lumbosacral plexus, L4–**L5**–S1

Needle Insertion:

Insert the needle three to four fingerbreadths proximal to the medial knee, lateral to the tendon of the semitendinosus

Activation:

Have the patient flex the knee

Key Clinical Points:

- May be abnormal in sciatic nerve lesions, lumbosacral plexopathy, or L5 radiculopathy. In general, the medial hamstrings are predominantly L5 whereas the lateral hamstrings are S1.

Cross-section Anatomy Key Points:

- Although the SM can be sampled along the entire medial thigh, at this location distal in the thigh, only the SM is present. The semitendinosus is predominantly tendinous at this location. Thus, sampling the medial hamstrings distally in the thigh samples the SM.

Semitendinosus (ST) *(Figure 13–47A,B)*

Innervation:

Sciatic nerve (tibial division), lumbosacral plexus, L4–**L5**–S1

Needle Insertion:

Insert the needle into the posterior thigh at the midpoint between the medial knee and ischial tuberosity

Activation:

Have the patient flex the knee

Key Clinical Points:

- May be abnormal in sciatic nerve lesions, lumbosacral plexopathy, or L5 radiculopathy. In general the medial hamstrings are predominantly L5 whereas the lateral hamstrings are S1.

Cross-section Anatomy Key Points:

- If the needle is too anterior, it will be in the long head of the biceps femoris.
- If the needle is too posterior, it will be in the SM. However, the SM and ST have the same nerve (sciatic) and myotomal (L4–**L5**–S1) innervation.

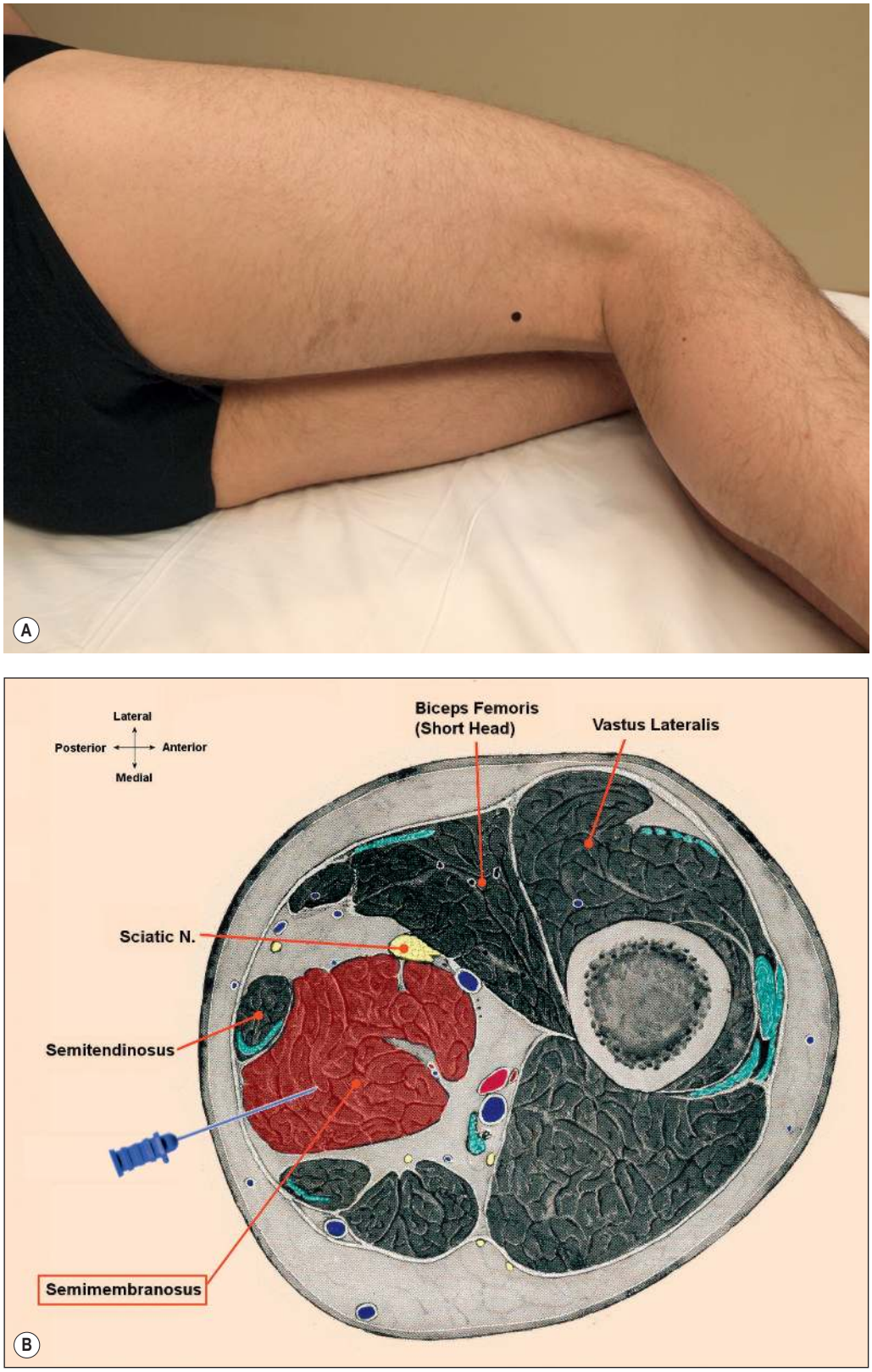


FIGURE 13–46 A. Semimembranosus insertion point.
B. Cross-section anatomy*.

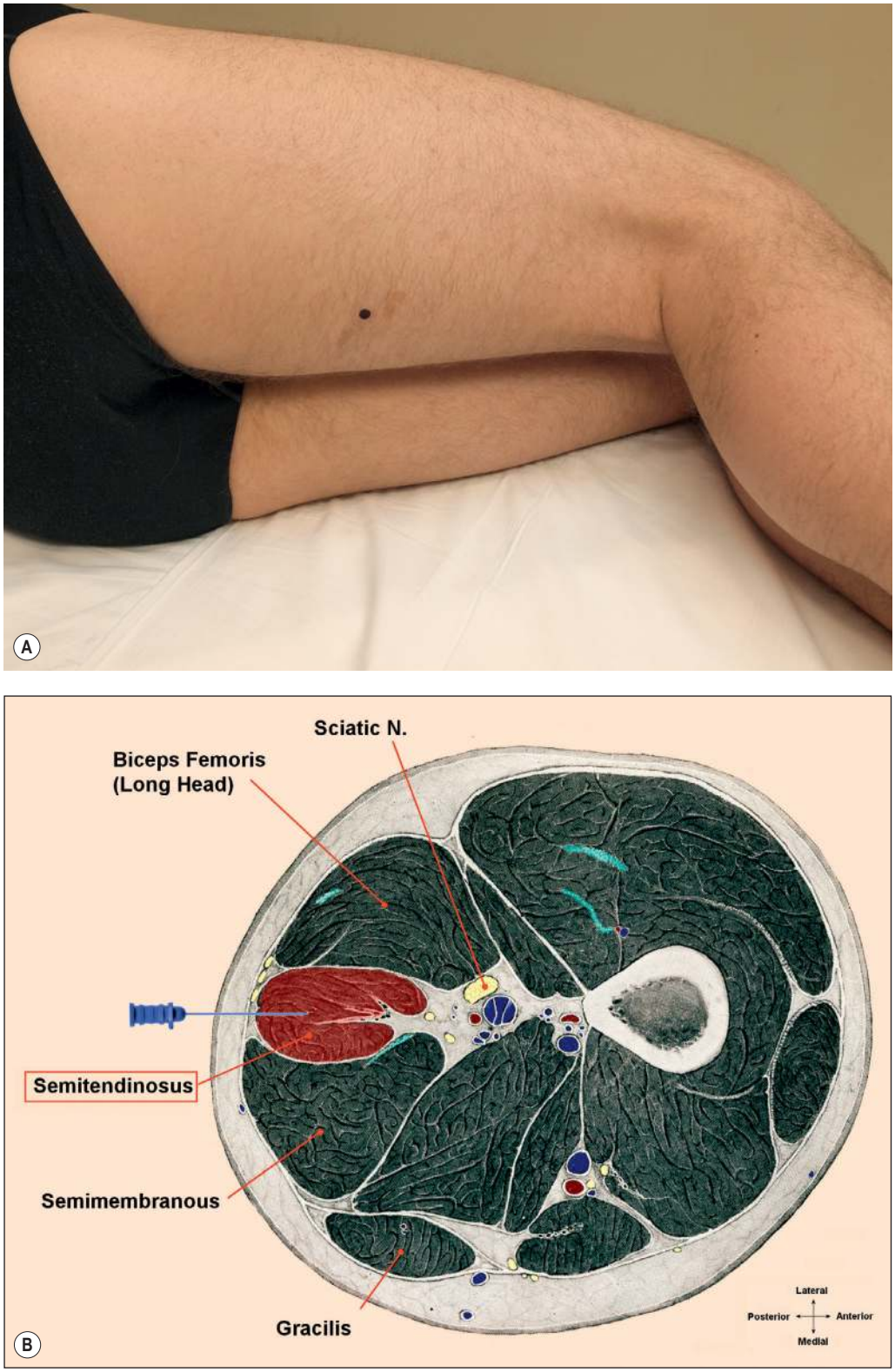


FIGURE 13–47 A. Semitendinosus insertion point.
B. Cross-section anatomy*.

OBTURATOR NERVE

Thigh Adductors (Gracilis, Adductor Longus, Adductor Magnus)

(Figure 13–48A,B)

Innervation:

Obturator nerve, lumbar plexus, L2–**L3**–L4

Needle Insertion:

Insert the needle into the medial thigh, three to four fingerbreadths distal to the pubis

Activation:

Have the patient adduct the thigh

Key Clinical Points:

- The thigh adductor muscles can be thought of as a functional unit that includes the adductor longus and brevis, gracilis and adductor magnus. In most individuals, adipose over the medial thigh makes anatomic differentiation difficult to impossible among these muscles. However, as they are all supplied by the same nerve (obturator) and same myotomes (L2–**L3**–L4), it is not critical to sample one specific muscle as opposed to another. The very lateral part of the adductor magnus is supplied by the sciatic nerve; however, as this part of the muscle is so deep, sampling it by mistake is not an issue.
- Useful to help differentiate lesions of the lumbar plexus or lumbar roots from femoral neuropathy.
- Often requires longer length needle to sample (37 or 50 mm).

Cross-section Anatomy Key Points:

- As long as this muscle is sampled from the medial approach, there are no other nearby vascular structures or major nerves.

FEMORAL NERVE

Vastus Lateralis (VL) *(Figure 13–49A,B)*

Innervation:

Femoral nerve, lumbar plexus, L2–**L3–L4**

Needle Insertion:

Insert the needle into the lateral thigh four to five fingerbreadths proximal to the lateral knee

Activation:

Have the patient extend the knee while lifting the heel from the bed

Key Clinical Points:

- Often abnormal in lesions of the femoral nerve, lumbar plexus, or lumbar roots.

Cross-section Anatomy Key Points:

- As long as this muscle is sampled from the lateral approach, there are no other nearby vascular structures or major nerves.
- If the needle is too deep, it will be in the vastus intermedialis. However, this muscle is supplied by the same nerve (femoral) and same myotomes (L2–**L3–L4**) as the VL.

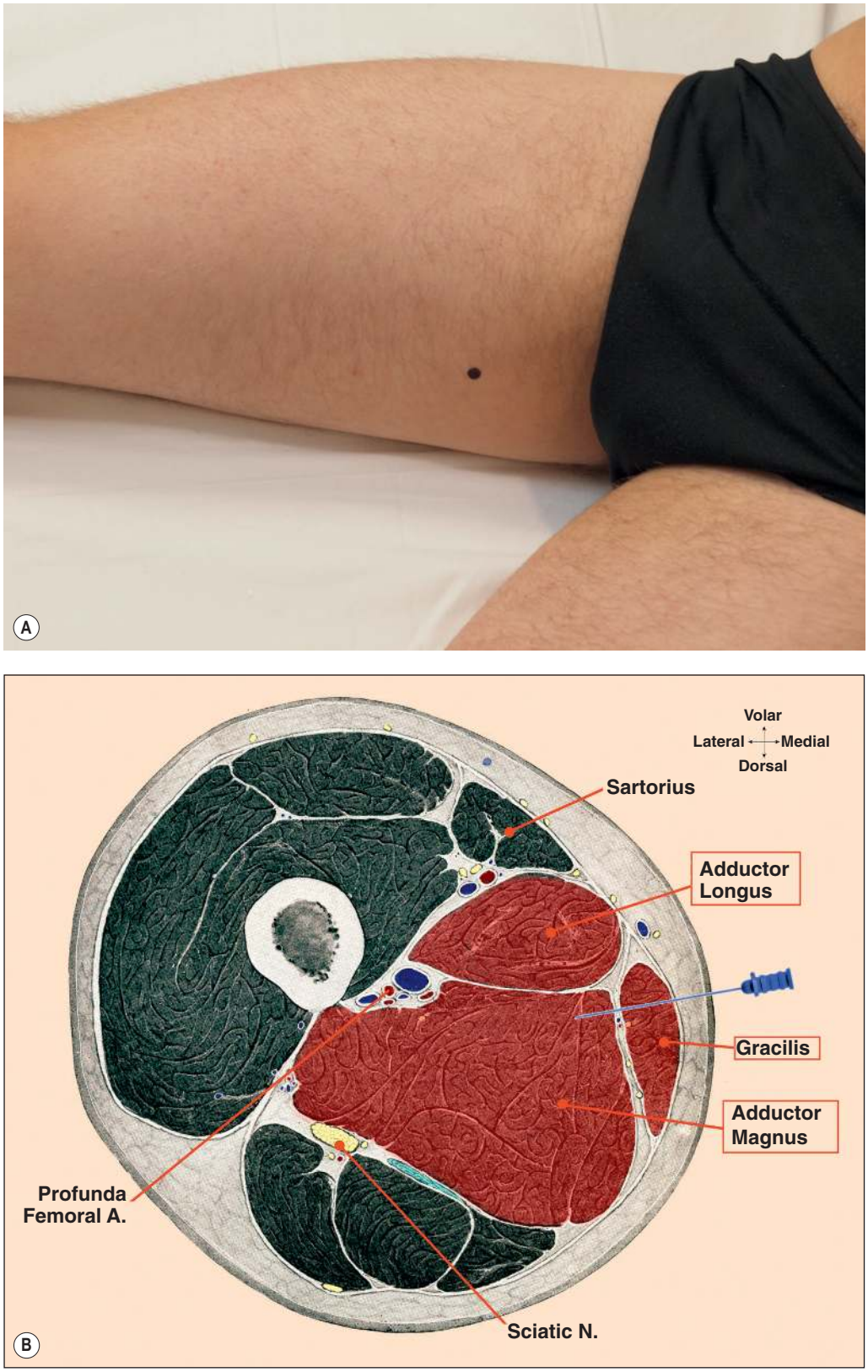


FIGURE 13–48 A. Thigh adductors insertion point.
B. Cross-section anatomy*.

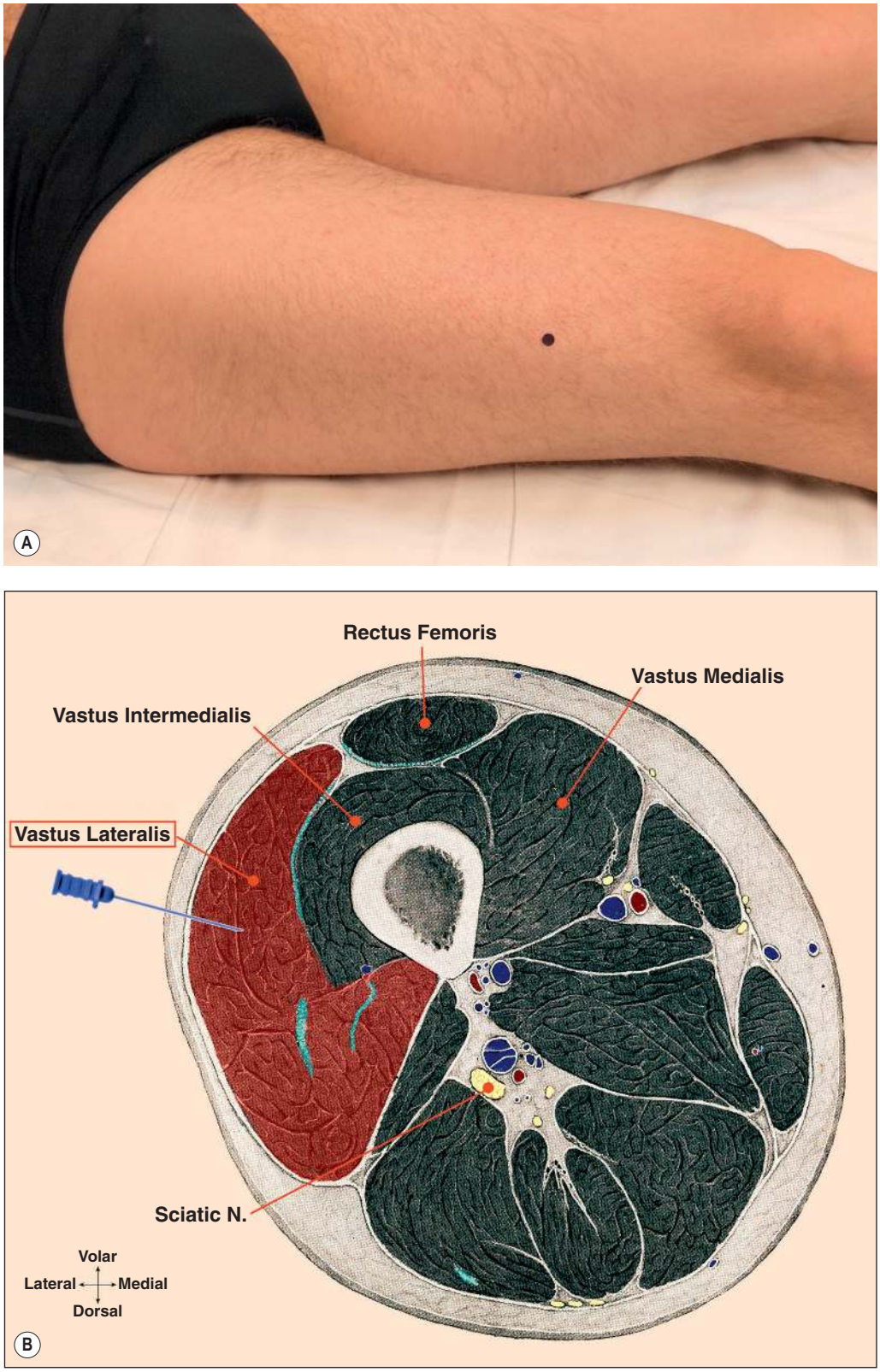


FIGURE 13–49 A. Vastus lateralis insertion point.
B. Cross-section anatomy*.

Vastus Medialis (VM) *(Figure 13–50A,B)*

Innervation:

Femoral nerve, lumbar plexus, L2–**L3–L4**

Needle Insertion:

Insert the needle into the medial thigh three to four fingerbreadths proximal to the medial knee

Activation:

Have the patient extend the knee while lifting the heel from bed

Key Clinical Points:

- Often abnormal in lesions of the femoral nerve, lumbar plexus, or lumbar roots.

Cross-section Anatomy Key Points:

- As long as this muscle is sampled from the medial approach, there are no other nearby vascular structures or major nerves.

Rectus Femoris (RF) *(Figure 13–51A,B)*

Innervation:

Femoral nerve, lumbar plexus, **L2–L3**–L4

Needle Insertion:

Insert the needle into the anterior thigh, at the mid-point between the hip and knee

Activation:

Have the patient extend the knee while lifting the heel from bed

Key Clinical Points:

- The RF is more difficult to activate than the VM or the VL.
- The RF is more of a hip flexor than a knee extensor.
- Often abnormal in lesions of the femoral nerve, lumbar plexus, or lumbar roots.

Cross-section Anatomy Key Points:

- As long as this muscle is sampled from the anterior approach, there are no other nearby vascular structures or major nerves.
- If the needle is too deep, it will be in the vastus intermedialis.

Iliacus *(Figure 13–52A,B)*

Innervation:

Femoral nerve, lumbar plexus, **L2–L3**–L4

Needle Insertion:

Insert the needle two to three fingerbreadths lateral to the femoral pulse below the inguinal ligament

Activation:

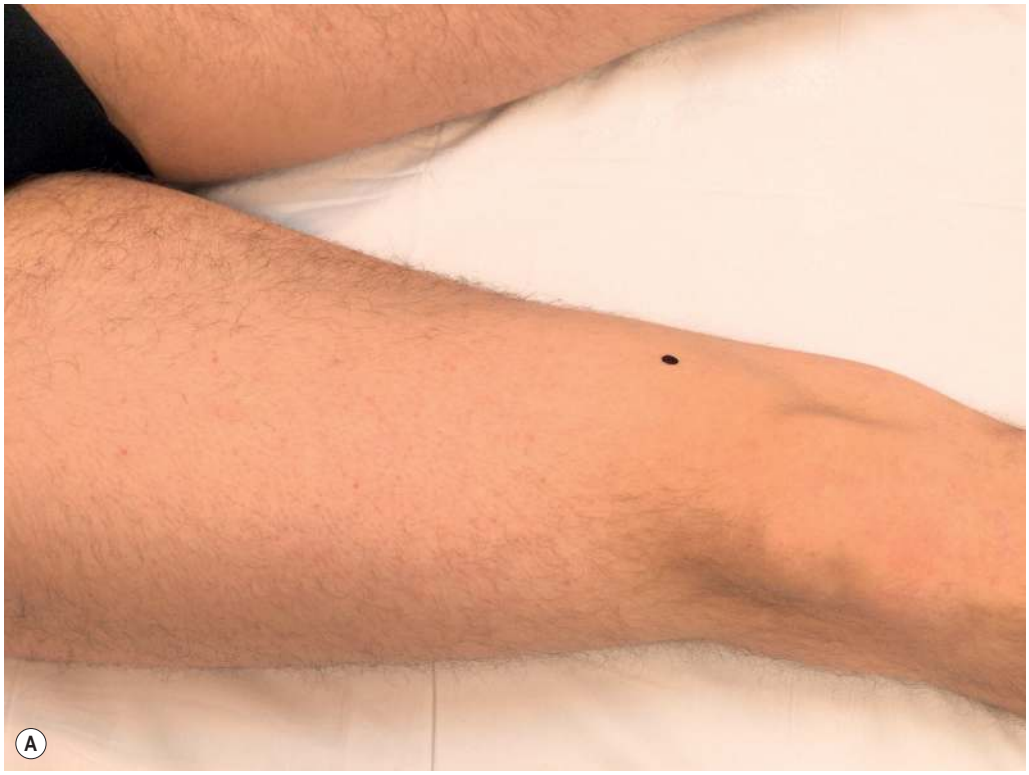
Have the patient flex the hip

Key Clinical Points:

- The iliacus and psoas form a functional unit that flexes the hip (the iliopsoas). However, at this site, only the iliacus is actually sampled.
- The iliacus is spared in entrapment of the femoral nerve at the inguinal ligament.
- This muscle is a useful proximal muscle to sample for myopathy and high lumbar radiculopathy.

Cross-section Anatomy Key Points:

- C*aution*: if the needle is too medial, the femoral nerve, artery and vein are vulnerable.
- If the needle is too superficial and slightly lateral, it may be in the Sartorius.
- C*aution*: the lateral femoral cutaneous nerve is just lateral to the insertion point.



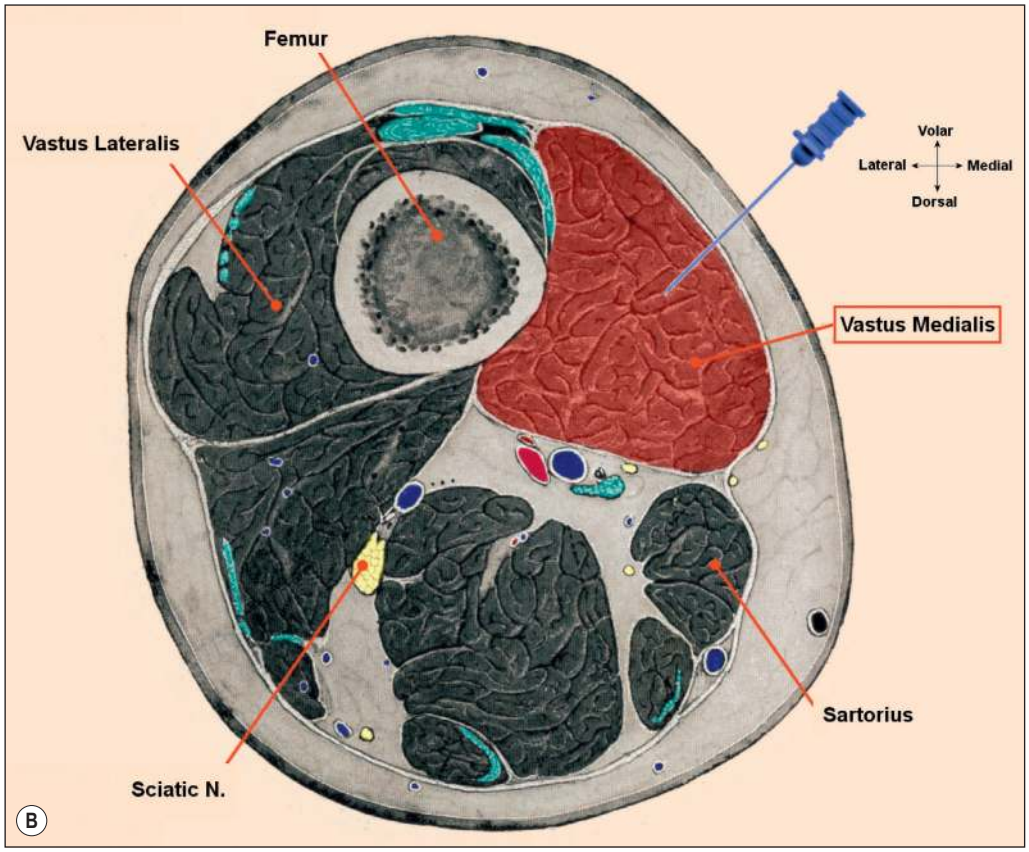
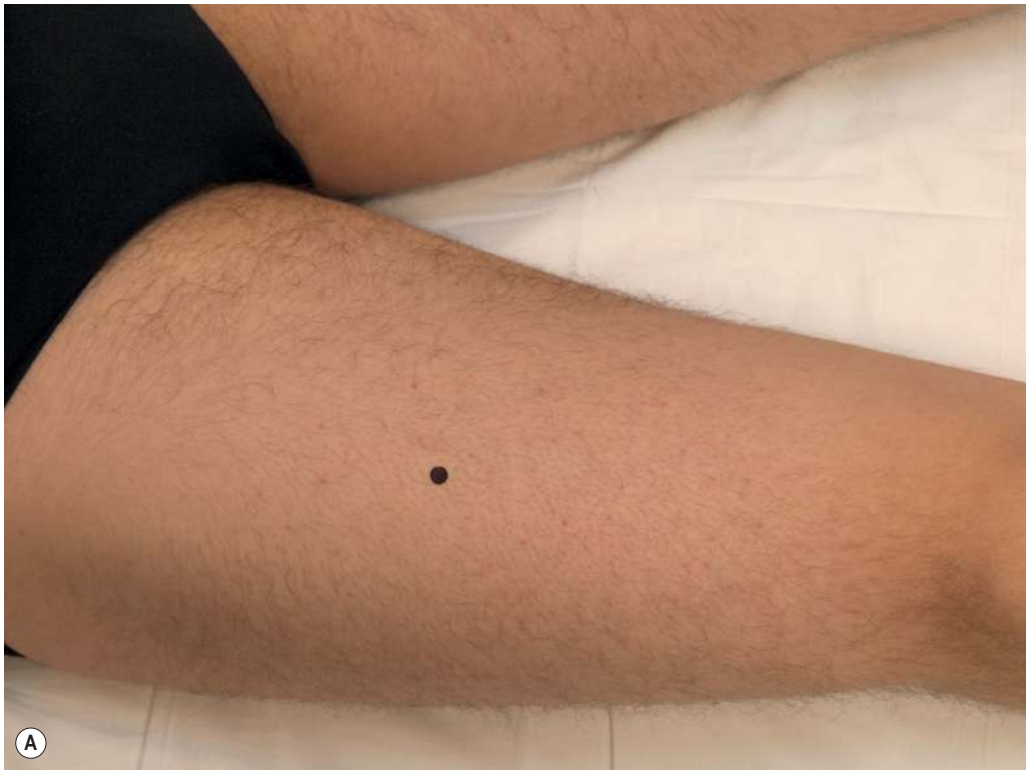


FIGURE 13–50 A. Vastus medialis insertion point.
B. Cross-section anatomy*.



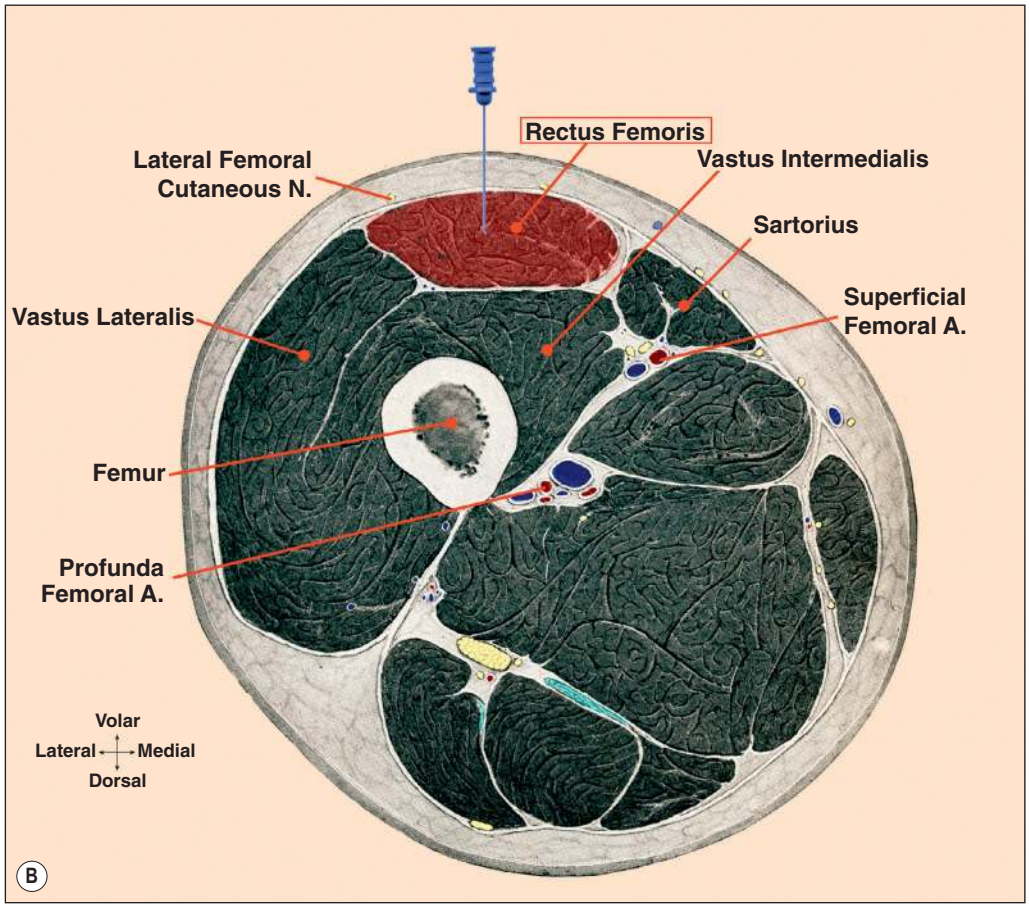
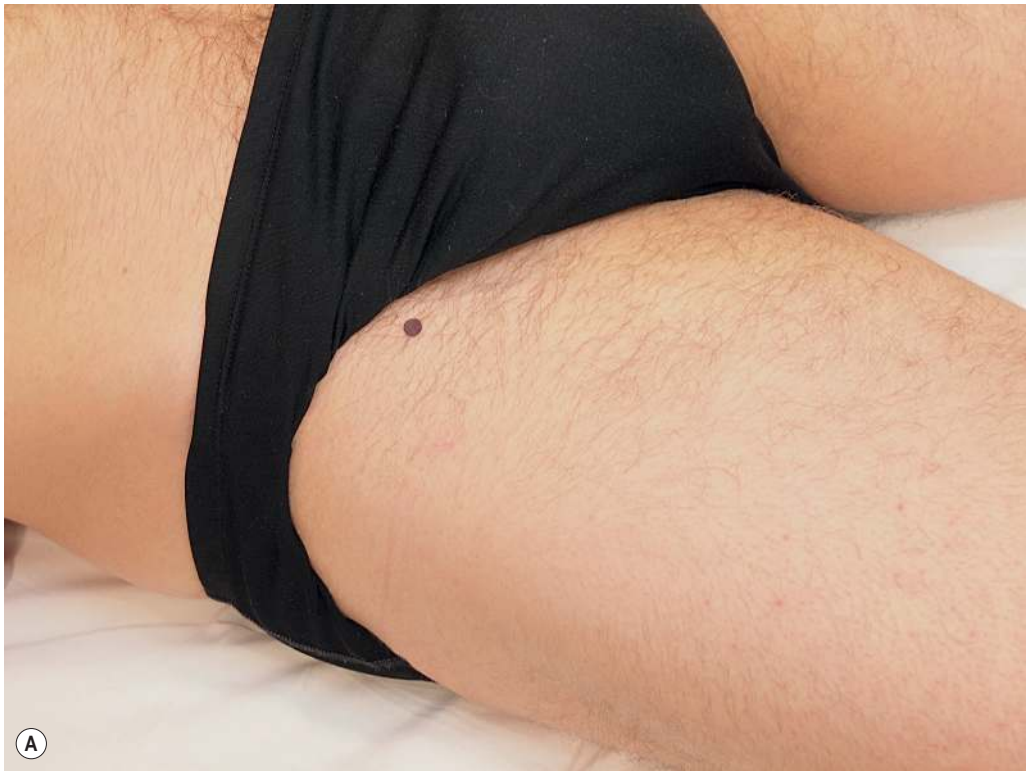


FIGURE 13–51 A. Rectus femoris insertion point.
B. Cross-section anatomy*.



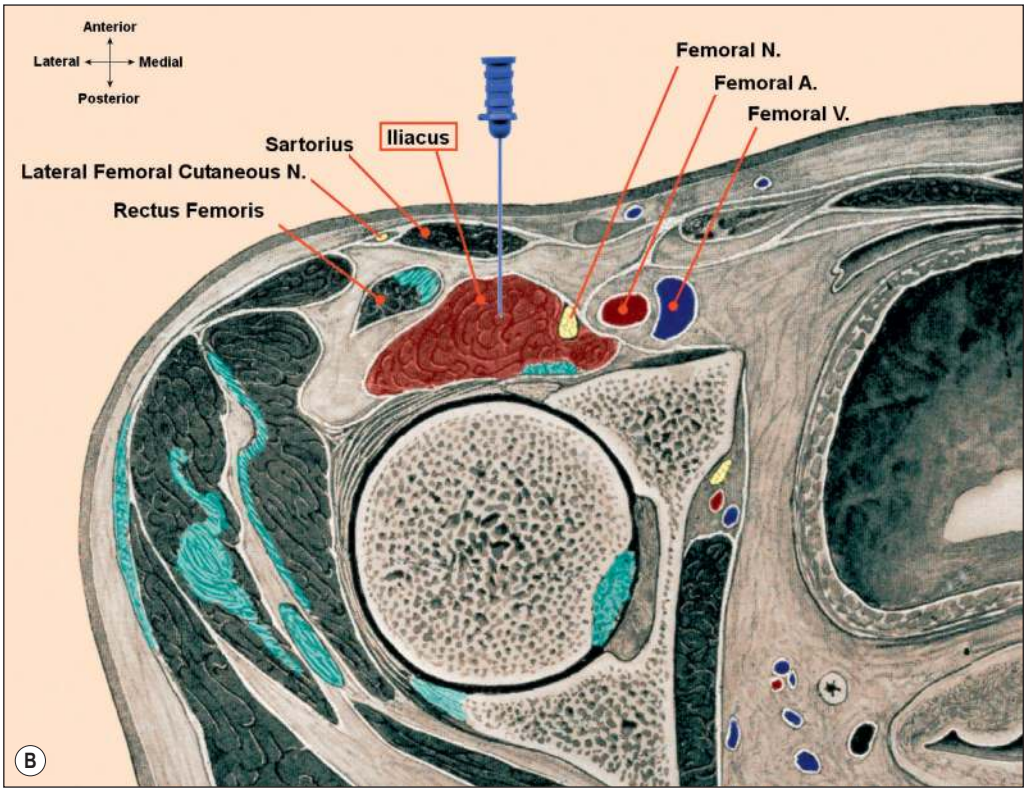


FIGURE 13–52 A. Iliacus insertion point.
B. Cross-section anatomy*.

SUPERIOR GLUTEAL NERVE

Gluteus Medius (GMED) *(Figure 13–53A,B)*

Innervation:

Superior gluteal nerve, lumbosacral plexus, L4–**L5**–S1

Needle Insertion:

With the patient lying on his or her side and the side to be studied placed upward, insert the needle into the lateral thigh two to three fingerbreadths distal to the iliac crest

Activation:

Have the patient abduct the thigh

Key Clinical Points:

- The GMED is a proximal predominantly L5-innervated muscle.
- Often used to differentiate lesions of the lumbosacral plexus or L5–S1 roots from sciatic nerve lesions.

Cross-section Anatomy Key Points:

- As long as this muscle is sampled from the lateral approach, there are no other nearby vascular structures or major nerves.

Tensor Fasciae Latae (TFL)

(Figure 13–54A,B)

Innervation:

Superior gluteal nerve, lumbosacral plexus, L4–**L5**–S1

Needle Insertion:

With the patient lying on his or her side and the side to be studied placed upward, insert the needle anterior to the greater trochanter below the anterior superior iliac crest

Activation:

Have the patient internally rotate the thigh (knees together, lift ipsilateral ankle toward ceiling)

Key Clinical Points:

- The TFL is a proximal predominantly L5-innervated muscle.
- Often used to differentiate lesions of the lumbosacral plexus or L5–S1 roots from sciatic nerve lesions.
- Although the TFL is also a hip abductor, its primary action is hip internal rotation.

Cross-section Anatomy Key Points:

- The muscle is very superficial.
- If the needle is too deep, it may be in the vastus lateralis or intermedialis.
- The lateral femoral cutaneous nerve is medial to the insertion site.

INFERIOR GLUTEAL NERVE

Gluteus Maximus (GMAX)

(Figure 13–55A,B,C)

Innervation:

Inferior gluteal nerve, lumbosacral plexus, L5–**S1**–S2

Needle Insertion:

Option 1: With the patient on their side, insert the needle into the upper outer quadrant of the buttock.

Option 2: With the patient on their side, insert the needle into the lower inner quadrant of the buttock

Activation:

Have the patient extend the thigh with the knee straight (for option 1), or have the patient squeeze the buttocks together (for option 2)

Key Clinical Points:

- The GMAX is the best proximal S1-innervated muscle for assessing S1 radiculopathy.
- Often used to differentiate lesions of the lumbosacral plexus or L5–S1 roots from sciatic nerve lesions.

Cross-section Anatomy Key Points:

- *Caution:* If the needle is in the center of the buttock or in the lower outer quadrant, and too deep, the sciatic nerve is within reach.

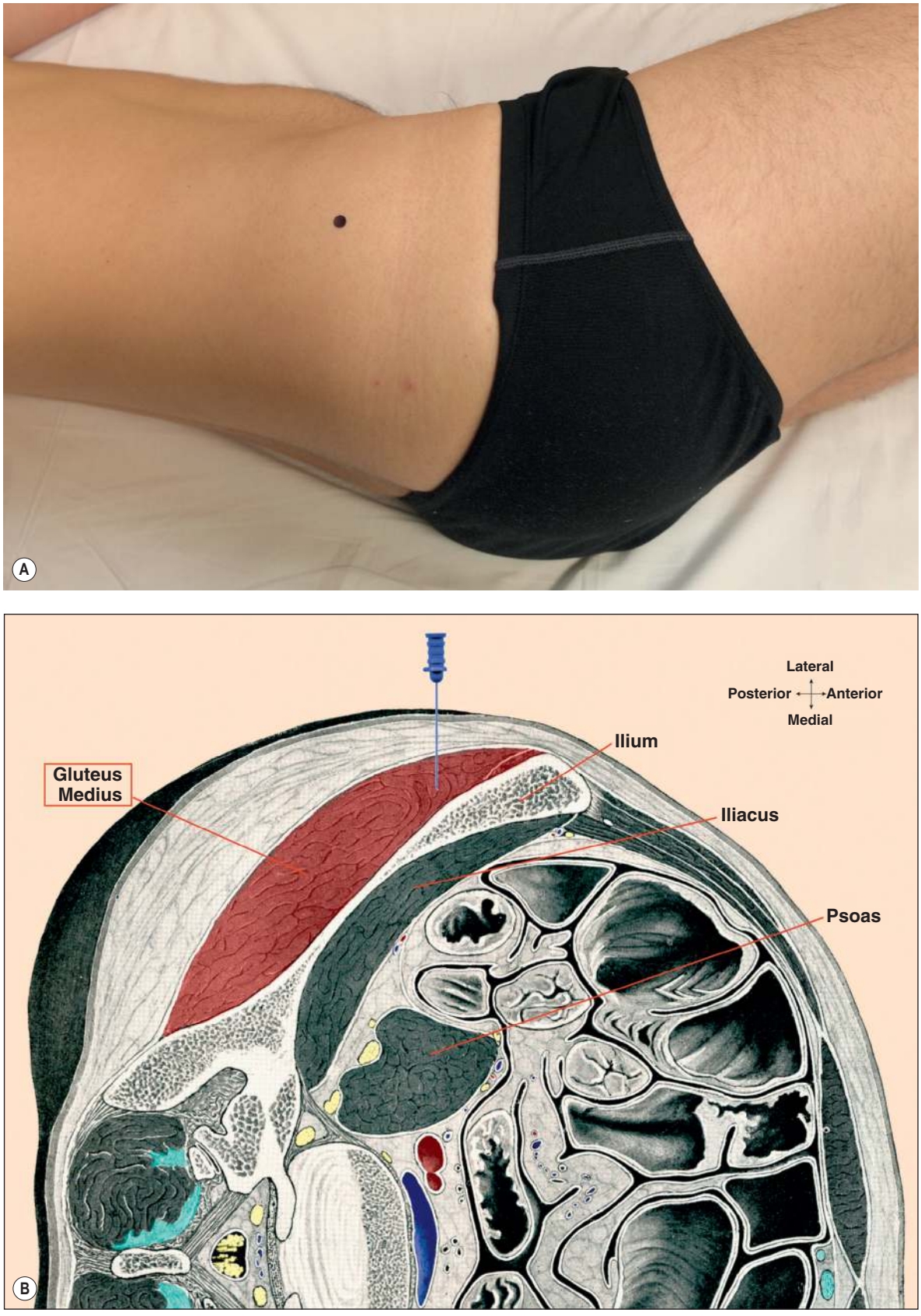


FIGURE 13–53 A. Gluteus medius insertion point. B. Cross-section anatomy*.

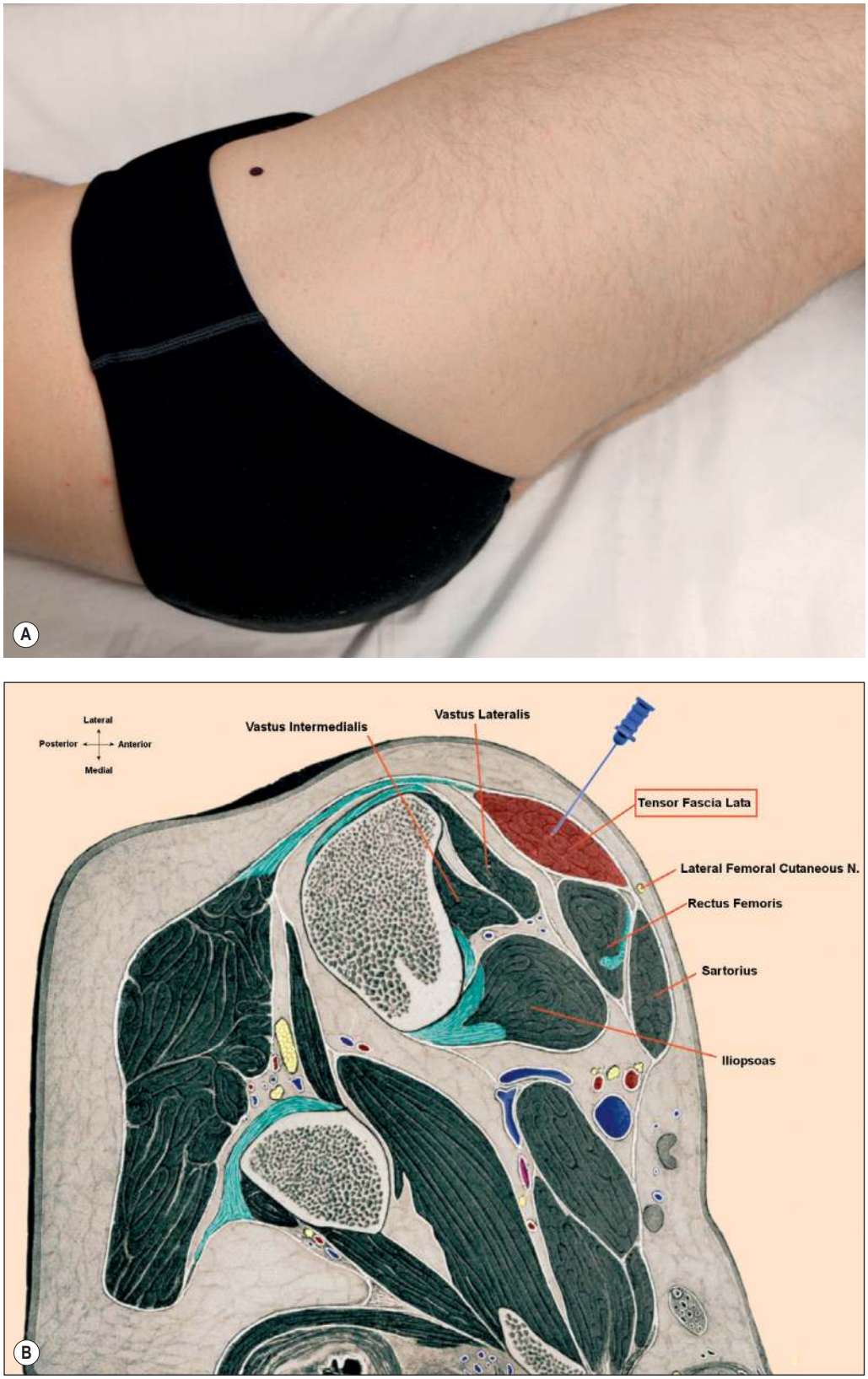


FIGURE 13–54 A. Tensor fasciae latae insertion point.
B. Cross-section anatomy*.

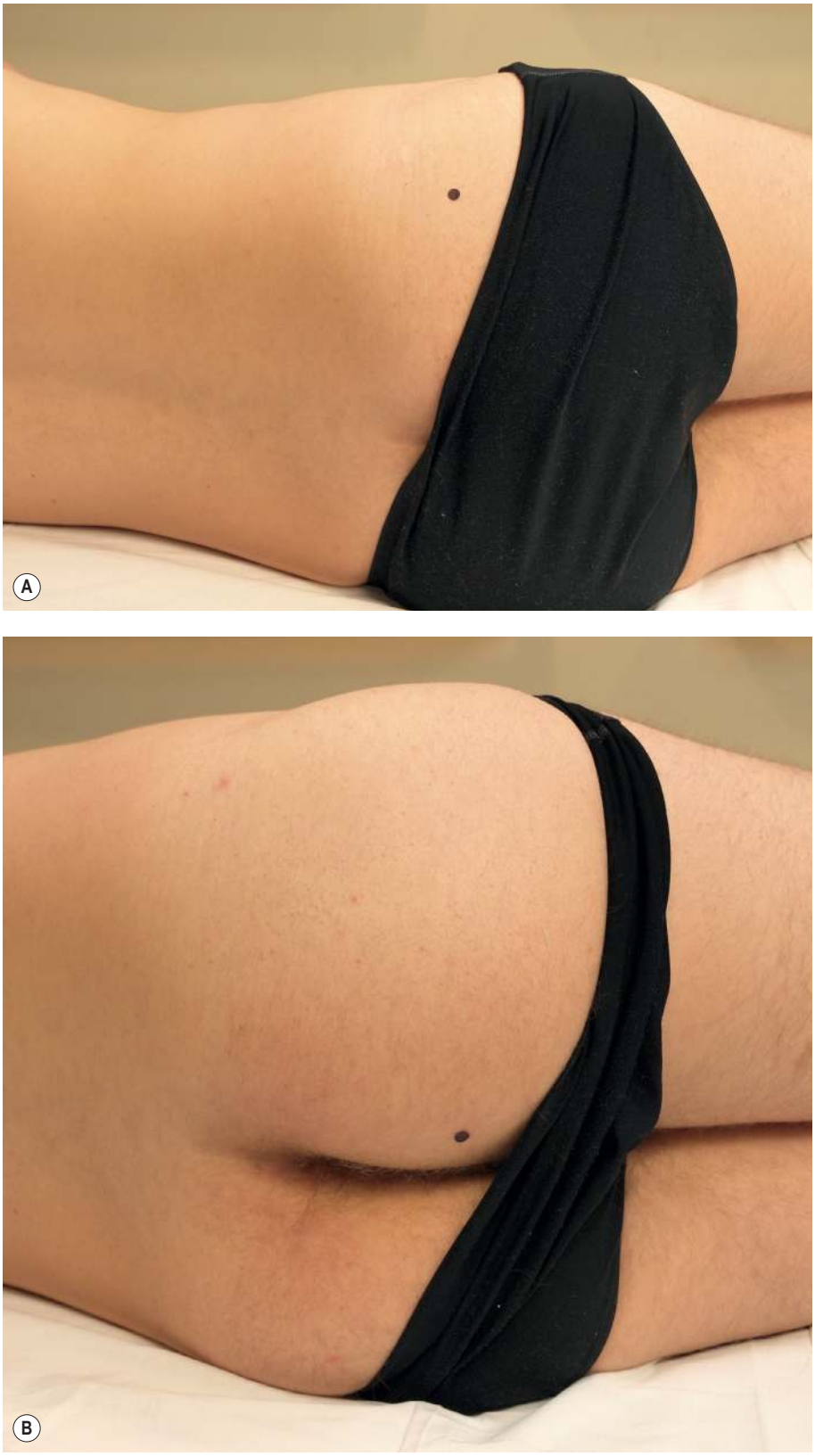


FIGURE 13–55 A. Gluteus maximus insertion point, option 1: upper outer quadrant of the buttock. B. Gluteus maximus insertion point, option 2: lower inner quadrant of the buttock.

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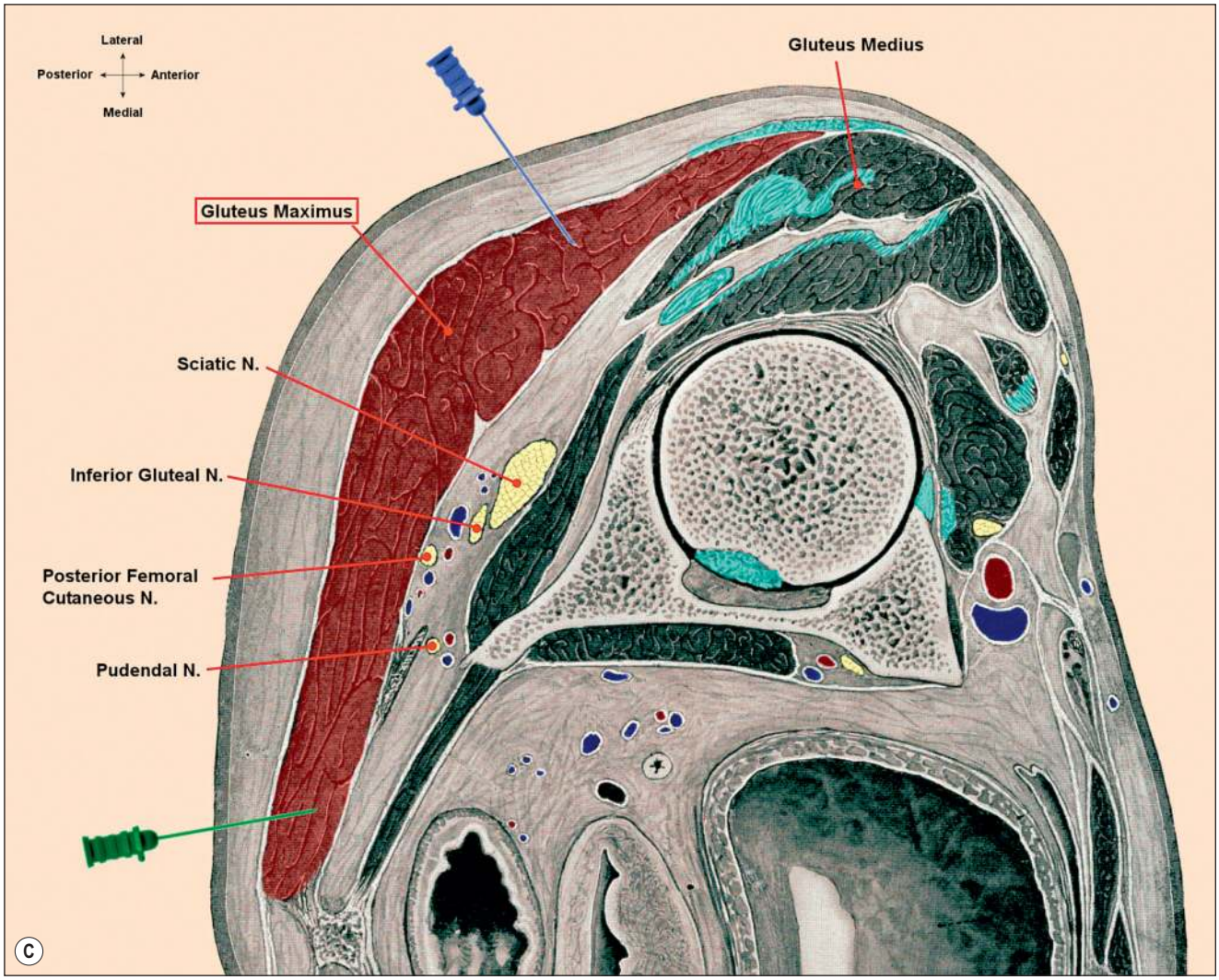


FIGURE 13–55, cont'd C. Cross-section anatomy*.

DORSAL RAMI

Paraspinal Muscles (PSP)

(Figures 13–56A,B, 13–57A,B, 13–58A,B)

Innervation:

Dorsal rami, spinal nerves, nerve roots

Needle Insertion:

With the patient lying on his or her side and the side to be studied placed upward, insert the needle two fingerbreadths from the midline spine with the needle directed slightly medially. To ensure that the needle is in the deeper layer of muscles, it should be advanced to just touch the lamina and then pulled back slightly

Activation:

Cervical: Have the patient extend the neck

Thoracic: Have the patient extend the back or take a deep breath

Lumbosacral: Have the patient extend the hip with the leg straight

Key Clinical Points:

- The paraspinal muscles are the most proximal muscles.
- Paraspinal muscles are useful to sample for radiculopathy and myopathy.
- In suspected neuropathic lesions, abnormalities in the paraspinal muscles only localize the lesion at or proximal to the root level. In radiculopathies, the specific root level is best determined by the limb muscles because of the wide overlap of adjacent myotomes, especially in the superficial layers.
- The paraspinal muscles often are difficult to relax. To best assess insertional/spontaneous activity, the patient should assume a fetal position, with the neck, hips, and knees flexed.
- These muscles often are difficult to activate.

Cross-section Anatomy Key Points:

- C*aution*: rare cases of pneumothorax have been reported with improper needle placement too laterally in the lower cervical and especially in the thoracic paraspinal muscles.
- In the lower cervical paraspinals, if the needle is too superficial, it may be in the upper trapezius.
- In the upper thoracic paraspinals, if the needle is too superficial, it may be in the trapezius or rhomboids.
- In the lower thoracic paraspinals, if the needle is too superficial, it may be in the trapezius or latissimus dorsi.

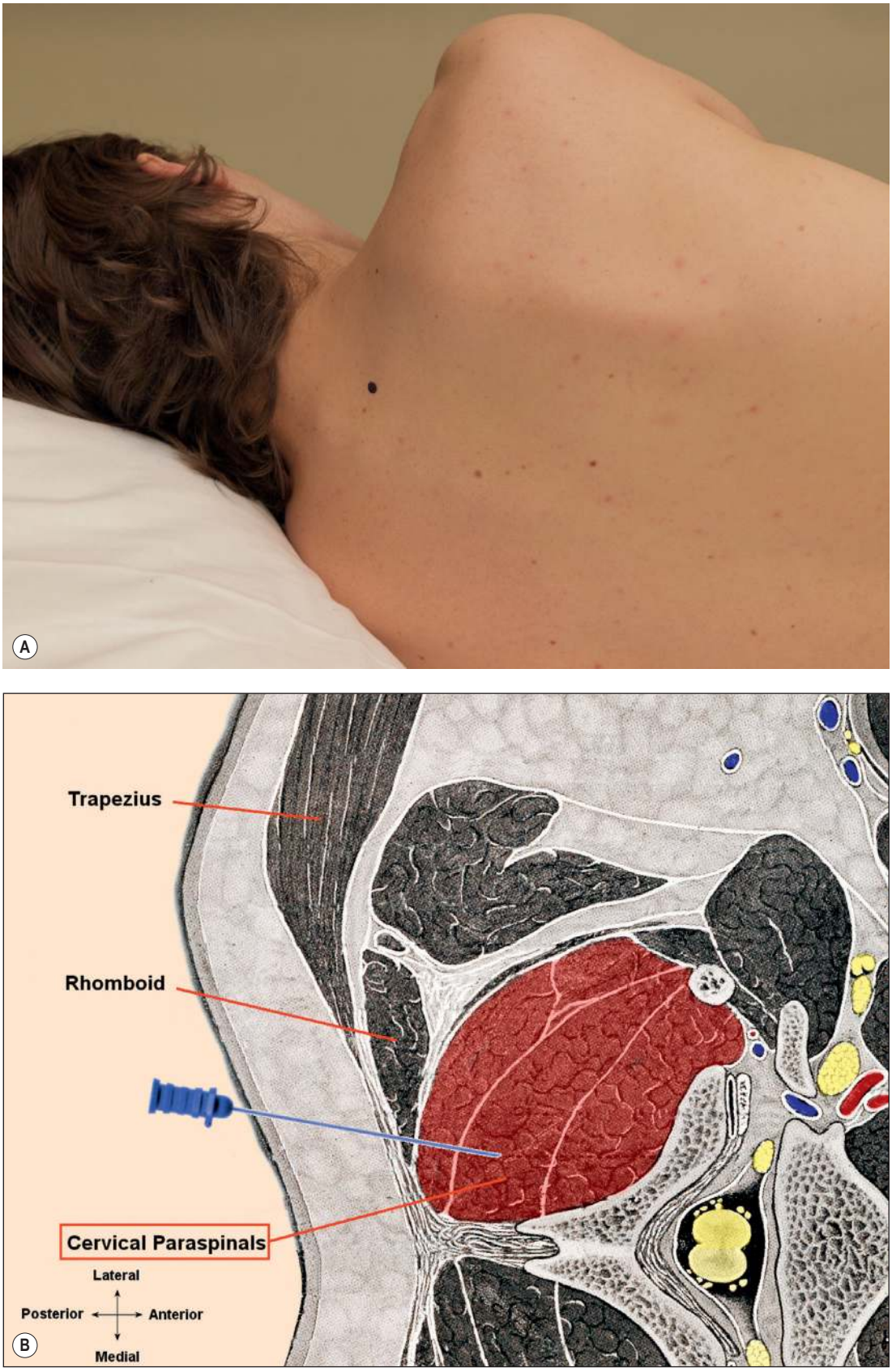


FIGURE 13–56 A. Lower cervical paraspinal muscles insertion point.
B. Cross-section anatomy*.

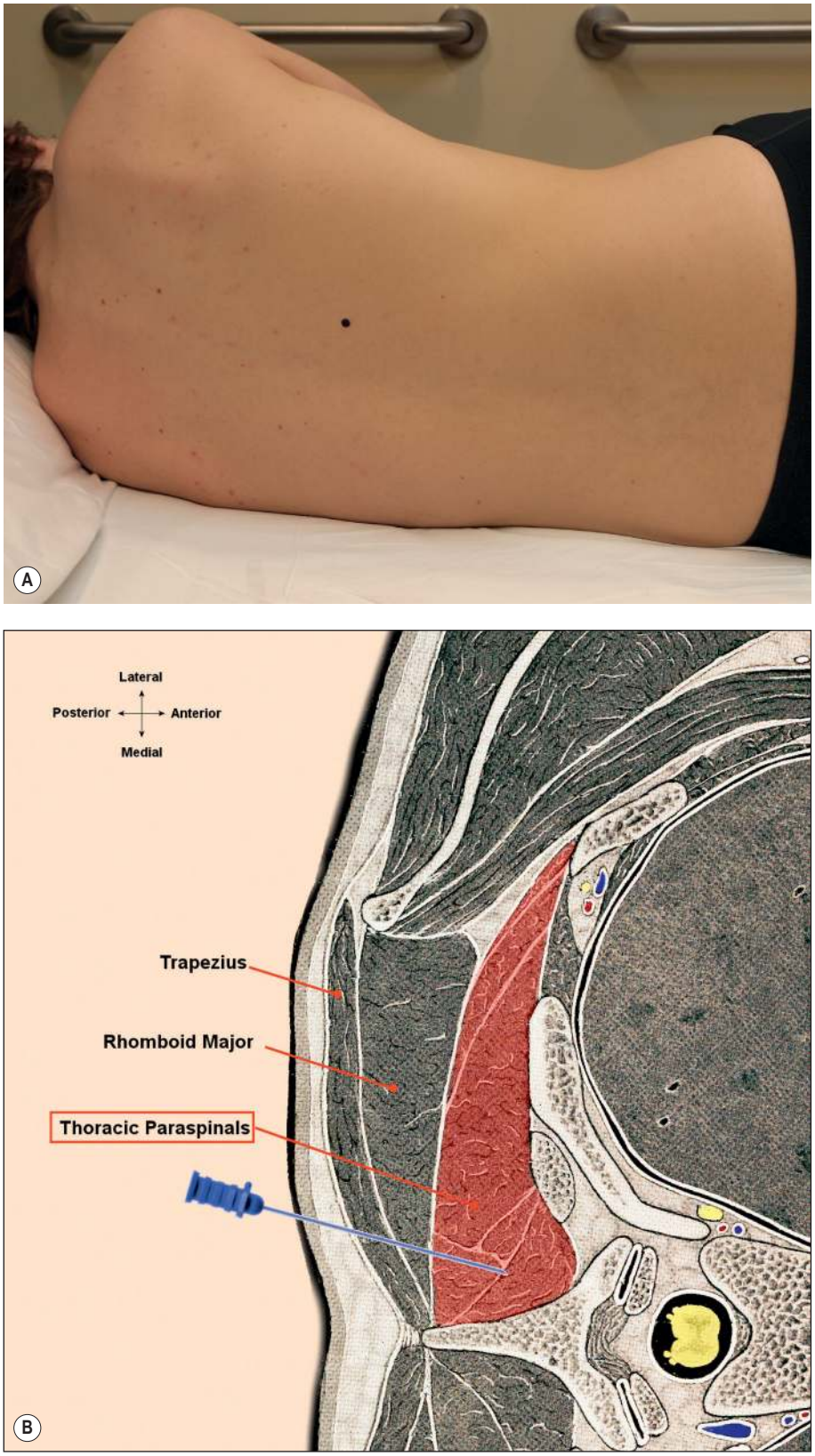


FIGURE 13–57 A. Thoracic paraspinal muscles insertion point.
B. Cross-section anatomy*.

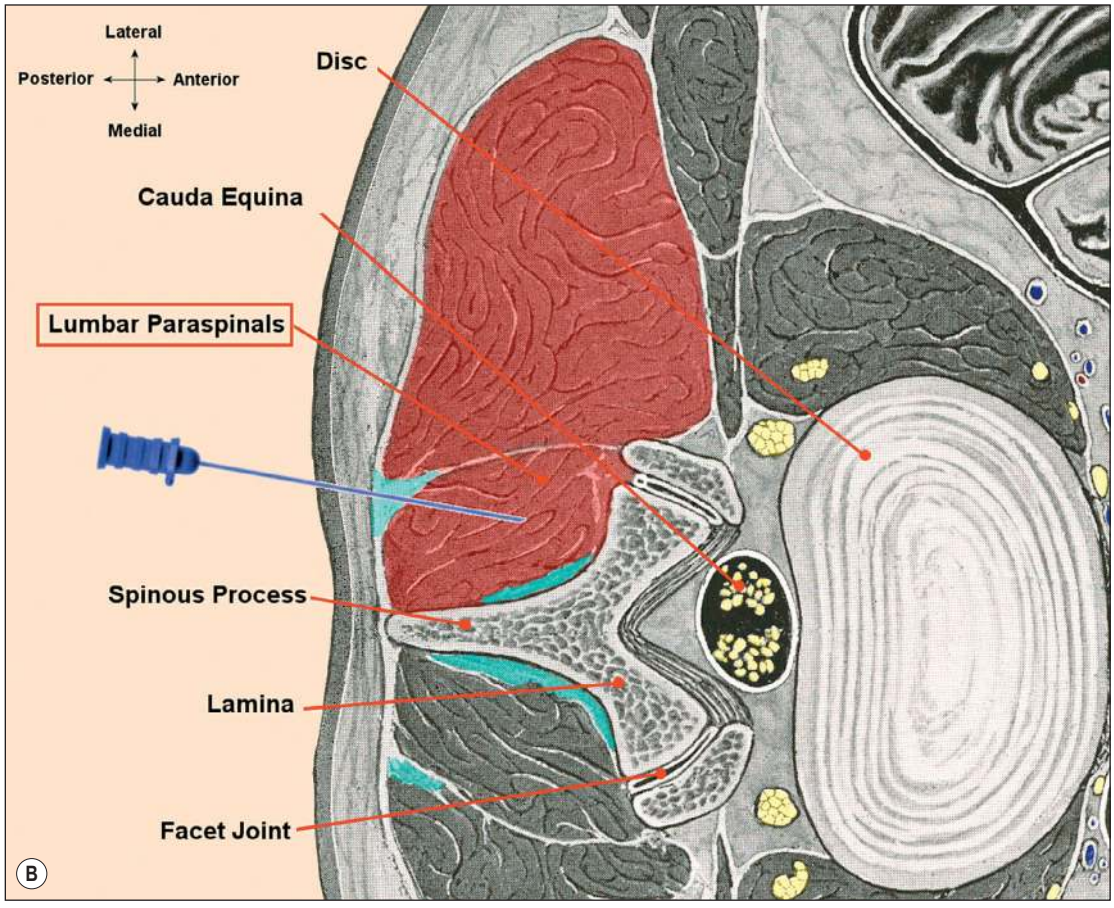


FIGURE 13–58 A. Lumbar paraspinal muscles insertion point.
B. Cross-section anatomy*.

CRANIOBULBAR MUSCLES

Genioglossus (Tongue) *(Figure 13–59A,B,C)*

Innervation:

Hypoglossal nerve (cranial nerve XII), medulla

Needle Insertion:

Option 1: The tongue can be sampled intraorally. The tongue is protruded and the examiner holds the end of the tongue with a gauze pad, and the needle is inserted laterally into the undersurface of the tongue (Figure 13–55A)

Option 2: The tongue can also be sampled percutaneously. The needle is inserted cephalad from beneath the anterior mandible, just lateral to the midline (Figure 13–55B and C)

Activation:

Have the patient stick out the tongue

Key Clinical Points:

- The tongue is difficult to relax; thus, assessment of spontaneous activity often is difficult.
- The tongue is very useful to sample in patients with suspected motor neuron disease.
- Motor unit action potential duration normally is briefer in craniobulbar muscles, including the tongue, compared with the limb muscles.

Cross-section Anatomy Key Points (Option 2):

- Insert the needle just off the midline; further lateral on both sides are the submental arteries which run under the chin and are major branches of the facial arteries.
- If the needle is too superficial, it will be in the geniohyoideus, supplied by the C1 nerve root.

Masseter *(Figure 13–60A,B,C)*

Innervation:

Mandibular nerve, trigeminal motor branch (V3), pons

Needle Insertion:

Insert the needle two fingerbreadths anterior to the angle of the jaw and one to two fingerbreadths cephalad, palpating the muscle as the patient clenches the jaw. Insert the needle on a line between the upper and lower teeth

Activation:

Have the patient clench the jaw

Key Clinical Points:

- The masseter is easy to activate.
- The masseter is useful to sample in patients with suspected motor neuron disease.
- Motor unit action potential duration normally is briefer in craniobulbar muscles, including the masseter, compared with the limb muscles.

Cross-section Anatomy Key Points:

- *Caution*: the needle should be placed anteriorly in the muscle to avoid the parotid gland.
- *Caution*: the needle should not be placed too cephalad to avoid the main parotid duct.

Frontalis *(Figure 13–61A,B)*

Innervation:

Frontal branch of the facial nerve (cranial nerve VII), medullary–pontine junction

Needle Insertion:

Insert the needle tangentially one to two fingerbreadths above the middle of the eyebrow

Activation:

Have the patient look up (raise the eyebrows)

Key Clinical Points:

- The muscle often is used for single-fiber EMG.
- The frontalis is useful for assessing Bell's palsy.
- The frontalis is useful to sample in patients with suspected motor neuron disease.
- Motor unit action potential duration normally is briefer in craniobulbar muscles, including the facial muscles, compared with the limb muscles.

Cross-section Anatomy Key Points:

- The frontalis is very thin; the needle must be inserted tangentially.

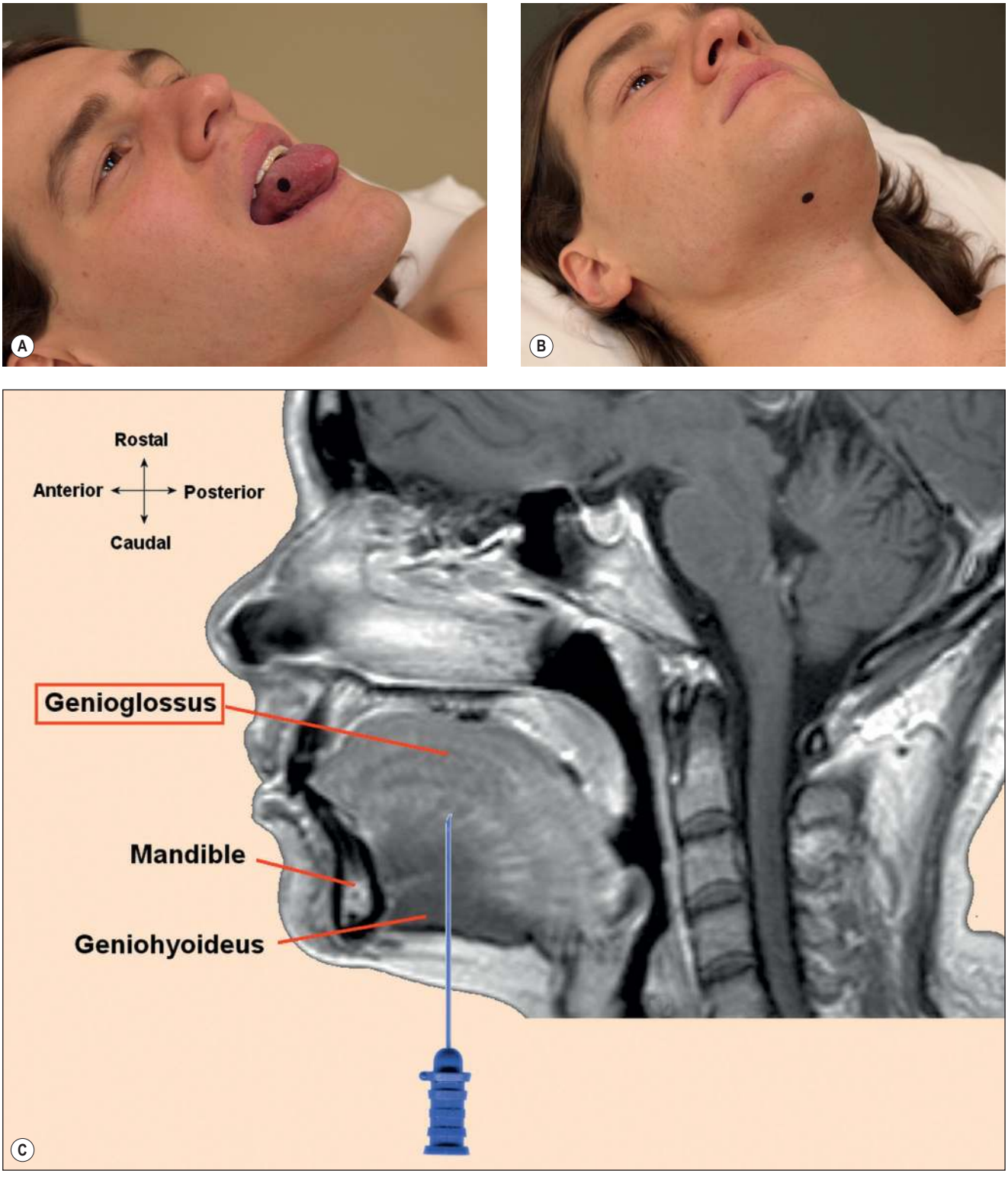


FIGURE 13–59 A. Genioglossus insertion point (intraoral)
B. Genioglossus insertion point (beneath the mandible).
C. Sagittal cross-section anatomy*.

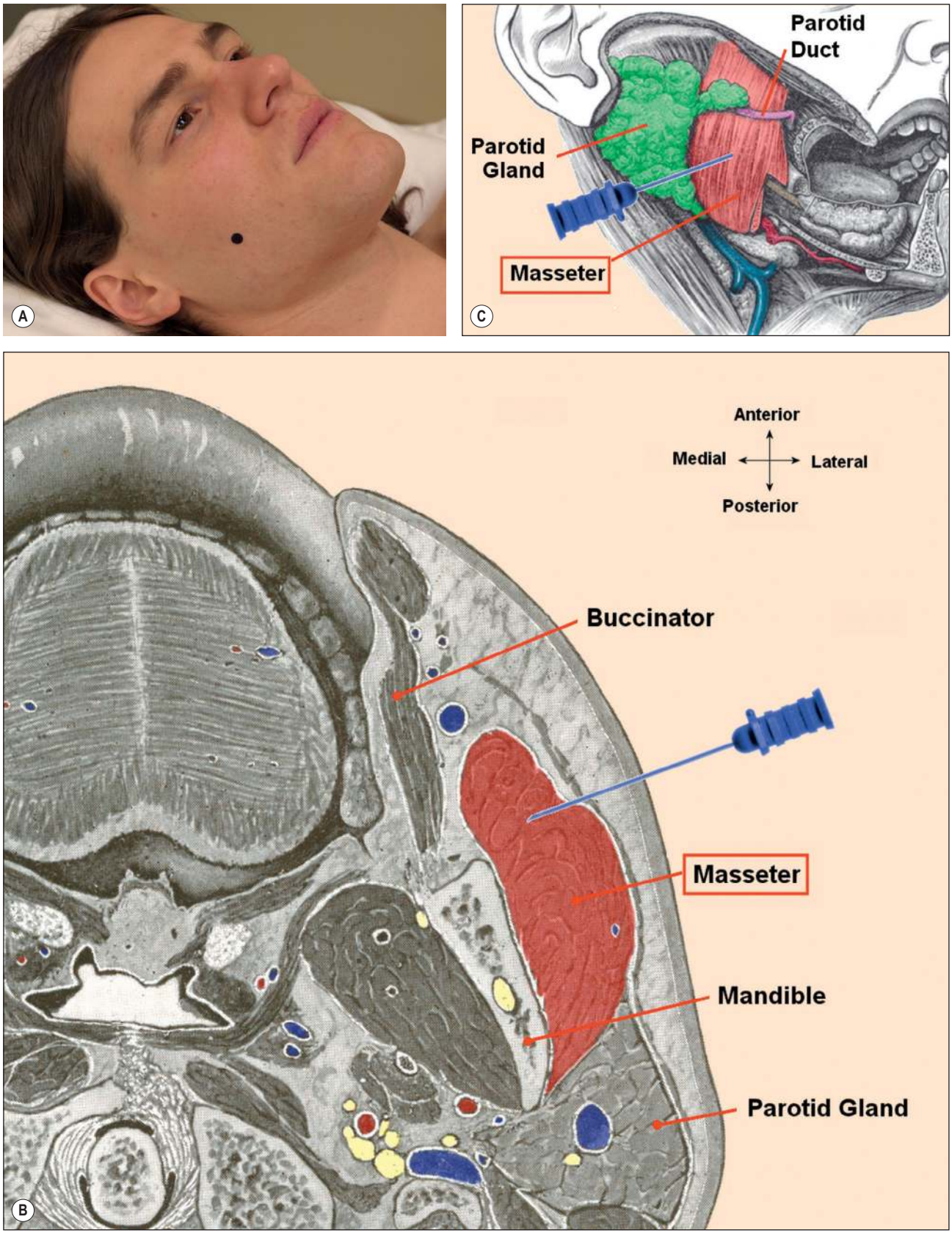


FIGURE 13–60 A. Masseter insertion point.
B. Cross-section anatomy*.
C. Anatomic relationship between the masseter and parotid gland/duct*.

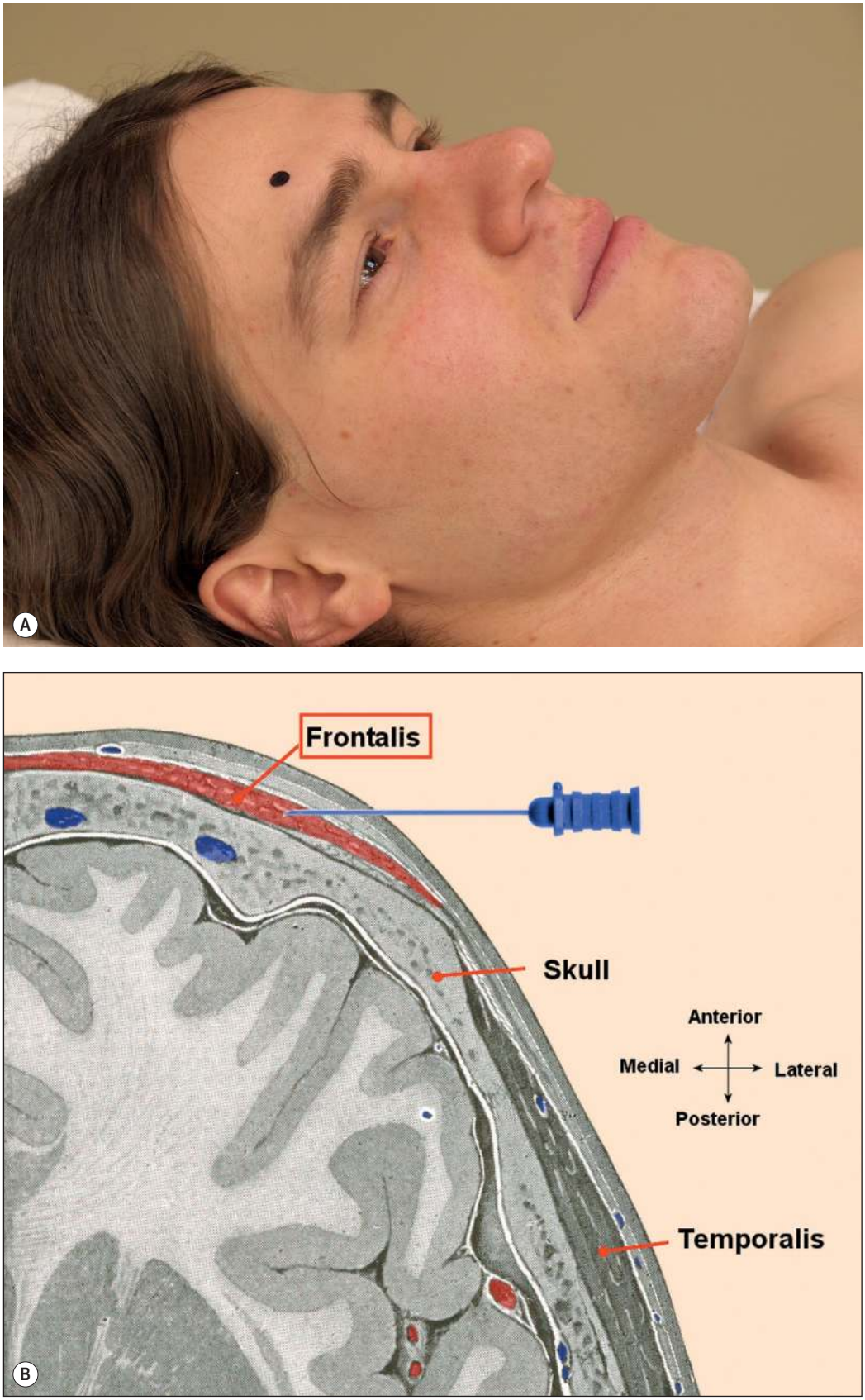


FIGURE 13–61 A. Frontalis insertion point.
B. Cross-section anatomy*.

Mentalis *(Figure 13–62A,B)*

Innervation:

Mandibular branch of the facial nerve (cranial nerve VII), medullary–pontine junction

Needle Insertion:

Insert the needle tangentially and superficially into the chin

Activation:

Have the patient purse the lips

Key Clinical Points:

- Useful for assessing Bell's palsy.
- The mentalis is useful to sample in patients with suspected motor neuron disease.
- Motor unit action potential duration normally is briefer in craniobulbar muscles, including the facial muscles, compared with the limb muscles.

Cross-section Anatomy Key Points:

- The muscle is very thin just superficial to the mandible; the needle must be inserted tangentially.

Orbicularis Oculi *(Figure 13–63A,B)*

Innervation:

Temporal branch of the facial nerve (cranial nerve VII), medullary–pontine junction

Needle Insertion:

Insert the needle tangentially, lateral to the inferior ridge of the eye socket, with the needle pointing away from the eye

Activation:

Have the patient close his or her eyes tightly

Key Clinical Points:

- Useful for assessing Bell's palsy.
- Motor unit action potential duration normally is briefer in craniobulbar muscles, including the facial muscles, compared with the limb muscles.

Cross-section Anatomy Key Points:

- The muscle is very thin; the needle must be inserted tangentially.

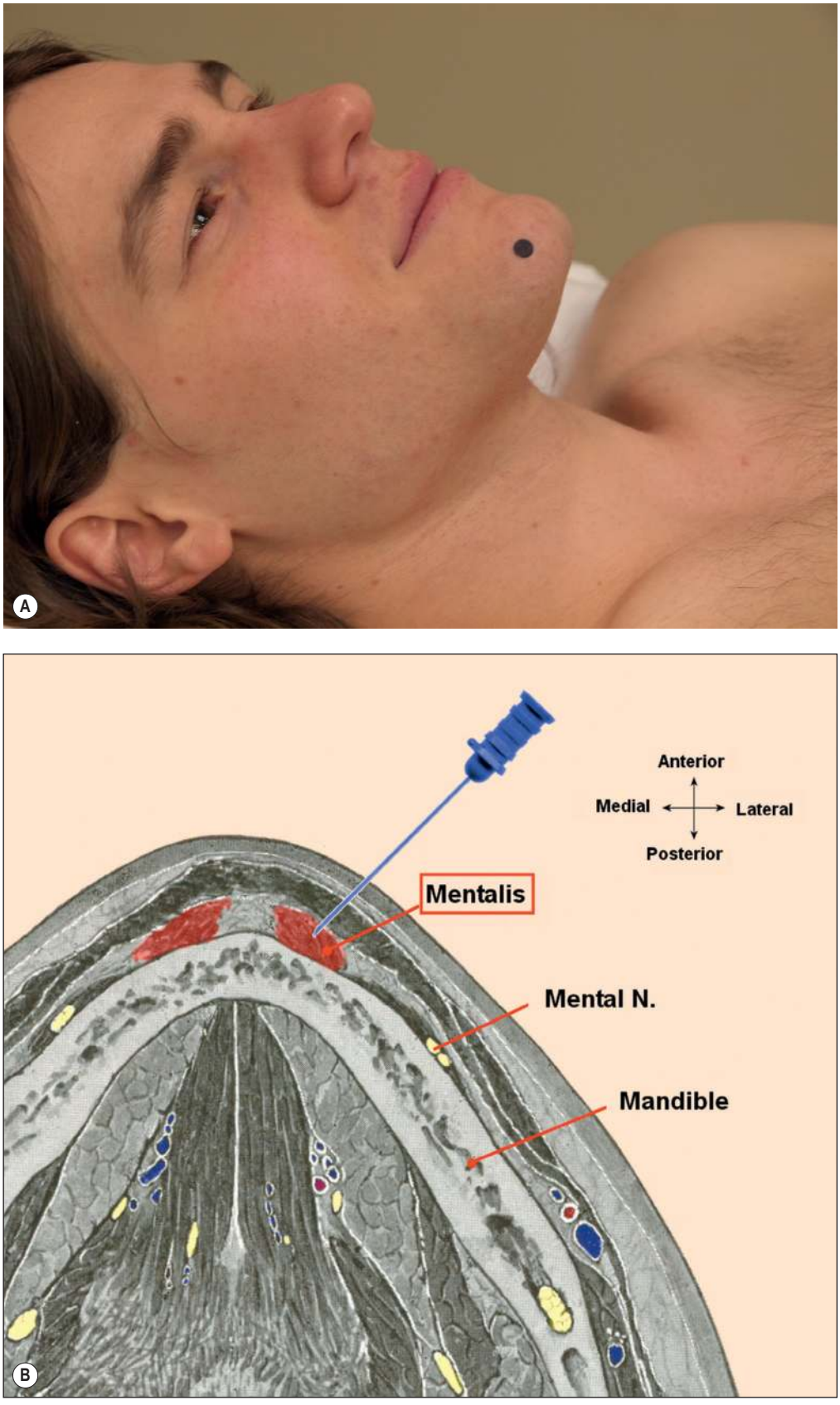
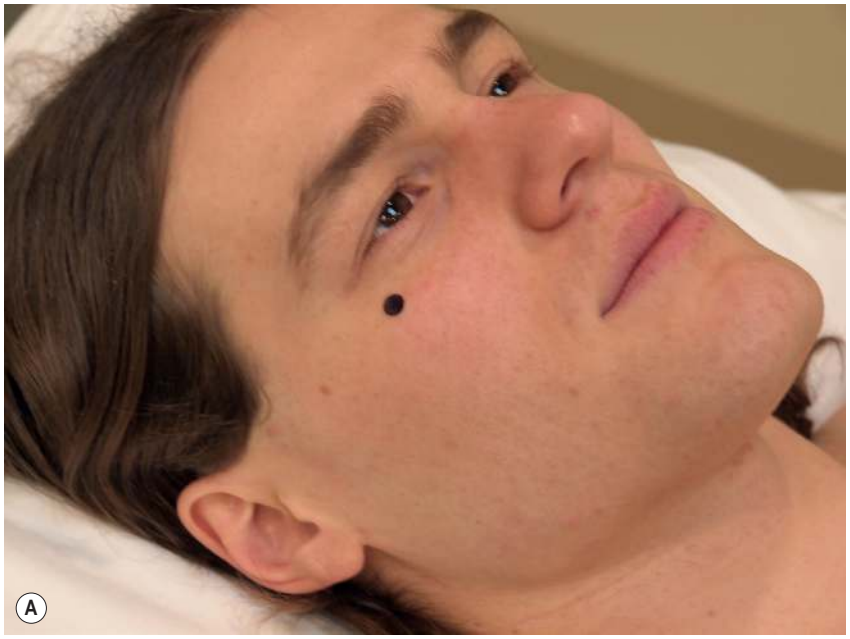


FIGURE 13–62 A. Mentalis insertion point.
B. Cross-section anatomy*.



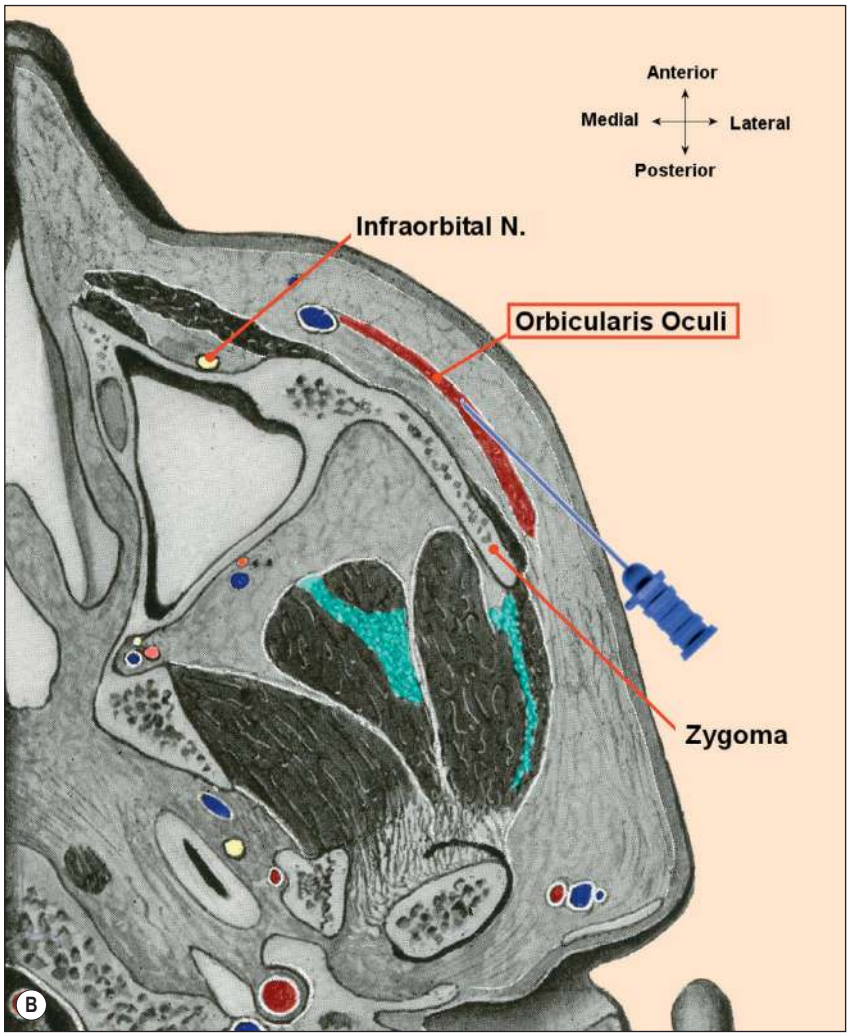


FIGURE 13–63 A. Orbicularis oculi insertion point.
B. Cross-section anatomy*.

14 Basic Electromyography:
Analysis of Spontaneous Activity

The recognition of abnormal spontaneous activity is one of the most important parts of the needle electromyography (EMG) examination. The presence of abnormal spontaneous activity on EMG can yield several key pieces of information. First, the distribution of abnormal spontaneous activity may indicate the neuroanatomic localization of the lesion. For example, in an isolated radiculopathy, denervation potentials are restricted to muscles in the same myotome. Second, the type of spontaneous activity often provides specific diagnostic information. Certain types of spontaneous activity are associated only with specific disorders. For example, myotonic discharges are seen only in a few myopathies and in hyperkalemic periodic paralysis. Third, the degree or amount of spontaneous activity often helps to determine the severity of the lesion. Finally, the presence of abnormal spontaneous activity may yield information regarding the time course of the lesion. For example, in a radiculopathy, several weeks must pass before fibrillation potentials are seen in the limbs.

ANALYSIS OF SPONTANEOUS ACTIVITY

The identification of any spontaneous activity can be achieved by either pattern recognition or analysis of the waveform. With experience, the characteristic sound and appearance of each waveform become easily recognizable. However, when first learning needle EMG or when encountering an unusual waveform, one must be able to systematically analyze the waveform according to the following attributes: (1) morphology, (2) stability, and (3) firing characteristics (Figure 14–1). Using this information, nearly every spontaneous waveform can be identified correctly.

Morphology

The source of a spontaneous discharge often can be identified by its distinctive morphology, including the size and shape of the potential (amplitude, duration, number of

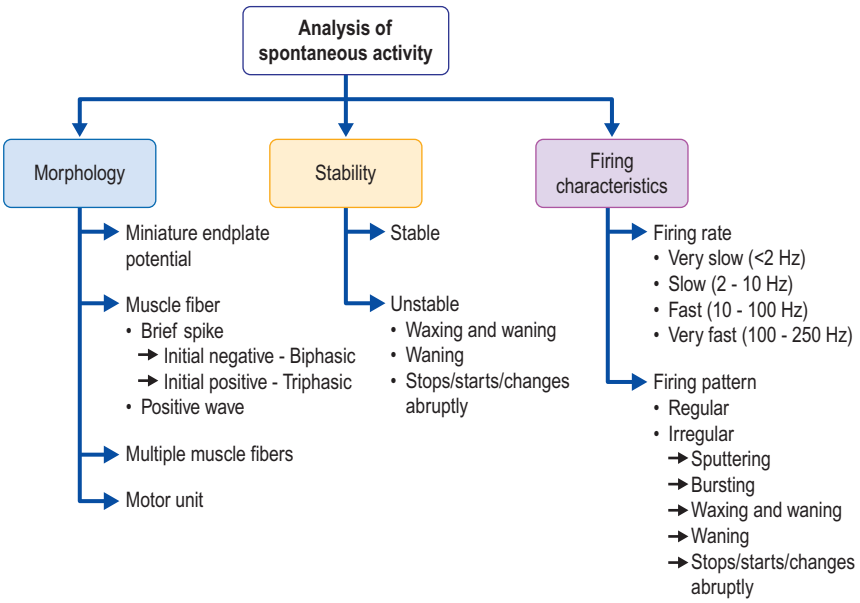


FIGURE 14–1 Algorithm for analysis of spontaneous activity.

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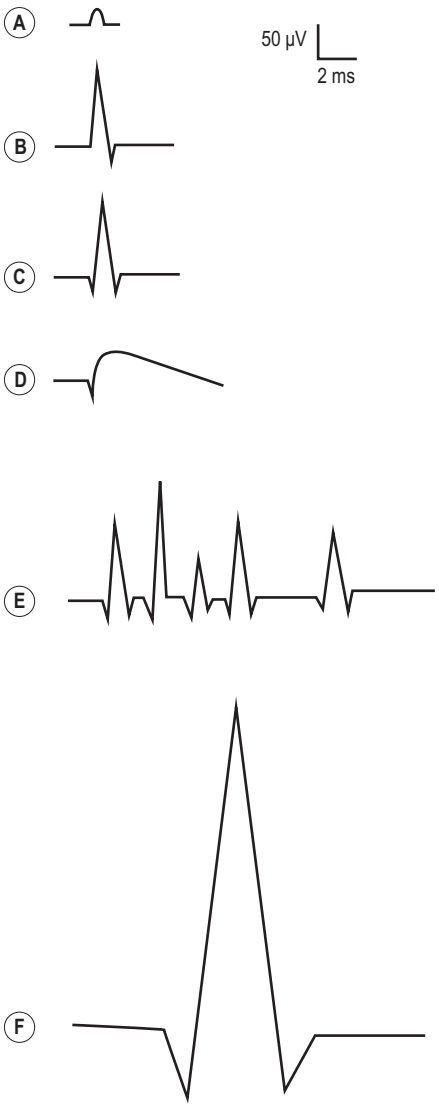

FIGURE 14–2 Spontaneous waveform morphologies. **A:** Miniature endplate potential (monophasic negative). **B:** Muscle fiber action potential, brief spike morphology. Triggered by needle-induced depolarization of a terminal nerve twig (initial negative, diphasic). **C:** Muscle fiber action potential, brief spike morphology (initial positive, triphasic). **D:** Muscle fiber action potential, positive wave morphology (initial positive, slow negative). **E:** Multiple different muscle fiber action potentials linked together. **F:** Motor unit action potential. Note the longer duration and higher amplitude compared with muscle fiber potentials shown above.

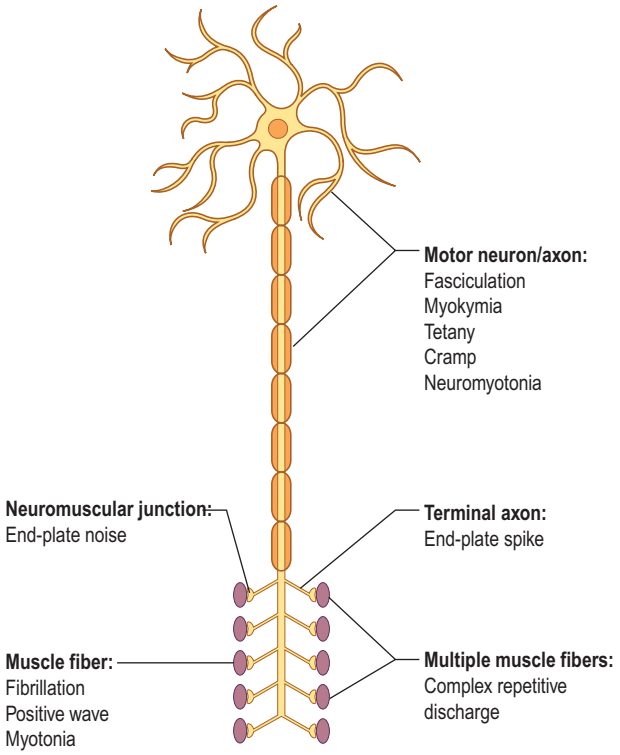

FIGURE 14–3 Spontaneous waveform source generators. Spontaneous activity originates from a variety of source generators. Each generator is associated with a specific morphology.

phases) and its initial deflection (Figure 14–2). By defining its source generator, the type of discharge usually can be identified. The source generators that must be differentiated include (1) the neuromuscular junction (NMJ), (2) a single muscle fiber, (3) the terminal axon twig, (4) a motor neuron/axon, and (5) multiple muscle fibers linked together (Figure 14–3, Table 14–1).

At the NMJ (i.e., endplate zone), miniature endplate potentials (MEPPs) occur spontaneously. They result from the normal spontaneous exocytosis of individual quanta of acetylcholine traveling across the NMJ, leading to a non-propagated, subthreshold endplate potential. If the EMG needle is near the endplate zone, MEPPs can often be recorded. They have a distinctive small amplitude and monophasic negative morphology (Figure 14–2A). These potentials are normal spontaneous discharges and are referred to as *endplate noise*.

When a muscle fiber depolarizes to threshold, a muscle fiber action potential (MFAP) is created. The MFAP can assume one of two basic morphologies, either a brief spike or a positive wave. The brief spike typically is 1 to 5 ms in duration, biphasic or triphasic, with a low amplitude (typically 10–100 µV). This brief spike morphology is seen most often when a muscle fiber depolarizes spontaneously, for example, in denervation, but it can also occur as the result of an individual terminal axon twig depolarizing and then propagating across the NMJ to create an MFAP. Attention to the initial deflection and to whether the brief spike is biphasic or triphasic often can help distinguish between the two (Figure 14–4). If the depolarization begins under the recording needle electrode, a biphasic potential is seen, wherein an initial negative peak is followed by a short positive phase (Figure 14–2B). This signifies that the needle is at the endplate zone, where the depolarization begins, and usually is the result of the EMG needle irritating the terminal nerve twigs near the endplate zone. A nerve twig action potential then leads to an MFAP, known as an *endplate spike*, which is a normal finding (see section on Endplate Spikes). The reason for the initial negativity is similar

Table 14–1. Spontaneous Activity

Potential	Source Generator/ Morphology	Sound on Loudpeaker	Stability	Firing Rate	Firing Pattern
Endplate noise	Miniature endplate potential (monophasic negative)	Seashell	–	20–40 Hz	Irregular (hissing)
Endplate spike	Muscle fiber initiated by terminal axonal twig (brief spike, diphasic, initial negative)	Sputtering, like fat in a frying pan	Stable	5–50 Hz	Irregular (sputtering)
Fibrillation potential	Muscle fiber (brief spike, diphasic or triphasic, initial positive)	Rain on a tin roof or tick-tock of a clock	Stable	0.5–10 Hz (occ. up to 30 Hz)	Regular
Positive sharp wave	Muscle fiber (diphasic, initial positive, slow negative)	Dull pops, rain on a roof or tick-tock of a clock	Stable	0.5–10 Hz (occ. up to 30 Hz)	Regular
Myotonic discharge	Muscle fiber (brief spike, initial positive, or positive wave)	Revving engine	Waxing/waning amplitude	20–150 Hz	Waxing/waning
Complex repetitive discharge	Multiple muscle fibers time-linked together	Machine	Usually stable; may change in discrete jumps	5–100 Hz	Perfectly regular (unless overdriven)
Fasciculation potential	Motor unit (motor neuron/axon)	Corn popping	Stable	Low (0.1–10 Hz)	Irregular
Doublets, triplets, multiplets	Motor unit (motor neuron/axon)	Horse trotting	Usually stable; may change in number of potentials	Variable (1–50 Hz)	Bursts of twos threes or a few potentials
Myokymic discharge	Motor unit (motor neuron/axon)	Marching soldiers	Usually stable; the number of potentials may change within the burst	1–5 Hz (interburst) 5–60 Hz (intraburst)	Bursting of the same individual motor unit potential
Cramp potential	Motor unit (motor neuron/axon)		Usually stable	High (20–150 Hz)	Interference pattern or one or more individual motor unit potentials
Neuromyotonic discharge	Motor unit (motor neuron/axon)	Pinging	Decrementing amplitude	Very high (150–250 Hz)	Waning
Rest tremor	Motor unit (motor neuron/axon)	Marching soldiers	Rising and falling amplitude	1–5 Hz (interburst)	Bursting – synchronous bursting of many different motor unit potentials

to that of the compound muscle action potential (CMAP) in motor nerve conduction studies, wherein the initial deflection is negative when the active recording electrode is properly placed over the motor endplate zone. Otherwise, brief spikes that occur from the spontaneous depolarization of a muscle fiber are associated with an initial positive, usually triphasic morphology. When the depolarization begins at a distance from the needle, there is an initial positive deflection as it moves toward the needle, followed by a negative phase as it moves beneath the needle, and then a final positive deflection as it moves away from the needle (Figure 14–2C).

In addition to the brief spike, an MFAP can assume a positive wave morphology, with an initial brief positive phase followed by a long negative phase (Figure 14–2D). Both positive waves and initial positive, triphasic brief spikes are seen most often as denervating potentials, known as *positive sharp waves* and *fibrillation potentials*,

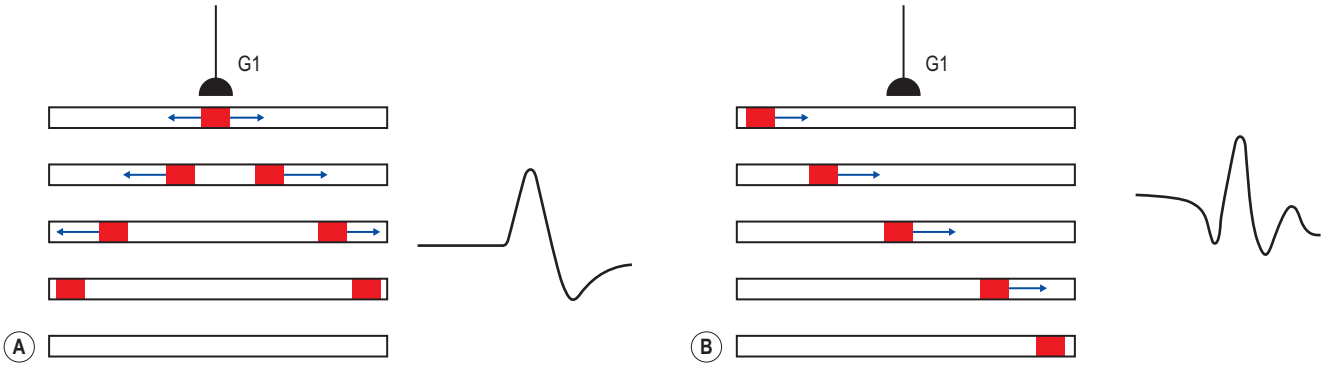

FIGURE 14–4 Waveform morphology and site of depolarization. **A:** Traveling depolarizing wave will create a biphasic potential if the waveform begins under the recording needle electrode (initial negative peak) and then moves away from the electrode (positive peak). An endplate spike shows this morphology. **B:** If the waveform begins at a distance from the needle, there is an initial positive deflection as it moves toward the needle, followed by a negative phase as it moves beneath the needle, and then a final positive deflection as it travels away. Fibrillation potentials show this morphology. Endplate spikes are differentiated from fibrillation potentials by the absence of an initial positive deflection because the depolarization begins at the endplate.

respectively. However, it should not be surprising that myotonic discharges, which also originate in muscle fibers, have the same basic morphology as denervating potentials, either positive waves or brief spikes. This point exemplifies the important concept that morphology alone cannot be used to identify a potential. Although the morphology of a potential usually can be used to correctly identify its source generator, additional information regarding its stability and firing characteristics is needed to fully characterize and identify any potential (see later).

The next major category of spontaneous discharges is that which arises from motor neurons or their axons. Any discharge that occurs as a result of the spontaneous depolarization of a motor neuron or its axon (prior to its terminal branches) leads to a potential with the morphology of a motor unit (Figure 14–2F) known as a *motor unit action potential* (MUAP). Spontaneous discharges generated by the motor neuron or its axon include fasciculation potentials, doublets, triplets, and multiplets, myokymic discharges, neuromyotonic discharges, and cramp potentials, all of which lie along the spectrum of abnormal spontaneous MUAPs. They can be differentiated from each other, however, by their stability and firing characteristics (described in the following subsections). If the motor unit is normal, the MUAP morphology will be normal: typically two to four phases, 5 to 15 ms in duration, and variable amplitude depending on the needle position. If the motor unit is pathologic, the number of phases, duration, and amplitude of the MUAP may be abnormal. Differentiating a MUAP from a single MFAP usually is straightforward and typically can be done quite simply by analyzing its duration and amplitude.

The last distinctive waveform that must be recognized is that of time-linked individual muscle fibers, such as occurs in complex repetitive discharges. One might ask how this waveform differs from an MUAP, which also represents many muscle fibers linked together. The difference is that the muscle fibers in a motor unit fire more or less synchronously and, in almost every situation, summate to create a larger potential 5 to 15 ms in duration. In contrast, the multiple muscle fibers in a complex repetitive discharge fire consecutively and usually are discernible as individual spikes that are time linked together (Figure 14–2E).

Stability

Assessment of the stability of a waveform can be very informative. Nearly all spontaneous potentials are relatively stable in their morphology. If the morphology of the potential changes, note should be made of whether it waxes and wanes, wanes (decrements), or changes abruptly. MFAPs that wax and wane in amplitude are characteristically seen in myotonic discharges. Marked decrementing of an MUAP amplitude occurs in neuromyotonic discharges. Complex repetitive discharges typically are perfectly stable, but if additional loops or circuits drop in or out, the morphology may change abruptly in distinct or quantal jumps.

Firing Characteristics

After assessing the potential's morphology and stability, the electromyographer should look at the potential's firing characteristics, including the discharge pattern and firing rate. Note whether the pattern is regular or irregular. If it is regular, is it perfectly regular? Fibrillation potentials and positive sharp waves are more or less regular, but complex repetitive discharges are perfectly regular. If it is irregular, is it sputtering (e.g., endplate spikes), waxing/waning (e.g., myotonic discharges), or waning (e.g., neuromyotonic discharges)? Is there a bursting pattern (relative electrical silence between groups of discharges)? Such a pattern is characteristic of doublets and triplets as seen in tetany, and myokymic discharges. Note if the firing rate is very slow (<4–5 Hz). This is important because a slow firing rate signifies that the discharges cannot be voluntary. Voluntary activation of a motor unit has a firing frequency of at least 4 to 5 Hz. Any potential that fires more slowly than 4 to 5 Hz cannot be under voluntary control. Conversely,

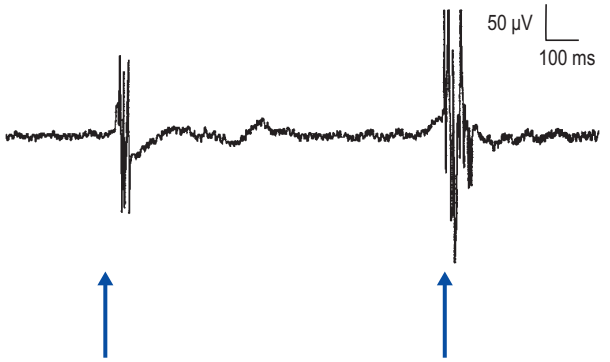

FIGURE 14–5 Normal insertional activity. Arrows show needle movement. With each needle movement, normal insertional activity is brief and usually lasts 300 ms or less. Increased insertional activity can be seen in both neuropathic and myopathic disorders. Note the long sweep speed.

extremely high firing rates are characteristic of neuromyotonic discharges, which can fire as fast as 150 to 250 Hz.

Table 14–1 summarizes the morphology, stability, and firing characteristics of the common spontaneous potentials seen during the needle EMG.

INSERTIONAL ACTIVITY

The needle EMG examination of each muscle begins with the assessment of insertional activity. When a needle is quickly moved through muscle, muscle fibers depolarize in a brief burst for several hundred milliseconds, known as insertional activity, which is a normal finding (Figure 14–5). The presence of insertional activity is important to the electromyographer to confirm that the needle is in muscle rather than fat or subcutaneous tissue. At least four to six brief needle movements are made in four quadrants of each muscle to assess insertional activity. Needle movement resulting in any waveform other than endplate potentials (see following section) that lasts longer than 300 ms indicates increased insertional activity. Increased insertional activity may be seen in both neuropathic and myopathic conditions. In rare conditions, where muscle has been replaced by fat and fibrous connective tissue, insertional activity may actually be decreased.

SPONTANEOUS ACTIVITY: NORMAL

All spontaneous activity is abnormal, with the important exception of potentials that occur in the muscle endplate zone (i.e., the NMJ). Muscle endplate usually is found near the center of the muscle belly and often is encountered during routine EMG. Patients frequently perceive a deep, burning, unpleasant sensation when the needle is placed in the endplate zone. Two types of spontaneous activity occur here: endplate noise and endplate spikes. It is of utmost importance to properly identify these potentials so as not to mistake them for pathologic spontaneous activity.

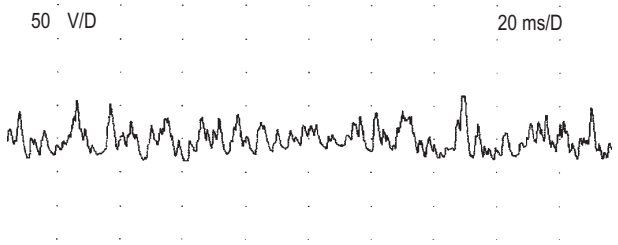

FIGURE 14–6 Endplate noise. Small, high-frequency, predominantly monophasic negative potentials, which are recognized by their characteristic shape and "seashell" sound on EMG.

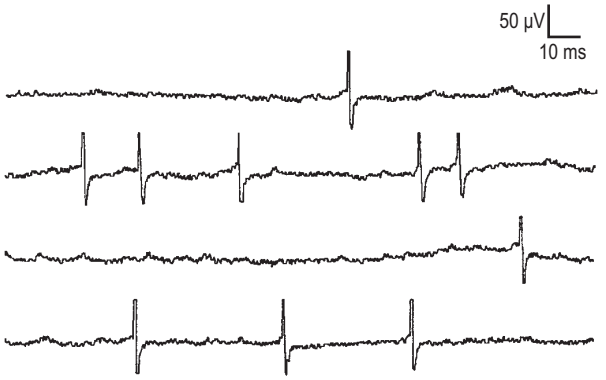

FIGURE 14–7 Endplate spikes. These result from needle-induced irritation of the terminal nerve twigs near the endplate zone. Note the initial negative deflection, brief duration, biphasic morphology, and the irregular, sputtering firing pattern, which differentiates them from fibrillation potentials.

Endplate Noise

These are low-amplitude, monophasic negative potentials that fire irregularly at 20 to 40 Hz and have a characteristic "seashell" sound on EMG (Figure 14–6). Physiologically, they represent MEPPs. They are recognized by their characteristic shape and sound and by their frequent association with endplate spikes (described in the next subsection).

Endplate Spikes ("Nerve Potentials")

Endplate spikes are MFAPs that fire irregularly up to a frequency of 50 Hz (Figure 14–7) and usually are seen along with endplate noise. They are biphasic, with an initial negative deflection, reflecting that the needle is at the site where the action potential is generated. They have a cracking, buzzing, or sputtering sound on EMG. The key features that differentiate endplate spikes from fibrillation potentials, which are also brief spikes, are their initial negative deflection and their highly irregular firing rate.

Endplate spikes are thought to occur as a result of needle-induced irritation of a terminal nerve twig and the subsequent activation of a nerve action potential leading to an MFAP (Figure 14–8). Thus, the needle is necessary to create these potentials. This is in contrast to endplate noise (MEPPs), which occurs spontaneously, without the presence of an irritating source. In summary, endplate spikes

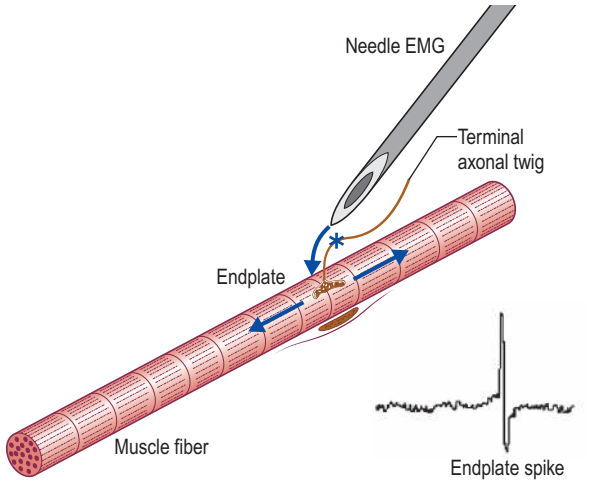

FIGURE 14–8 Generation of an endplate spike. Endplate spikes are thought to occur as a result of the EMG needle irritating a terminal nerve twig. This results in an action potential that runs down the terminal twig which subsequently results in a muscle fiber action potential (MFAP). The resulting waveform is biphasic and initially negative, signifying that the needle is right on top of where the MFAP originates.

only occur when a needle is in the muscle and close to the endplate zone, close enough to mechanically irritate nearby terminal nerve twigs.

SPONTANEOUS ACTIVITY: ABNORMAL MUSCLE FIBER POTENTIALS

Muscle is normally electrically silent outside of the endplate zone. Any persistent spontaneous activity outside of the endplate zone, usually defined as lasting longer than 3 seconds, is abnormal. Spontaneous activity may be ongoing when the needle is placed in the muscle or may be triggered by needle movement, voluntary muscle contraction, muscle percussion, or electrical stimulation.

Fibrillation Potentials

A fibrillation potential is derived from the extracellular recording of a single muscle fiber (Figures 14–9 and 14–10). These spontaneous depolarizations of muscle fibers are the electrophysiologic markers of active denervation. Although they typically are associated with neuropathic disorders (i.e., neuropathies, radiculopathies, motor neuron disease), they also may be seen in some muscle disorders (especially the inflammatory myopathies and dystrophies) and rarely in severe diseases of the NMJ (especially botulism). As they are generated in muscle fiber, fibrillation potentials are recognized by their single MFAP morphology: a brief spike with an initial positive deflection, 1 to 5 ms in duration, and low in amplitude (typically 10–100 μV). The firing pattern is very regular, with a rate usually 0.5 to 10 Hz, occasionally up to 30 Hz. In very chronic conditions (lasting >6–12 months), fibrillation potentials may become very tiny (<10 μV in amplitude) (Figure 14–11). On EMG, single fibrillation potentials sound like "rain on the roof." Although fibrillation potentials fire at a regular rate, they may slow down very gradually over several seconds before stopping.

FIGURE 14–9 Fibrillation potential. Spontaneous depolarization of a single muscle fiber. Note the initial positive deflection, brief duration, and triphasic morphology.

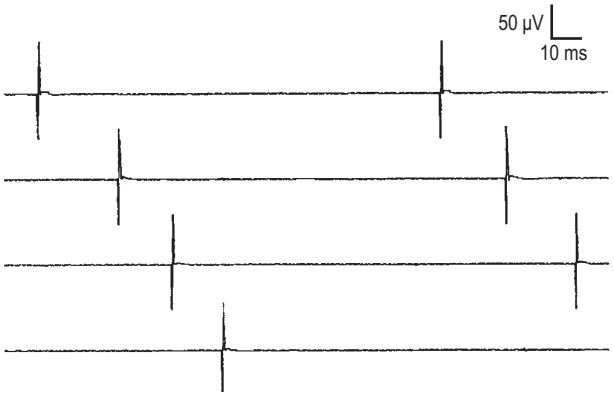

FIGURE 14–10 Fibrillation potential (rastered traces). Note the regular firing pattern, which helps identify the waveform as a fibrillation potential.

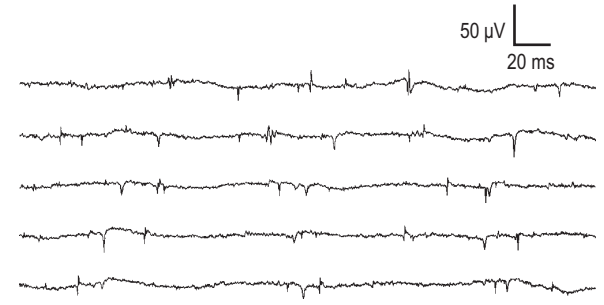

FIGURE 14–11 "Tiny" fibrillation potentials. In very chronic conditions (usually >6–12 months' duration), fibrillation potentials may become very small (<10 μV in amplitude). This trace is from a patient with a lumbar radiculopathy that had persisted for 2 years. Note several very small fibrillation potentials and positive sharp waves.

Positive Sharp Waves

Positive sharp waves have the same significance as fibrillation potentials: they are the spontaneous depolarization of a muscle fiber (Figure 14–12) and signify active denervation. Positive sharp waves have a brief initial positivity followed by a long negative phase. They sound like a dull pop because of their slow negative phase and long duration. The amplitude is variable (usually 10–100 μV, occasionally up to 3 mV). Like fibrillation potentials, they have a regular firing pattern, with a rate usually between 0.5 and 10 Hz, occasionally up to 30 Hz. This is a key point because voluntary motor unit potentials at a distance occasionally will have a positive wave morphology but can be distinguished by their lack of a regular firing pattern. Positive sharp waves usually are accompanied by fibrillation potentials, but they may be seen alone, sometimes early in denervation.

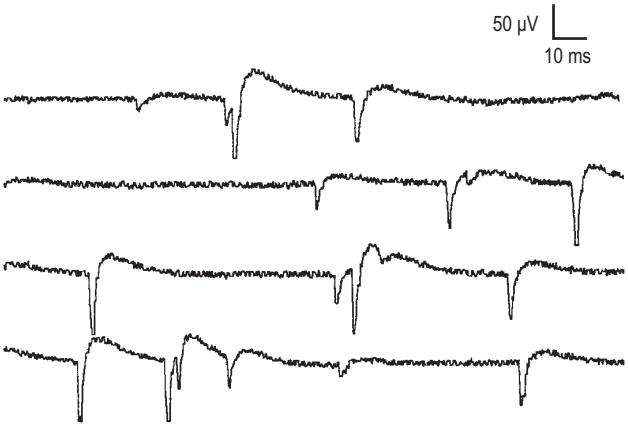

FIGURE 14–12 Positive sharp waves (rastered traces). Positive sharp waves have the same significance as fibrillation potentials: they represent the spontaneous depolarization of a muscle fiber. Note the initial positive deflection and the slow negative phase.

The mechanism by which a single muscle fiber action potential can assume either a fibrillation potential (i.e., brief spike) or a positive sharp wave morphology is not completely agreed upon. Fibrillation potentials occasionally will change to positive sharp waves with EMG needle movement, and vice versa (Figure 14–13). In order for a positive sharp wave to be formed, it is thought that the needle mechanically deforms a muscle fiber, rendering that segment of the membrane inexcitable. When a spontaneous depolarization arises distally in the muscle fiber, it can propagate toward the needle (creating the initial positive phase), but as it approaches the needle and the waveform begins to turn negative as expected, it cannot travel beyond the point of the mechanical deformation. The action potential then dissipates (Figure 14–13, right). This had been thought to be the most likely explanation for the generation of a positive sharp wave. This might also account for the fact that positive sharp waves are occasionally seen earlier than fibrillation potentials: the presence of the needle is required to help generate these positive sharp waves.

However, more recently, an additional explanation for positive sharp wave generation was proposed by Dumitru and colleagues. They postulated that positive sharp waves could originate, rather than terminate, at the recording needle electrode. In an eloquent series of experiments, two separate needle recording electrodes were placed along a single muscle fiber. By moving one needle and deforming the muscle membrane, spontaneous potentials could be generated. These were recorded by the needle near the origin of the spontaneous discharge, and then by the second

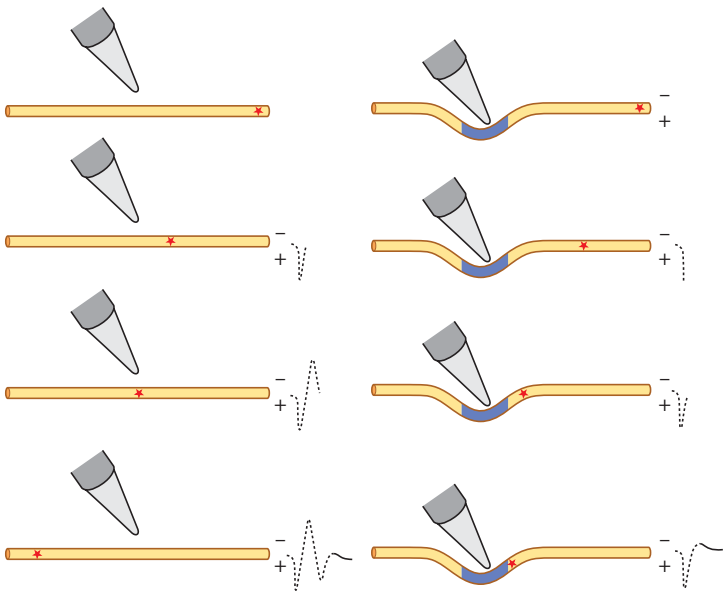

FIGURE 14–13 Generation of a fibrillation potential versus a positive sharp wave. **Left:** When the EMG needle is near a denervated fiber, the spontaneous firing of that fiber typically results in a triphasic brief spike potential (positive, negative, then positive) as the depolarization approaches, then is directly under, and then travels away from, the needle tip, respectively. **Right:** In the case of a positive sharp wave, the needle electrode mechanically deforms the fiber, which then makes the membrane electrically inexcitable at the segment (blue area). As the traveling depolarization wave approaches the needle, an initial positive wave is generated. With failure of conduction beyond the needle, the steep negative phase is aborted, and the waveform returns to baseline.
(Adapted with permission from Dimitru, D., 1989. Volume conduction: theory and application. In: Dimitru, D., (Ed.), Clinical electrophysiology: physical medicine and rehabilitation state of the art reviews. Hanley Belfus, Philadelphia.)

needle as the discharge propagated down the muscle fiber. When normal muscle fibers were studied, they demonstrated that normal insertional activity could result in local potentials that had either a positive sharp wave or brief biphasic spike (negative–positive) morphology. As these normal insertional activity potentials propagated down the muscle fiber and were recorded by the second needle, the potentials all had the morphology of a brief, triphasic spike (positive–negative–positive), the same as a fibrillation potential. However, when a denervated muscle fiber was studied, they demonstrated that when the needle deformed the muscle fiber membrane, a positive wave was recorded by that needle, but a time-locked fibrillation potential was recorded by the second needle at a distance down the same muscle fiber (Figure 14–14). Furthermore, if the first needle did not deform the muscle membrane, both needles recorded a fibrillation potential. Thus, the difference between whether positive sharp waves or fibrillation potentials were generated appeared to depend on whether or not the needle deformed the muscle fiber. The deformation of the muscle fiber by the needle is thought to create a "crushed zone," an area of membrane that cannot propagate action potentials but which remains connected to normal membrane on both sides. Near the crush zone, the extracellular recording of a spontaneous muscle fiber depolarization appears the same as its intracellular action potential (i.e., a positive depolarization).

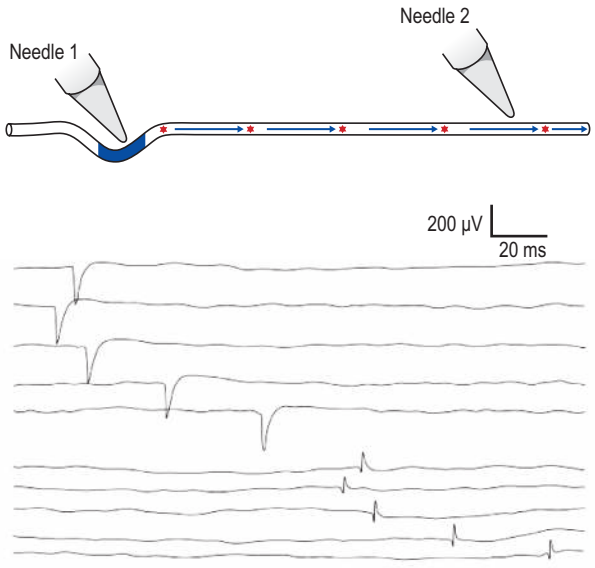

FIGURE 14–14 Additional explanation of positive sharp wave generation. **Top:** Two needle electrodes were placed along the same denervated muscle fiber. Needle 1 deformed the muscle fiber membrane and created a "crushed zone" effect. **Bottom, first 5 traces:** The spontaneous discharges of the muscle fiber recorded by Needle 1 all had a positive wave morphology. **Bottom, last 5 traces:** The corresponding time-locked potentials generated near Needle 1 had the morphology of fibrillation potentials when recorded at Needle 2.
(Adapted with permission from Dumitru, D., Martinez, C.T.J., 2006. Propagated insertional activity: a model of positive sharp wave generation. Muscle Nerve 34, 457–462.)

Regardless of whether the positive wave terminates or originates at the needle electrode, the take home message is that denervation results in both fibrillation potentials and positive sharp waves. They both represent the spontaneous firing of a single muscle fiber with an unstable resting membrane. The only difference between positive sharp waves and fibrillation potentials is that in the case of positive sharp waves, there is needle-induced deformation of the muscle membrane.

When positive sharp waves and/or fibrillation potentials are present in a muscle, they are conventionally graded on a scale from 0 to 4 as follows:

0 None present
+1 Persistent single trains of potentials (>2–3 seconds) in at least two areas
+2 Moderate number of potentials in three or more areas
+3 Many potentials in all areas
+4 Full interference pattern of potentials

Fibrillation potentials and positive sharp waves are the most common of all the abnormal spontaneous potentials, seen in a large number of common disorders (e.g., radiculopathy, entrapment neuropathies). With experience, their recognition becomes fairly straightforward, especially when one hears the characteristic "rain on the roof" sound. The exception is when one encounters the +4 grade of fibrillation potentials (Figure 14–15). In this situation, the screen is completely filled, and individual potentials cannot be seen. It is common to think at first that the patient is not relaxed and that the screen is filled with voluntary motor unit potentials. However, once the electromyographer is convinced that the patient is relaxed, one can still discern the sound pattern of "rain on the roof" when listening closely, but in this case it is a heavy downpour. This pattern is distinctly uncommon and is seen only in unusual situations where all or nearly all muscle fibers are denervated simultaneously. Most common among these situations are trauma (e.g., from nerve laceration) and infarction (e.g., from vasculitis).

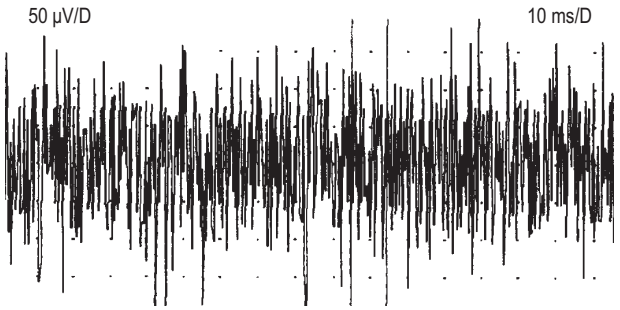

FIGURE 14–15 Grade +4 fibrillation potentials. The number of fibrillation potentials is so profuse that the screen is filled with a complete interference pattern. This pattern is distinctly uncommon and is seen only in unusual situations whereby all or nearly all muscle fibers are denervated simultaneously. Most common among these situations are trauma (e.g., from nerve laceration) and infarction (e.g., from vasculitis).

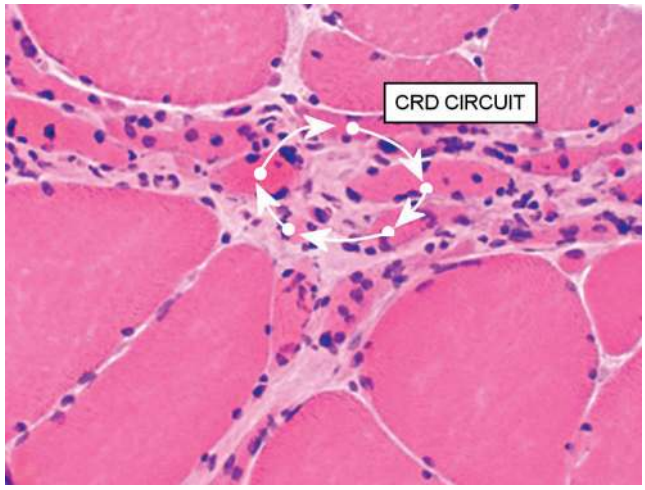

FIGURE 14–16 Pathophysiology of a complex repetitive discharge (CRD). A spontaneous depolarization occurs from ephaptic transmission from one denervated muscle fiber to an adjacent one. If the original pacemaker is reactivated, a circus movement is formed without an intervening synapse. In neuropathic conditions, the pathologic correlate is grouped atrophy, wherein denervated fibers lie next to other denervated fibers.

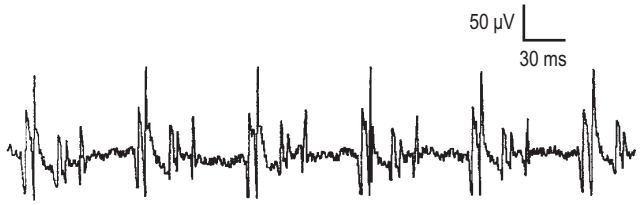

FIGURE 14–17 Typical complex repetitive discharge. Note the multiple spikes (each spike within the complex representing a different single muscle fiber) and the perfectly repetitive nature.

Complex Repetitive Discharges

Complex repetitive discharges (CRDs) are one of the most distinctive waveforms encountered on the needle EMG examination. They result from depolarization of a single muscle fiber followed by ephaptic spread to adjacent denervated fibers (i.e., direct spread from muscle membrane to muscle membrane). If the depolarization spreads in a circus movement whereby the original pacemaker muscle fiber is reactivated, a recurrent discharge develops (Figure 14–16). The morphology of a CRD is that of individual muscle fibers, discernible as individual spikes, that fire consecutively and are time linked together (Figure 14–17). On EMG, CRDs are recognized as high-frequency (typically 5–100 Hz), multi-serrated repetitive discharges with an abrupt onset and termination. These discharges usually occur spontaneously (e.g., when the pacemaker is a fibrillation potential) or following needle movement. Less frequently, they are triggered by a stimulated MUAP or by a voluntary MUAP.

CRDs are identical in morphology from one discharge to the next, creating a characteristic machine-like sound on EMG (Figure 14–18). They occur in both chronic neuropathic and myopathic disorders; they may arise in any

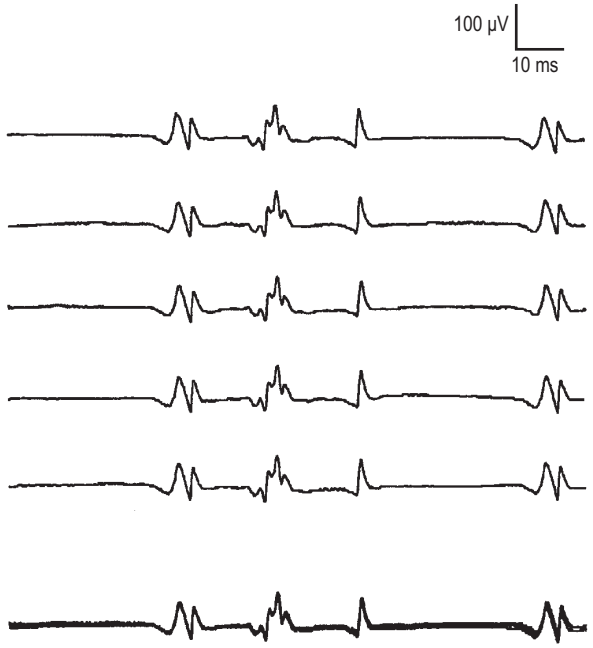

FIGURE 14–18 Complex repetitive discharge (CRD) triggered on a delay line (top five traces). Traces superimposed (bottom trace). Note the perfectly repetitive nature of a CRD. When superimposed, there is little or no jitter between successive potentials.

setting in which denervated muscle fibers lie adjacent to other denervated muscle fibers. Because muscle fibers from many different motor units intermix in normal muscle, CRDs do not usually occur in the acute setting because denervated muscle fibers do not lie adjacent to other denervated fibers in this setting. To create a setting whereby denervated muscle fibers lie adjacent to one another, in neuropathic conditions, there has to be denervation followed by reinnervation (i.e., fiber type grouping) and subsequent denervation (i.e., grouped atrophy). This situation may also occur in myopathic disorders associated with denervation (i.e., myopathies associated with necrosis or inflammation) or those associated with muscle fiber splitting.

Occasionally, individual phases or additional loops drop in and out, creating an abrupt change in frequency and sound (Figure 14–19). In rare cases, if the pacemaker is overdriven by another discharge, the CRD may be irregular. As soon as the overdriving pacemaker frequency falls below the inherent frequency of the CRD, the CRD once again becomes perfectly regular.

Because CRDs are generated by muscle fibers, they usually persist with NMJ blockade. On single-fiber EMG, there is a characteristic finding: abnormally low jitter. This occurs because the discharge spreads ephaptically from one muscle fiber to another; there is no intervening synapse, which would normally give rise to some jitter.

Myotonic Discharges

A myotonic discharge is the spontaneous discharge of a muscle fiber (similar to fibrillation potentials and positive

sharp waves) but is differentiated by its characteristic waxing and waning of both amplitude and frequency (Figures 14–20 and 14–21). The firing rate is generally between 20 and 150 Hz. An individual myotonic potential may have either a positive wave or a brief spike morphology (identifying the source generator as a muscle fiber). Myotonic discharges are characteristically seen in myotonic dystrophy, myotonia congenita, and paramyotonia congenita. They may also occur in other myopathies (acid maltase deficiency, polymyositis, myotubular myopathy), hyperkalemic periodic paralysis, and, rarely, in denervation of any cause. It is important to remember this last point: a single brief run of myotonic discharges may occur in any denervating disorder, although it is never the predominant waveform.

Myotonic discharges have a characteristic "revving engine" sound on EMG, due to the waxing and waning of amplitude and frequency. One of the most common pitfalls in the interpretation of needle EMG is to mistake myotonic discharges for acute denervation (i.e., fibrillation potentials and positive sharp waves). This error of interpretation occurs because both have the same basic morphology and both are generated in muscle fiber, and denervation potentials are common whereas myotonic discharges are uncommon in clinical practice. However, once the waxing and waning sound of myotonic discharges is recognized, the differentiation is easily made. More than one patient with myotonia congenita or myotonic dystrophy has been erroneously given the diagnosis of motor neuron disease based on the electromyographer's misinterpretation of myotonic discharges as widespread denervation potentials.

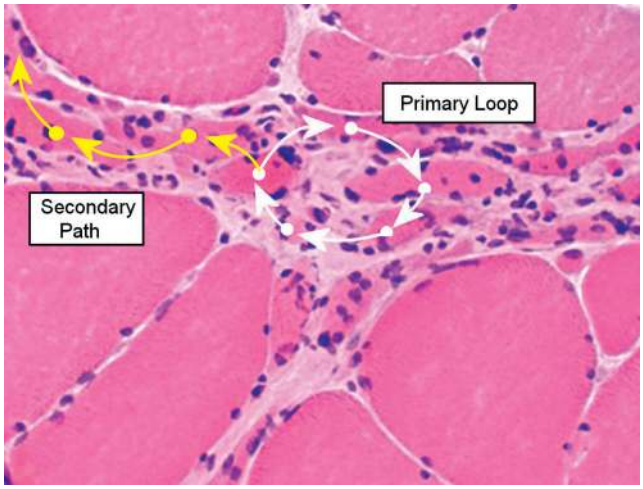

FIGURE 14–19 Complex repetitive discharges. These may change abruptly in frequency or number of potentials when extra paths or circuits drop in and out (note the secondary path compared with Figure 14–16).

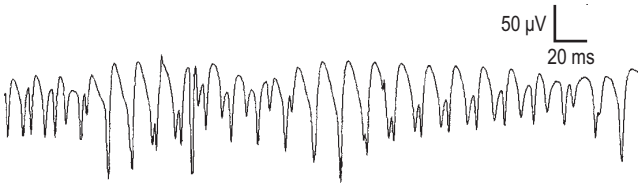

FIGURE 14–20 Myotonic discharge (spontaneous discharge). Note the waxing and waning of both amplitude and frequency.

SPONTANEOUS ACTIVITY: ABNORMAL MOTOR UNIT POTENTIALS

Fasciculation Potentials

A fasciculation potential is a single, spontaneous, involuntary discharge of an individual motor unit (Figure 14–22). Unlike voluntary motor unit potentials, fasciculation potentials generally fire very slowly and irregularly, usually less than 1 to 2 Hz. In contrast, voluntary motor unit potentials begin firing at 4 to 5 Hz when a patient is asked to slightly contract a muscle and cannot fire more slowly than this. Thus, potentials that fire more slowly than 4 to 5 Hz are not under voluntary control. The source generator of fasciculation potentials is the motor neuron or its axon, prior to its terminal branches. On EMG, fasciculation potentials usually have the morphology of simple MUAPs, or they can be complex and large if they represent a pathologic (i.e., reinnervated) motor unit. Despite the notorious association of fasciculations with diseases of the anterior horn cell, the actual site of origin of most fasciculations has been found to be distal in the axon.

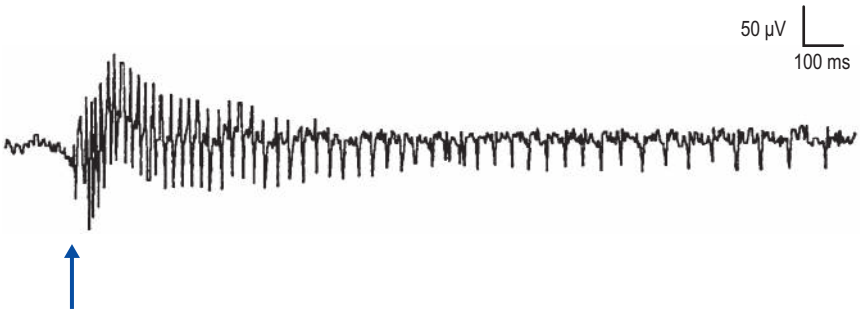

FIGURE 14–21 Myotonic discharge (needle induced). Arrow marks needle movement triggering the discharge. Myotonic discharges may occur spontaneously or be triggered by needle movement, voluntary contraction, or muscle percussion.

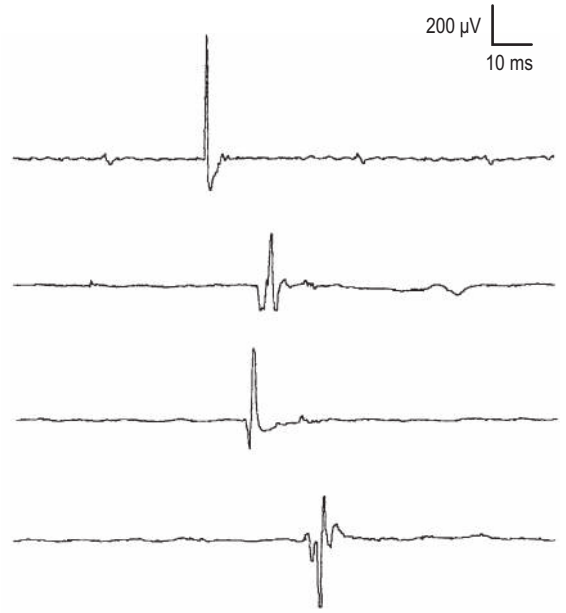

FIGURE 14–22 Fasciculation potentials (rastered traces). Each potential has the morphology of a motor unit potential. They are recognized by their morphology and irregular, slow firing pattern.

Clinically, fasciculations are recognized as individual brief twitches that seldom result in significant movement of a joint. Fasciculations are associated with numerous disease processes affecting the lower motor neuron. Motor neuron disease, such as amyotrophic lateral sclerosis, is the best known. However, fasciculations can be seen in radiculopathies, polyneuropathies, and entrapment neuropathies. In addition, most normal individuals have some fasciculations, so-called *benign fasciculations*.

Distinguishing "benign" from "malignant" fasciculations on a clinical basis is nearly impossible. However, benign fasciculations are not associated with muscle weakness, wasting, or any abnormality of reflexes. In general, benign fasciculation potentials tend to fire faster and affect the same site repetitively (e.g., eyelid twitching), as opposed to fasciculation potentials in pathologic conditions such as motor neuron disease, which tend to be more random.

On EMG, fasciculation potentials have the sound of "corn popping": they are dull, irregular pops. Because fasciculation potentials usually are very slow, they can be easily missed on needle EMG if the electromyographer does not wait a sufficient amount of time with the needle in the muscle at rest. It is often said that the best way to look for fasciculation potentials is to place the needle in the muscle and then have the electromyographer take his or her hand off the needle and wait.

Doublets, Triplets, and Multiplets

Spontaneous MUAPs that fire in groups of two are known as *doublets* (Figure 14–23). When they fire in groups of three or multiple potentials, they are known as *triplets* and *multiplets*, respectively. These potentials have the same

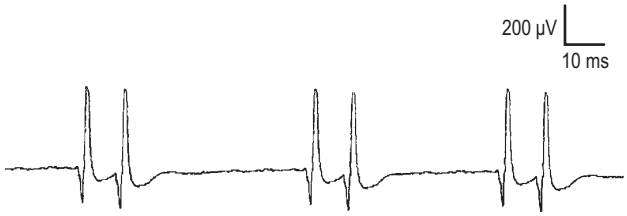

FIGURE 14–23 Doublets. Spontaneous discharges of motor unit action potentials that fire in groups of twos are known as doublets. Doublets often accompany fasciculations as well as groups of three potentials (triplets) or multiple potentials (multiplets). These potentials fundamentally have the same significance as fasciculation potentials and are seen in neuropathic conditions, but they also are characteristically seen in tetany from hypocalcemia.

significance as fasciculation potentials: they represent the spontaneous depolarization of a motor unit or its axon. They are often seen with fasciculation potentials. In this situation, fasciculation potentials may be referred to as singlets. Doublets, triplets, and multiplets can be seen in any situation where fasciculation potentials occur (i.e., neuropathic conditions), but they also are characteristically seen in tetany from hypocalcemia (Figure 14–24). Tetany, which is the involuntary contraction of muscles associated with hypocalcemia, predominantly affects the distal muscles, with involuntary spasms affecting the hands and feet (carpopedal spasms). In the hands, a characteristic posture develops: adduction of the thumb and fingers, extension of the interphalangeal joints, and flexion of the metacarpal–phalangeal joints and wrist.

Myokymic Discharges

Electrically, myokymic discharges (Figure 14–25) are rhythmic, grouped, spontaneous repetitive discharges of the same motor unit (i.e., grouped fasciculations). The firing frequency within the burst typically is 5 to 60 Hz. The number of potentials within a burst varies widely and may change from burst to burst (Figure 14–26). The firing frequency between bursts is much slower (typically <2 Hz) and produces a marching sound on EMG. Changing to a longer sweep speed often makes it easier to recognize the bursting pattern of a myokymic discharge. Freezing the screen often makes it easier to recognize the presence of the same motor unit potential firing repetitively in bursts. The origin of myokymic discharges likely involves spontaneous depolarization of or ephaptic transmission along demyelinated segments of nerve.

Clinically, myokymia usually is recognized as continuous involuntary quivering, rippling, or undulating movement of muscle. The finding of myokymic discharges on EMG is very helpful in limiting the differential diagnosis (Box 14–1). Limb myokymia occurs in a variety of conditions but is most characteristically seen in radiation-induced nerve damage. The most typical situation occurs in a patient with a progressive plexopathy who has a prior history of cancer treated with radiation therapy. In this situation, the

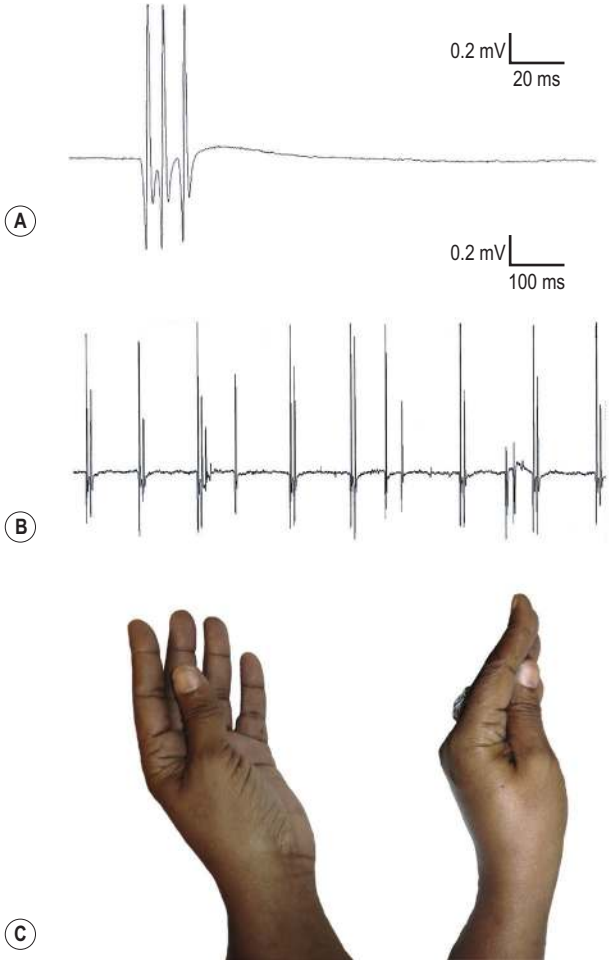

FIGURE 14–24 Tetany and carpopedal spasm. EMG traces and photo from a patient who developed hypoparathyroidism resulting in hypocalcemia following total thyroidectomy. This patient reported intermittent paresthesias in the fingers and toes, as well as around the mouth, with involuntary spasms of the hands. Routine nerve conduction and needle EMG were normal. When a blood pressure cuff was inflated above systolic blood pressure with the EMG needle in a distal hand muscle, paresthesias developed within a minute. Two minutes later, occasional doublets and triplets were present on EMG. **A:** Isolated triplet. This was followed by the firing of many singlets, doublets and triplets. **B:** The sweep speed has been increased to 100 ms/division. Note the irregular firing of doublets, triplets, and an occasional singlet. The hand then went into an involuntary spasm. **C:** Note the characteristic posture of carpopedal spasm associated with tetany when a blood pressure cuff was inflated above systolic pressure (Trousseau sign): adduction of the thumb and fingers, extension of the interphalangeal joints, and flexion of the metacarpal–phalangeal joints). When the blood pressure cuff was deflated, all the spontaneous EMG activity ceased within seconds. The Trousseau sign is provoked by making the limb ischemic with a blood pressure cuff and is useful both clinically and during EMG to demonstrate the potentials associated with tetany.

differential diagnosis often lies between relapse of the cancer with invasion of the plexus and a delayed radiation-induced plexopathy. The presence of myokymic discharges on needle EMG strongly supports a diagnosis of radiation plexitis rather than recurrent neoplastic invasion. Limb myokymia also occurs infrequently in radiculopathy,

Box 14–1. Disorders Commonly Associated with Myokymic Discharges

Radiation injury (usually brachial plexopathy)
Guillain–Barré syndrome (facial)
Multiple sclerosis (facial)
Pontine tumors (facial)
Hypocalcemia
Timber rattlesnake envenomization

Occasionally seen in
- Guillain–Barré syndrome (limbs)
- Chronic inflammatory demyelinating polyneuropathy
- Nerve entrapments
- Radiculopathy

entrapment neuropathy, and spinal cord lesions associated with demyelination.

Facial myokymia characteristically occurs with brainstem lesions associated with multiple sclerosis, pontine gliomas, and vascular disease, but it can also be seen after radiation. In Guillain–Barré syndrome, facial myokymia may occur in 15% of patients, usually occurring early in the illness and remitting as the patient clinically improves.

Myokymia from peripheral nerve lesions can be provoked or enhanced by lowering serum ionized calcium with hyperventilation or with the use of acid–citrate–dextrose anticoagulant as is commonly given during plasma exchange. Administration of calcium can transiently decrease the generation of myokymic discharges.

Cramp Potentials

Cramps are painful, involuntary contractions of muscle that tend to occur when a muscle is in the shortened position and contracting. Surprisingly, cramp potentials are actually high-frequency discharges of motor axons and are not primarily a muscle phenomenon. EMG characteristically shows several normal appearing motor unit potentials firing repetitively and sometimes irregularly at high frequencies (usually 40–75 Hz) (Figure 14–27). Cramps may be benign (e.g., nocturnal calf cramps, post-exercise cramps) or may be associated with a wide range of neuropathic, endocrinologic, and metabolic conditions. Clinically, cramps may resemble the contractures that occur in several of the metabolic muscle diseases. However, the needle EMG of a cramp potential is quite different from that of a contracture, which typically is completely electrically silent (see Chapter 35).

Neuromyotonic Discharges

Neuromyotonic discharges are high-frequency (150–250 Hz), decrementing, repetitive discharges of a single motor unit that have a characteristic "pinging" sound on EMG (Figure 14–28). They have the highest frequency of any discharge. They are a rare phenomenon and represent the end of the spectrum of abnormal spontaneous activity generated in motor nerve (Figure 14–29).

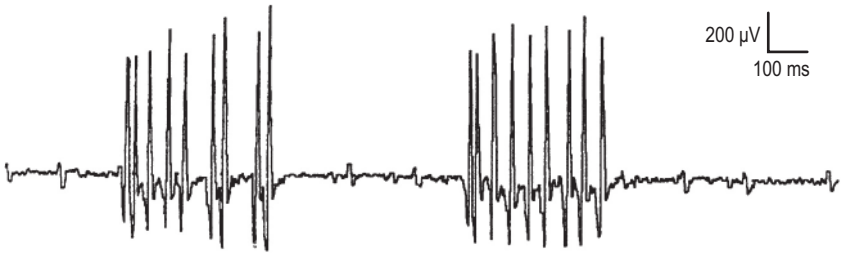

FIGURE 14–25 Myokymic discharges. Involuntary grouped repetitive discharges of the same motor unit action potential. Note the high-frequency pattern within the burst and the slow frequency between the bursts. Myokymia produces a marching sound on electromyogram.

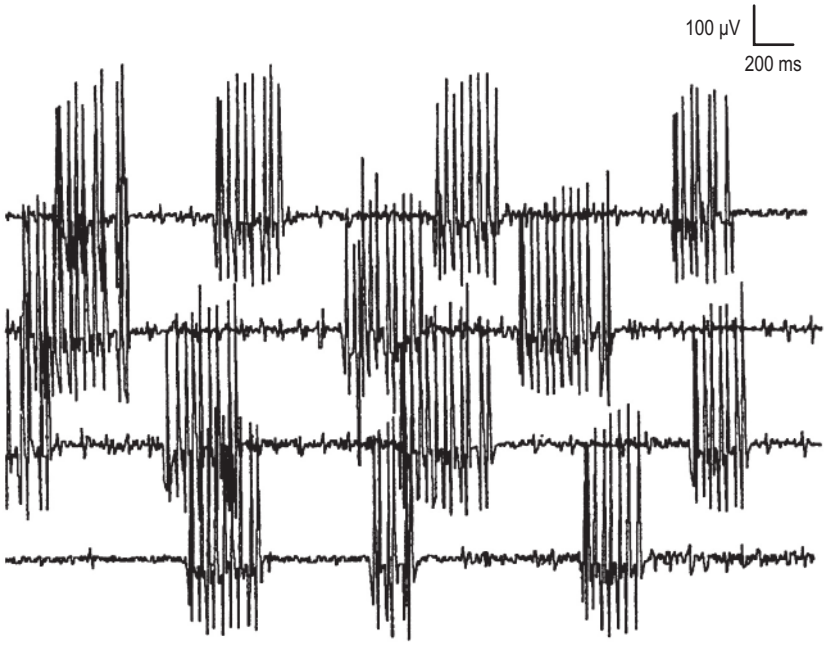

FIGURE 14–26 Myokymic discharges (rastered traces, long sweep speed). Note that the number of potentials within a burst may change from burst to burst.

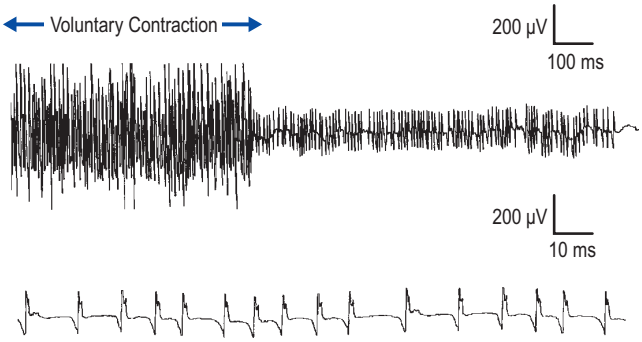

FIGURE 14–27 Cramp discharge. In the figure, the subject is actively contracting the muscle, followed by relaxation. The cramp discharge is seen in the relaxation phase **(upper trace)** following voluntary contraction. In the **lower trace,** the cramp discharge is expanded. Note that the cramp discharge is composed of the same MUAP firing quickly but slightly irregularly. Clinically, cramps are painful, involuntary contractions of muscle that tend to occur when a muscle is in the shortened position and contracting. Cramps are high-frequency discharges of motor axons, with the electromyogram characteristically showing motor unit action potentials (MUAPs) with a normal morphology firing repetitively and sometimes irregularly at high frequencies.

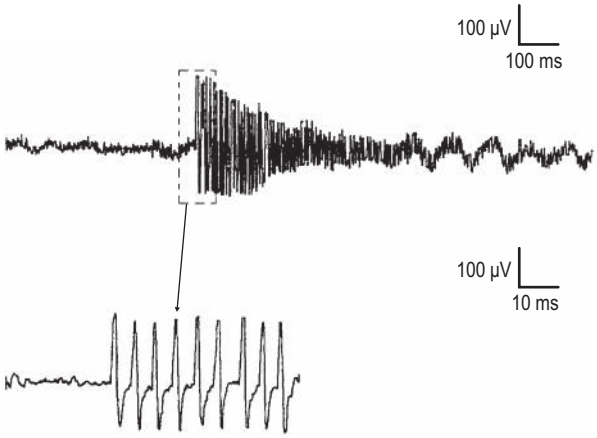

FIGURE 14–28 Neuromyotonic discharges. Spontaneous discharges of a single motor unit potential at very high frequencies (150–250 Hz). Note the decrementing response. **Inset:** Change in sweep speed identifies each potential as the same motor unit potential.

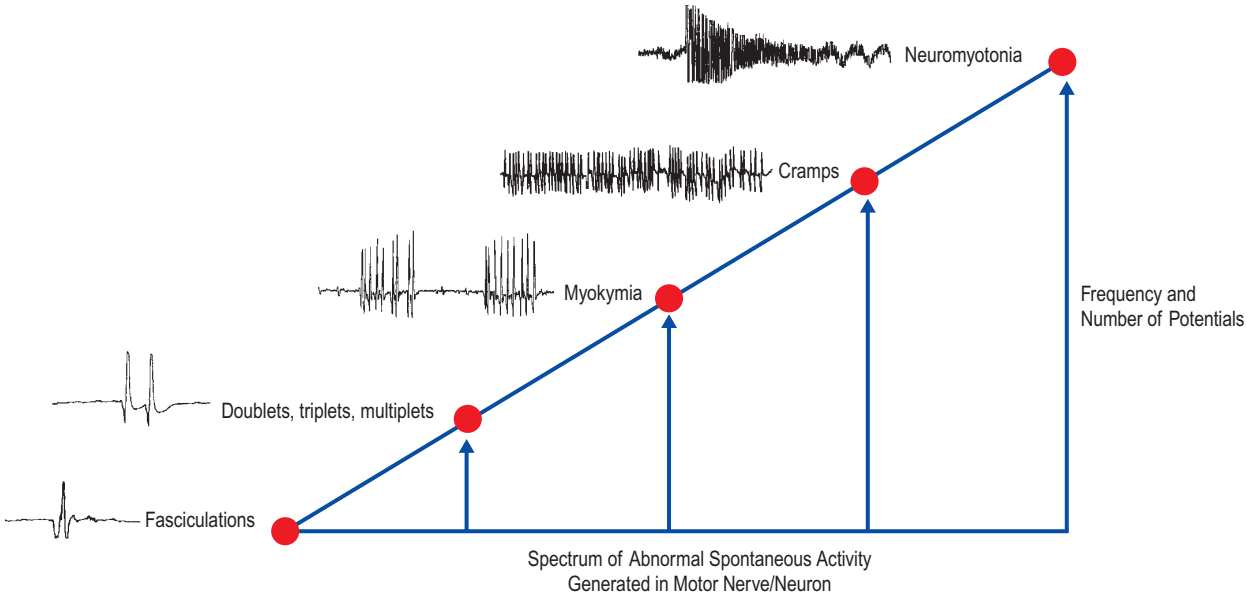

FIGURE 14–29 Spectrum of abnormal spontaneous activity generated in the motor nerve/neuron. Conceptually, it is useful to consider spontaneous activity that arises from the motor nerve/neuron to be on a spectrum. They all share the same basic morphology: that of a motor unit action potential. They are differentiated by their stability and firing characteristics. Often, these potentials accompany one another. For instance, cramp discharges and fasciculation potentials are commonly seen together.

Clinically, patients with neuromyotonia display generalized stiffness, hyperhidrosis, and delayed muscle relaxation after contraction. The delay in relaxation and improvement with repetitive use can be difficult to distinguish clinically from myotonia of muscle origin. However, in myotonia of muscle origin, direct muscle percussion may elicit myotonia, whereas this does not occur in neuromyotonia. Electrically, these syndromes are easily differentiated. Whereas myotonic syndromes are associated with spontaneous discharges of muscle fibers (with a positive wave or brief spike morphology), neuromyotonic disorders are associated with involuntary spontaneous discharges of motor neurons or their axons (with an MUAP morphology). In the neuromyotonic disorders, it is not unusual to see other spontaneous discharges that originate in the motor nerve, including fasciculation potentials and myokymic discharges.

Several lines of evidence suggest that these discharges are generated by peripheral motor axons. The activity persists during sleep, as well as during spinal or general anesthesia, and is abolished by curare. Progressively distal nerve blocks diminish the intensity of the spontaneous discharges. Phenytoin and carbamazepine frequently are helpful in reducing symptoms.

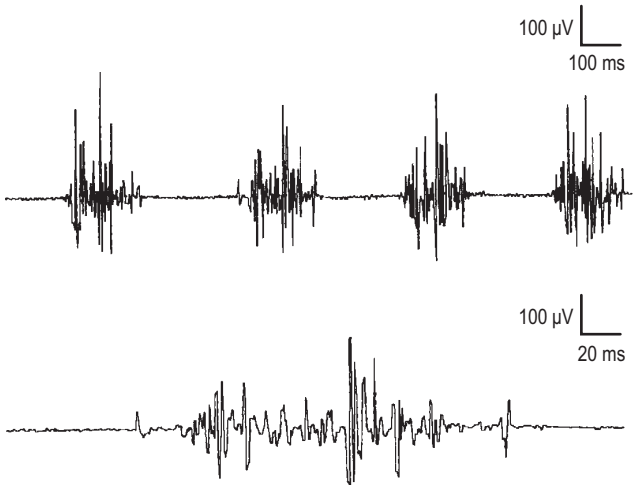

FIGURE 14–30 Rest tremor is recognized as a bursting pattern of motor unit action potentials (MUAPs) separated by relative silence **(top).** Because multiple different MUAPs overlap, polyphasia appears increased and individual MUAP morphology is difficult to assess **(bottom).**

The nomenclature of the neuromyotonic syndromes is complicated; they have been referred to as Isaac's syndrome, neuromyotonia, pseudomyotonia, neurotonia, normocalcemic tetany, and continuous muscle fiber activity. Although the neuromyotonic syndromes are rare, neuromyotonic discharges are seen most commonly in the syndrome of acquired neuromyotonia. There is now considerable evidence that this disorder is an autoimmune channelopathy, with the target antigen being a peripheral nerve voltage-gated potassium channel. An association with myasthenia gravis, thymoma, various malignancies, and inflammatory demyelinating polyneuropathies, among other conditions, has been reported. Some cases have been reported to improve with immunosuppressive therapy. Neuromyotonic discharges also may be seen in extremely chronic neuropathic diseases (especially old poliomyelitis and adult spinal muscular atrophy). Rare cases of familial neuromyotonia have been described, with the age of onset

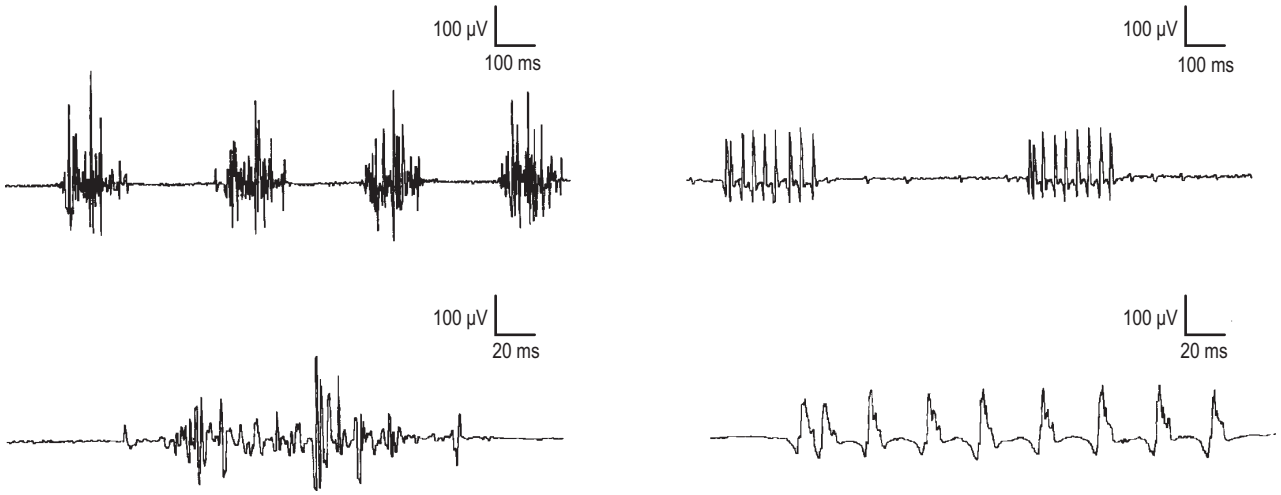

FIGURE 14–31 Tremor versus myokymia. When tremor occurs at rest **(left traces),** it may be mistaken for myokymic discharges. Myokymic discharges **(right traces)** also result in a bursting pattern. Myokymia can be differentiated from tremor by noting that the same motor unit action potential (MUAP) fires repetitively in a myokymic burst, compared with many different MUAPs firing simultaneously in tremor.

ranging from infancy to the eighth decade. It should be noted that neuromyotonic discharges are not seen in stiff-person syndrome, which is a central disorder of spinal interneurons, wherein involuntary firing of normal-appearing MUAPs is seen and for which diazepam is frequently helpful.

Rest Tremor

Although tremor, if present, usually occurs during voluntary contraction, it can complicate the interpretation of spontaneous activity on EMG if it is present at rest. Tremor is recognized as a synchronous bursting pattern of MUAPs separated by relative silence (Figure 14–30). As multiple MUAPs fire simultaneously, the morphology of individual MUAPs may be difficult to assess, and there appears to be increased polyphasia. When tremor occurs at rest (e.g., Parkinson's disease), the spontaneous bursting discharge may be mistaken for myokymic discharges. Although myokymic discharges and tremor both result in a bursting pattern of MUAPs, the major difference is that in myokymia the same MUAP fires repetitively in a burst, whereas in tremor the burst is composed of many different MUAPs (Figure 14–31). Also, if one freezes the screen and looks closely at the burst, one can see that the amplitude often will rise and fall in tremor, whereas it remains relatively unchanged in myokymia.

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15 Basic Electromyography: Analysis of Motor Unit Action Potentials

After assessment of insertional and spontaneous activity, the needle electromyography (EMG) examination moves on to the evaluation of motor unit action potentials (MUAPs). In a process similar to the analysis of spontaneous activity, MUAPs must be assessed for morphology (duration, amplitude, phases), stability, and firing characteristics. The pattern of MUAP abnormalities that emerges from this part of the examination usually will allow a determination of whether a disorder is primarily neuropathic or myopathic and often helps determine the time course (acute vs. chronic) and severity of the lesion. The assessment of MUAPs often is demanding and improves with the experience of the electromyographer over time. The task of evaluating MUAPs is made all the more difficult by the wide variation in what is considered a normal MUAP, depending on the muscle being studied and the age of the patient.

PHYSIOLOGY

The basic component of the peripheral nervous system is the motor unit, defined as an individual motor neuron, its axon, and associated neuromuscular junctions (NMJs) and muscle fibers. The extracellular needle EMG recording of a motor unit is the MUAP (Figure 15–1). The number of muscle fibers per motor unit varies greatly, from 5 to 10 in laryngeal muscles to a couple of thousand in the soleus. The transverse territory of a motor unit usually ranges from 5 to 10 mm in adults, with many motor unit territories overlapping with one another. Because of this overlap, two muscle fibers from the same motor unit rarely lie adjacent to each other. Transverse motor unit territory increases greatly with age, doubling from birth to adulthood, mostly because of the increase in individual muscle fiber size.

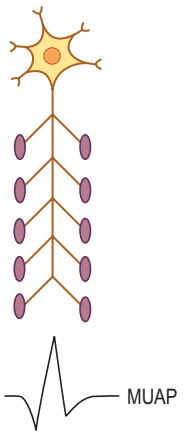

FIGURE 15–1 The motor unit. The basic component of the peripheral nervous system is the motor unit, defined as an individual motor neuron, its axon, and associated neuromuscular junctions and muscles fibers. The extracellular needle electromyography recording of a motor unit is the motor unit action potential (MUAP).

When a motor neuron depolarizes to threshold, a nerve action potential is generated and propagates down the axon. Under normal circumstances, this results in all muscle fibers of the motor unit being activated and depolarizing more or less simultaneously. Any variability between muscle fiber depolarization times is due to differences in the length of the terminal axons and in NMJ transmission times.

The "size principle" governs many of the properties of motor units (Figure 15–2). The size of the motor neuron is directly related to (1) the size of the axon, (2) the thickness of the myelin sheath, (3) the conduction velocity of the axon, (4) the threshold to depolarization, and (5) the metabolic type of muscle fibers that are innervated. The larger motor neurons have larger axons, with the thickest myelin sheath (hence, the fastest conduction velocity), highest threshold to depolarization, and connections to type II, fast twitch muscle fibers. Conversely, the smaller motor neurons have smaller axons, less myelin sheath, slower conduction velocity, lower threshold to depolarization, and, in general, connections to type I, slow twitch muscle fibers. Thus, with voluntary contraction, the smallest motor units with the lower thresholds fire first. As contraction increases, progressively larger motor units begin to fire. The largest type II motor units fire with maximum contraction. During routine needle EMG, most MUAPs analyzed are thus from the smaller motor units that innervate type I muscle fibers.

During the needle EMG examination, each MUAP recorded represents the extracellular compound potential of the muscle fibers of a motor unit, weighted heavily toward the fibers nearest to the needle. A MUAP recorded just outside a muscle membrane is 1/10 to 1/100 the amplitude of the actual transmembrane potential and the amplitude decreases rapidly as the distance between the needle and the membrane increases. *The classification of an MUAP as normal, neuropathic, or myopathic rests on*

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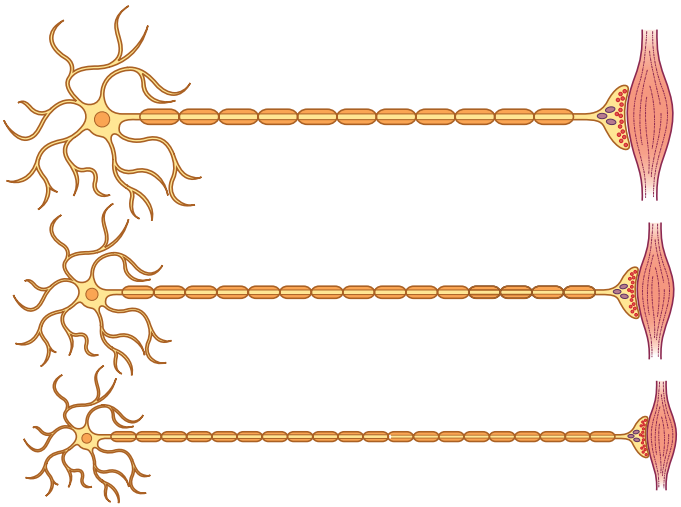

Neuron	Axon	Myelin	CV	Threshold	Fiber Type
Large	Large	Thick	Fast	High	Type II
Medium	Medium	Medium	Medium	Medium	Type I/II
Small	Small	Thin	Slow	Low	Type I

FIGURE 15–2 Size principle and motor unit properties.

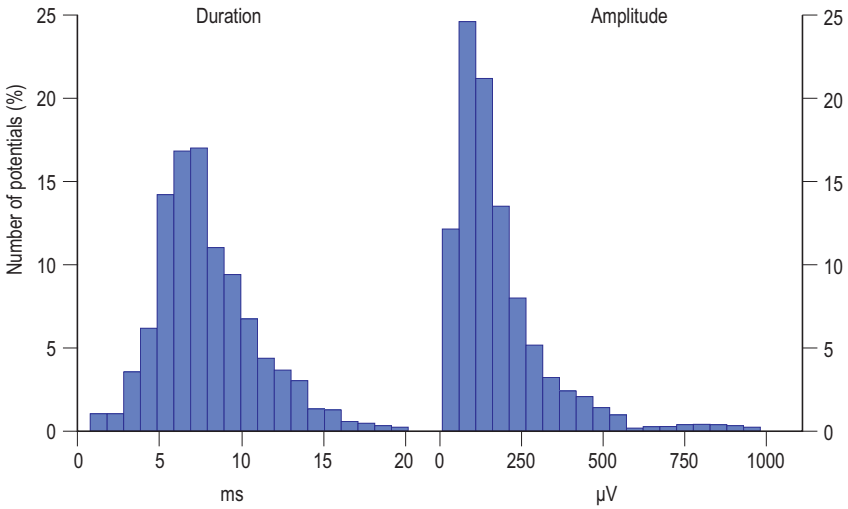

FIGURE 15–3 Range of normal motor unit action potential (MUAP) duration and amplitude. Histogram of MUAP duration and amplitude in the biceps brachii of a normal subject. Note that both MUAP duration and amplitude vary markedly in normal muscles, with small and large units in the same muscle. MUAP duration or amplitude should not be classified as abnormal based on one or two MUAPs but requires a mean of many motor units.
(Reprinted with permission from Buchthal, F., Guld, C., Rosenfalck, P., 1954. Action potential parameters in normal human muscle and their dependence on physical variables. Acta Physiol Scand 32, 200.)

no single finding. As is true of spontaneous activity, recorded MUAPs must be assessed for morphology (duration, polyphasia, amplitude), stability, and firing characteristics before any conclusions can be reached.

MORPHOLOGY

MUAP properties vary widely both within and between different muscles. Even within a muscle, there is a wide range of normal motor unit morphology, with MUAP size following a bell-shaped distribution curve (Figure 15–3). Due to this normal variability, normal values of MUAP morphology are based on the mean of many different MUAPs. The analysis of MUAP morphology can be performed on either a qualitative or a quantitative basis. To perform quantitative MUAP analysis, one must isolate 20 different MUAPs for each muscle being studied and measure their individual durations, amplitudes, and number of phases. From these values, the mean duration, amplitude, and number of phases are calculated and compared with a set of normal values for that particular muscle and age group. MUAP morphology varies depending on the muscle being studied and the patient's age. This is particularly true of MUAP duration (Table 15–1). In general, MUAPs in proximal muscles tend to be shorter in duration than those in more distal muscles. MUAP size in adults is larger than in children, primarily because of an increase in the size of muscle fibers during development. In addition, MUAP size is generally larger in older individuals, probably as the result of dropout of motor units from the normal effects of aging, leading to some compensatory "normal" reinnervation. The loss of motor units has been estimated to be approximately 1% per year, beginning in the third decade of life, which then increases rapidly after age 60.

Only by comparing mean MUAP morphology in each muscle studied to normal values for that particular muscle and age group can one determine whether the morphology is truly abnormal. Previously, quantitative MUAP analysis was tedious and time consuming. However, many modern

Table 15–1. Mean Motor Unit Action Potential Duration Based on Age and Muscle Group

Age of Subjects	Arm Muscles					Leg Muscles					
	Deltoid	Biceps	Triceps	Thenar	ADM	Quad, BF	Gastroc	Tib Ant	Per Long	EDB	Facial
0–4	7.9–10.1	6.4–8.2	7.2–9.3	7.1–9.1	8.3–10.6	7.2–9.2	6.4–8.2	8.0–10.2	6.8–7.4	6.3–8.1	3.7–4.7
5–9	8.0–10.8	6.5–8.8	7.3–9.9	7.2–9.8	8.4–11.4	7.3–9.9	6.5–8.8	8.1–11.0	5.9–7.9	6.4–8.7	3.8–5.1
10–14	8.1–11.2	6.6–9.1	7.5–10.3	7.3–10.1	8.5–11.7	7.4–10.2	6.6–9.1	8.2–11.3	5.9–8.2	6.5–9.0	3.9–5.3
15–19	8.6–12.2	7.0–9.9	7.9–11.2	7.8–11.0	9.0–12.8	7.8–11.1	7.0–9.9	8.7–12.3	6.3–8.9	6.9–9.8	4.1–5.7
20–29	9.5–13.2	7.7–10.7	8.7–12.1	8.5–11.9	9.9–13.8	8.6–12.0	7.7–10.7	9.6–13.3	6.9–9.6	7.6–10.6	4.4–6.2
30–39	11.1–14.9	9.0–12.1	10.2–13.7	10.0–13.4	11.6–15.6	10.1–13.5	9.0–12.1	11.2–15.1	8.1–10.9	8.9–12.0	5.2–7.1
40–49	11.8–15.7	9.6–12.8	10.9–14.5	10.7–14.2	12.4–16.5	10.7–14.3	9.6–12.8	11.9–15.9	8.6–11.5	9.5–12.7	5.6–7.4
50–59	12.8–16.7	10.4–13.6	11.8–15.4	11.5–15.1	13.4–17.5	11.6–15.2	10.4–13.6	12.9–16.9	9.4–12.2	10.3–13.5	6.0–7.9
60–69	13.3–17.3	10.8–14.1	12.2–15.9	12.0–15.7	13.9–18.2	12.1–15.8	10.8–14.1	13.4–17.5	9.7–12.7	10.7–14.0	6.3–8.2
70–79	13.7–17.7	11.1–14.4	12.5–16.3	12.3–16.0	14.3–18.6	12.4–16.1	11.1–14.4	13.8–17.9	10.0–13.0	11.0–14.3	6.5–8.3

ADM, abductor digiti minimi; BF, biceps femoris; EDB, extensor digitorum brevis; Gastroc, gastrocnemius; Per Long, peroneus longus; Quad, quadriceps; Tib Ant, tibialis anterior.

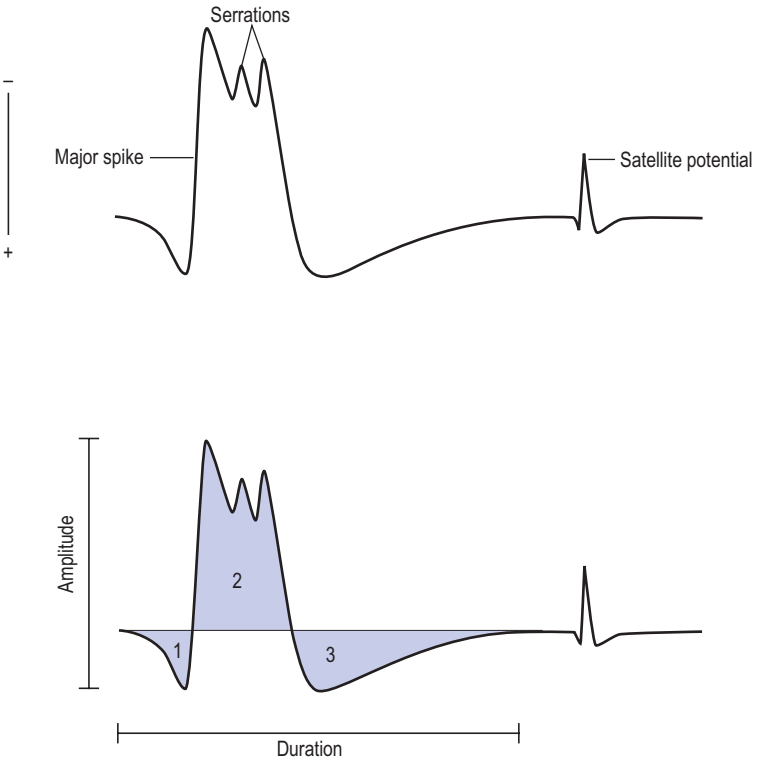

FIGURE 15–4 Motor unit action potential (MUAP) measurements. Duration is measured as the time from the initial deflection of the MUAP from baseline to its final return to baseline. It is the parameter that best reflects the number of muscle fibers in the motor unit. Amplitude reflects only muscle fibers very close to the needle and is measured peak to peak. Phases (shaded areas) can be determined by counting the number of baseline crossings and adding one. MUAPs are generally triphasic. Serrations (also called turns) are changes in direction of the potential that do not cross the baseline. The major spike is the largest positive-to-negative deflection, usually occurring after the first positive peak. Satellite, or linked, potentials occur after the main potential and usually represent early reinnervation of muscle fibers.

EMG machines now have programs that largely automate the procedure. With experience over time, however, the well-trained electromyographer usually can perform qualitative MUAP assessment with the same precision as can be achieved using quantitative methods. Essentially the same procedure is used. The needle is moved to several locations within the muscle until approximately 20 different MUAPs have been examined, qualitatively analyzed, and compared to the expected normal values for that particular muscle and age group.

Duration

MUAP duration is the parameter that best reflects the number of muscle fibers within a motor unit (Figure 15–4). Typical MUAP duration is between 5 and 15 ms. *Duration*

is defined as the time from the initial deflection from baseline to the final return of the MUAP to baseline. It depends primarily on the number of muscle fibers within the motor unit and the dispersion of their depolarizations over time. Dispersion in turn depends on the longitudinal and transverse scatter of endplates and on variations in terminal distances and conduction velocities. Duration lengthens as the number of fibers and the territory of a motor unit increase; it varies directly with age (increased age, increased duration) and inversely with temperature (decreased temperature, increased duration) and depends on the individual muscle being studied. Proximal and bulbofacial muscles in general have MUAPs of shorter duration. When performing EMG, it often is more rewarding to listen to the potential than to see it. This is especially true when evaluating MUAP duration, because *duration correlates with pitch*. Long-duration MUAPs (low frequencies) sound dull and thuddy, whereas short-duration MUAPs (higher frequencies) sound crisp and static-like. As the electromyographer gains experience, the sound of a long-duration versus a short-duration MUAP becomes unmistakable.

Polyphasia, Serrations, and Satellite Potentials

Polyphasia is a measure of synchrony, that is, the extent to which the muscle fibers within a motor unit fire more or less at the same time. This is a nonspecific measure and may be abnormal in both myopathic and neuropathic disorders. The number of phases can be easily calculated by counting the number of baseline crossings of the MUAP and adding one (Figure 15–4). Normally, MUAPs have two to four phases. However, increased polyphasia may be seen in up to 5 to 10% of the MUAPs in any muscle and is considered normal. The one exception is the deltoid, where up to 25% polyphasia may be normal. Increased polyphasia beyond 10% in most muscles and 25% in the deltoid is always abnormal. Through the speaker, polyphasic MUAPs are recognized as a high-frequency "clicking" sound.

Serrations (also called turns) are defined as changes in the direction of the potential that do not cross the baseline. Increased polyphasia and serrations have similar implications, indicating less synchronous firing of muscle fibers within a motor unit. Often, a serration can be changed into an additional phase with needle movement.

Satellite potentials (also known as *linked potentials* or *parasite potentials*) are interesting phenomena seen in early reinnervation. After denervation, muscle fibers often are reinnervated by collateral sprouts from adjacent intact motor units. The newly formed sprout often is small, unmyelinated or thinly myelinated, and therefore very slowly conducting. Because of the slow conduction time and increased distance, reinnervated muscle fibers are seen as time-locked potentials that trail the main MUAP (Figures 15–5 and 15–6). These satellite potentials are extremely unstable (see section on Stability) and may vary slightly in their firing rate or may block and not fire at all

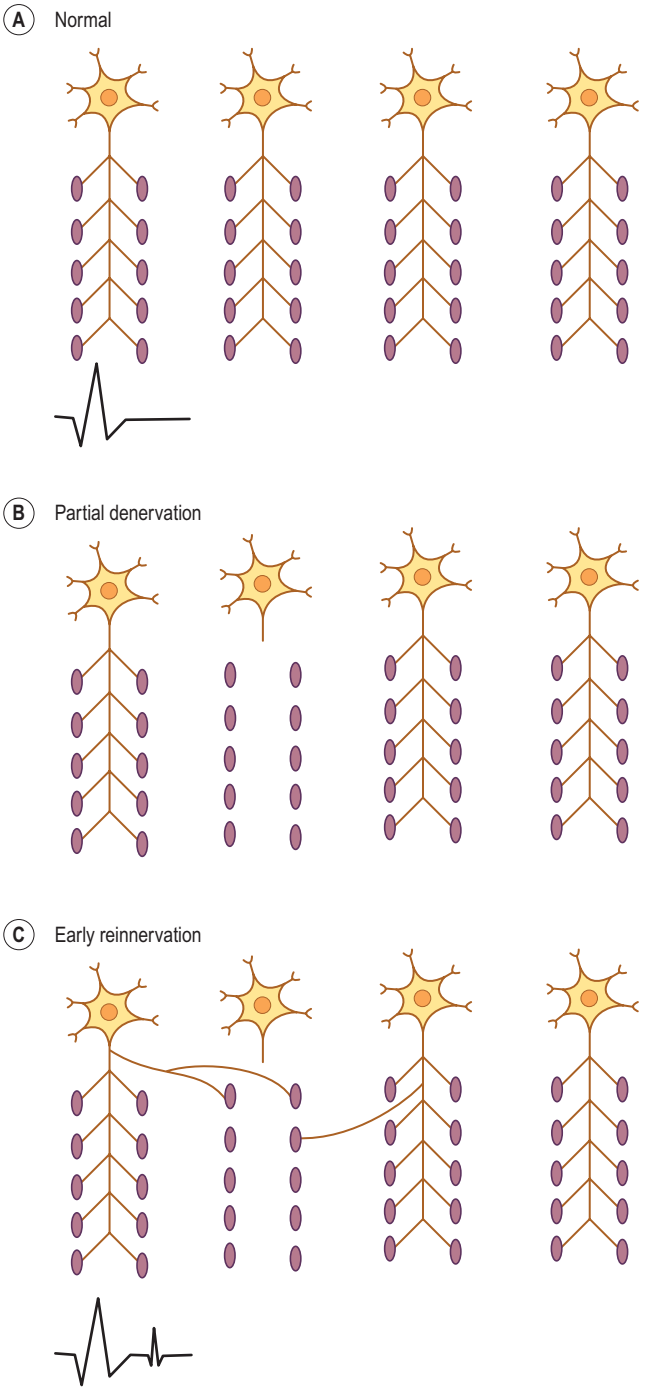

FIGURE 15–5 Collateral sprouting and satellite potentials. **A:** Normal state. **B:** Following partial denervation, the injured axon(s) undergoes wallerian degeneration. **C:** Reinnervation commonly occurs from sprouting by adjacent surviving axons. In early reinnervation, sprouts are small and thinly myelinated and conduct slowly. Because of the slow conduction time and increased distance, these reinnervated fibers initially occur as time-locked potentials (satellite potentials) trailing the main motor unit action potential (MUAP). As sprouts mature and conduct more quickly, the time-locked potentials are eventually incorporated into the main MUAP, resulting in an MUAP with increased amplitude, duration, and number of phases.

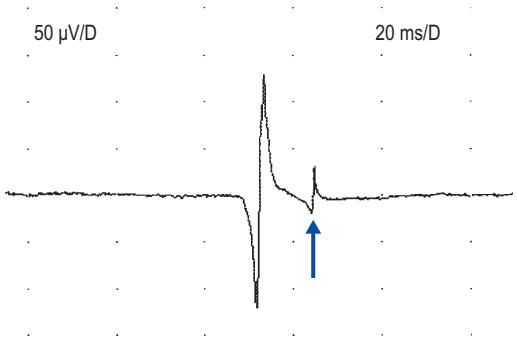

FIGURE 15–6 Satellite potential. Note in the tracing the small potential that is time locked to the main motor unit action potential (MUAP). This is a satellite potential, a sign of early reinnervation. After denervation, muscle fibers often are reinnervated by collateral sprouts from adjacent intact motor units. The newly formed sprout often is small, unmyelinated or thinly myelinated, and therefore very slowly conducting. Because of the slow conduction time and increased distance, reinnervated muscle fibers are seen as time-locked potentials that trail the main MUAP.

(Figure 15–7). Over time, the sprout matures, and the thickness of the myelin and consequently the conduction velocity increase. The satellite potential then fires more closely to the main potential and ultimately will become an additional phase or serration within the main complex. It is usually necessary to put the main MUAP on a delay line to appreciate a satellite potential and to demonstrate that it is time locked to the main potential.

Amplitude

MUAP amplitude varies widely among normal subjects. Most MUAPs have an amplitude greater than 100 µV and less than 2 mV. Amplitude is generally measured from peak to peak of the MUAP (Figure 15–4). Amplitude is essentially a high-frequency response. Tissue between the needle and muscle fibers effectively acts as a high-frequency filter. Thus, unlike duration, most muscle fibers of a motor unit contribute little to the amplitude. *MUAP amplitude reflects only those few fibers nearest to the needle (only 2–12 fibers)*. Hence, amplitude is not as helpful as duration in judging motor unit size. Several factors are associated with increased amplitude, including (1) the proximity of the needle to the motor unit (Figure 15–8), (2) increased number of muscle fibers in a motor unit, (3) increased diameter of muscle fibers (i.e., muscle fiber hypertrophy), and (4) more synchronized firing of the muscle fibers. *Listening to the EMG, the amplitude of MUAPs is correlated not with pitch but with volume.*

Major Spike

The major spike is the largest positive-to-negative component of the MUAP and usually occurs after the first positive peak (Figure 15–4). The major spike is the highest-frequency component of the MUAP. Because tissue acts as a high-frequency filter, as the needle is moved closer to the MUAP, the major spike increases in amplitude and its rise time shortens, indicating the proximity of the needle to the motor unit. MUAP parameters should be measured only when the needle is very close to the motor unit (Figure 15–9). When the needle is close to the motor unit, the MUAP becomes "sharp." The sharp sound represents the high-frequency component of the major spike, occurring when the major spike rise time is less than 500 µs, indicating proper needle placement.

STABILITY

MUAPs usually are stable in morphology from potential to potential. This stability is due to the fact that each time a nerve action potential is generated, there is normally effective transmission across the NMJs, and all muscle fibers of

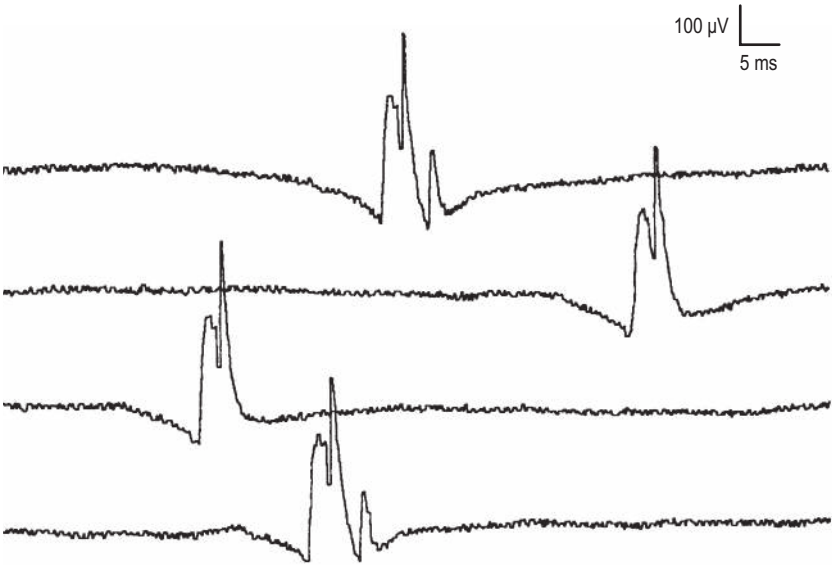

FIGURE 15–7 Unstable satellite potential. Note the satellite potential in the first and fourth firing of the MUAP. However, the satellite potential is not present in the second and third firing of the MUAP. In early reinnervation, collateral sprouts attach to nearby denervated fibers which results in satellite potentials. However, the newly formed NMJs are immature, and do not always reach threshold, resulting in intermittent firing of the satellite potential. Eventually the satellite potential becomes incorporated into the main MUAP. This is the basis of unstable MUAPs that occur following reinnervation.

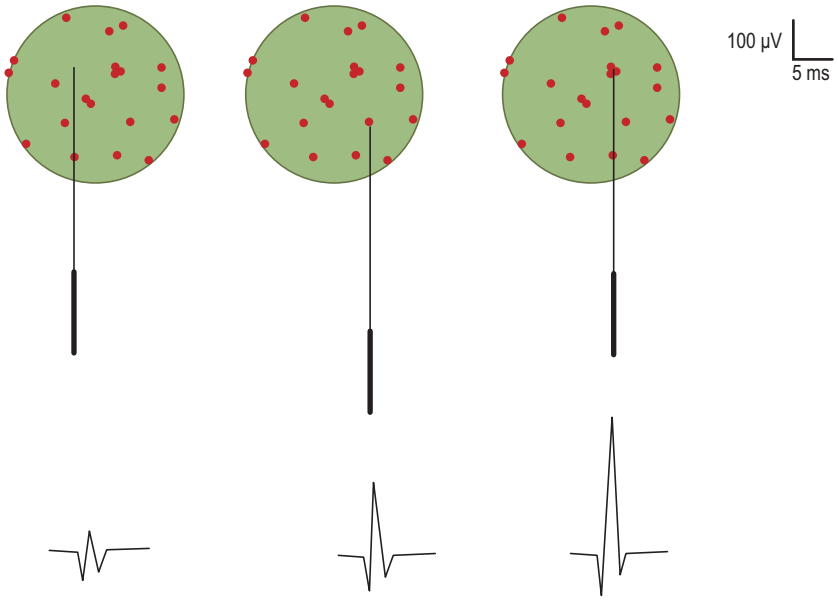

FIGURE 15–8 Relationship of motor unit action potential (MUAP) amplitude to needle position. Of all MUAP parameters, amplitude is most dependent on needle position. Only muscle fibers very close to the needle contribute to amplitude, as opposed to duration, wherein most muscle fibers contribute. Note change in amplitude as needle is moved to different locations within the same motor unit.

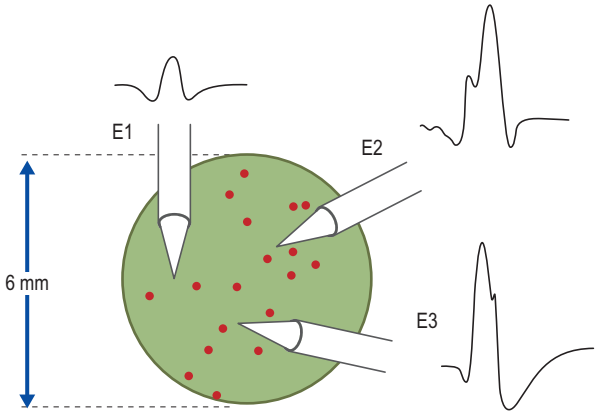

FIGURE 15–9 Motor unit action potential (MUAP) morphology and needle electromyography (EMG) position. The position of the EMG needle influences the morphology of the recorded MUAP. To properly assess MUAP parameters, the major spike must be as steep as possible, indicating the proximity of the needle to the motor unit. Note that needle electrode position E3 has the shortest major spike rise time and is the preferable position in which to assess the MUAP. Also note that although MUAP amplitude changes markedly with needle position (compare position E1 with E3), duration is relatively unaffected.
(From Dimitru, D., DeLisa, J.A., 1991. AAEM minimonograph #10: volume conduction. Muscle Nerve 14, 605. Reprinted by permission of Wiley.)

the motor unit fire. If there is impaired NMJ transmission, unstable MUAPs may result (Figure 15–10). Unstable MUAPs occur when individual muscle fibers either are blocked or come to action potential at varying intervals, leading to an MUAP that changes in configuration from impulse to impulse. There is a change between potentials in either the amplitude or the number of phases (or serrations), or both. Although unstable MUAPs always indicate unstable NMJs, they occur not only in primary disorders of the NMJ (e.g., myasthenia gravis, Lambert–Eaton

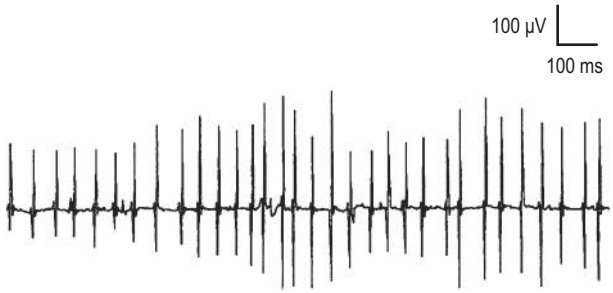

FIGURE 15–10 Unstable motor unit action potentials (MUAPs). MUAPs that change in either amplitude or number of phases from impulse to impulse are called unstable MUAPs. Unstable MUAPs occur in both primary neuromuscular junction (NMJ) disorders and disorders associated with new or immature NMJs, as commonly occur early in reinnervation. Note change in amplitude from potential to potential.

myasthenic syndrome) but are also often seen as secondary phenomena in both neuropathic and myopathic disorders. Any disorder associated with denervation may demonstrate unstable MUAPs. During the process of early reinnervation, newly formed, immature NMJs often fail to conduct NMJ transmission faithfully. The result is variability in endplate transmission or intermittent blocking of transmission across some of the muscle fibers within a motor unit (Figure 15–7).

FIRING PATTERN (ACTIVATION, RECRUITMENT, INTERFERENCE PATTERN)

One of the most important and yet most difficult tasks for the electromyographer is the assessment of firing pattern and its relationship to the number of MUAPs. MUAPs normally fire in a *semi-rhythmic pattern*, that is, there is

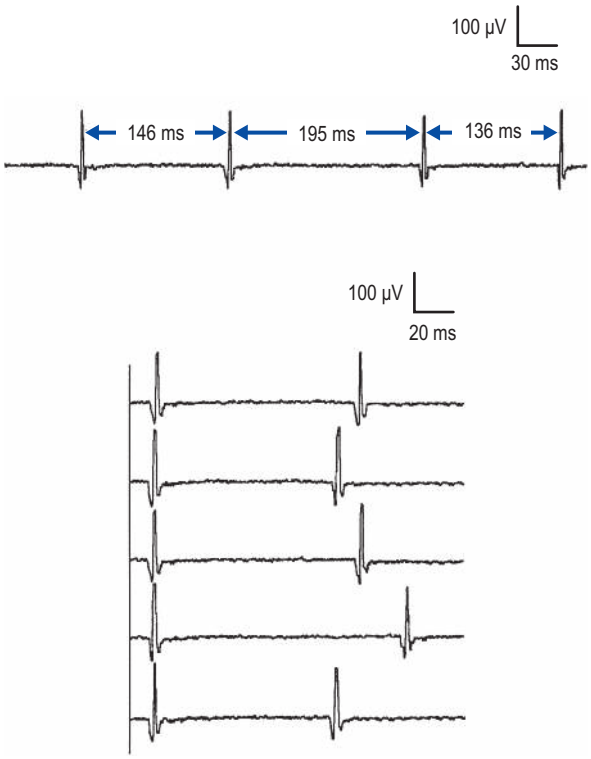

FIGURE 15–11 Motor unit action potential (MUAP) firing pattern. Normally, MUAPs fire in a semi-rhythmic pattern, with a slight variation in the interval between potentials. **Top:** Single voluntary MUAP firing at approximately 6 Hz. Note the variation in interpotential intervals. **Bottom:** Single voluntary MUAP placed on a delay line and rastered. First potential of each sweep triggers sweep. Note the variation between firing time of the next consecutive MUAP. The pattern is not quite regular (i.e., it is semi-rhythmic). This firing pattern is seen only with voluntarily activated MUAPs.

slight variation in the time interval between the same MUAP as it fires consecutively (Figure 15–11). This unique firing pattern helps to identify the potential as an MUAP under voluntary control, in contrast to various spontaneous waveforms that are not under voluntary control, and have other distinct firing patterns, such as fibrillation potentials and positive sharp waves, which are regular; complex repetitive discharges, which are perfectly regular or change abruptly; myotonic discharges, which have a waxing/waning amplitude; or fasciculation potentials, which are very slow and irregular.

During muscle contraction, there are only two ways to increase muscle force: either motor units can increase their firing rate (up to tetanic fusion frequency which is approximately 50 Hz), or additional motor units can fire (Figure 15–12). Normally, one increases force using a combination of these two processes, resulting in an orderly recruitment of motor units. With the smallest contraction, a single motor unit action potential normally begins firing semi-rhythmically at 4 to 5 Hz. Any potential that fires more slowly than 4 to 5 Hz cannot be an MUAP under voluntary control and must be a spontaneous potential. As one increases force, the first motor unit action potential increases its firing rate, and then a second motor unit action

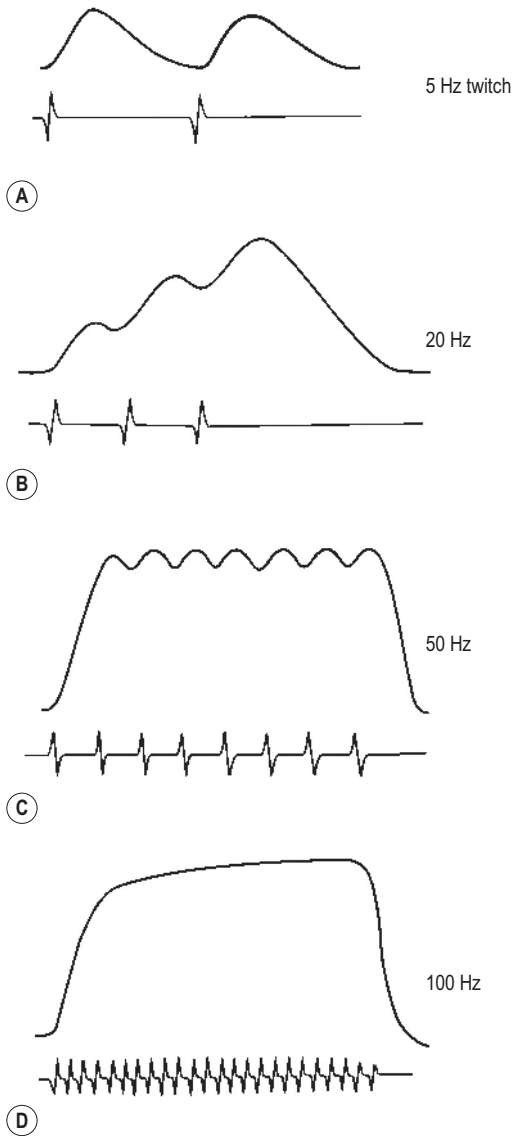

FIGURE 15–12 Relationship of force to firing frequency. **Top traces** of each pair show twitch forces; **bottom traces** show motor unit action potentials (MUAPs) firing at different frequencies. Note increased force with increased firing frequencies. To increase muscle twitch force, either motor units must fire faster or additional motor units must be added. Although the electrical MUAP lasts only 5 to 15 ms, the mechanical twitch lasts more than 100 ms. As MUAP firing rate increases, twitch forces summate. Force increases up to a frequency of approximately 50 Hz (tetanic fusion frequency). Near that frequency, the maximal overlap occurs between muscle myosin and actin filaments. Firing above that frequency may result in more even firing but does not appreciably change the amount of force generated.
(Adapted with permission from Kandel, E.R., Schwartz, J.H., Jessell, T.M. (Eds.), 1991. Principles of neural science, third ed. Appleton & Lange, Norwalk, CT.)

potential begins to fire, and so forth. This process continues, with the firing rate increasing and additional motor unit action potentials being recruited as force is increased. Normally, the ratio of firing frequency to the number of different MUAPs firing is approximately 5:1. Thus, by the time the first MUAP firing frequency reaches 10 Hz, a

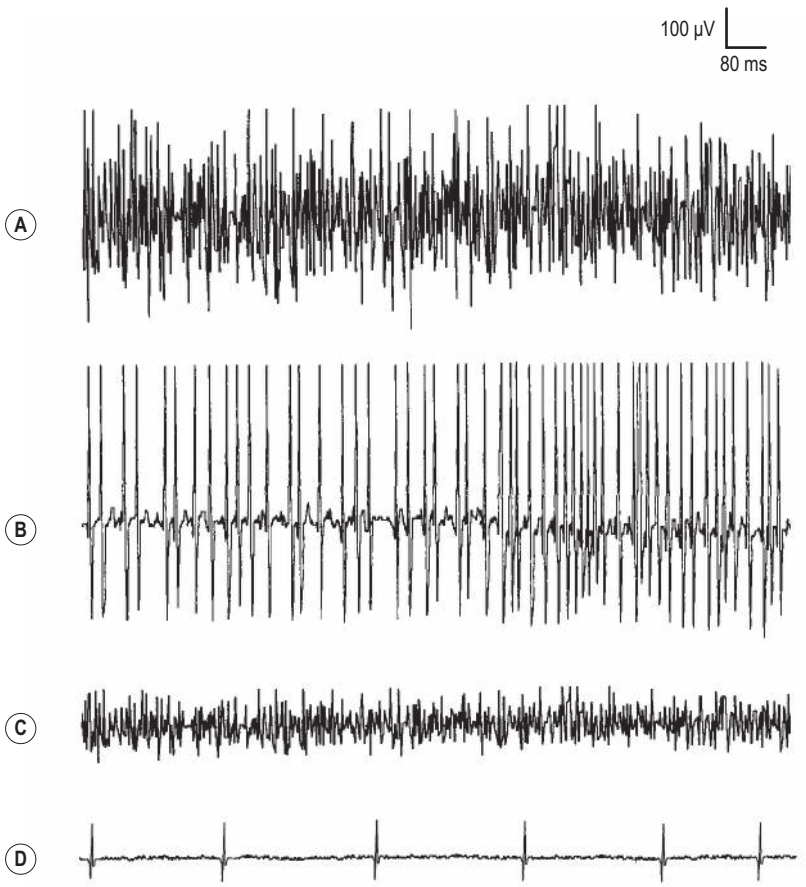

FIGURE 15–13 Interference patterns. **A:** Normal. **B:** Neuropathic. **C:** Myopathic. **D:** Central. In each trace, the patient is asked to contract maximally. In normal subjects, so many motor unit action potentials (MUAPs) fire during maximal contraction that differentiating individual motor unit action potentials is difficult. In neuropathic recruitment, a reduced number of MUAPs fire at a high frequency, resulting in an incomplete interference pattern (often referred to as the "picket fence" pattern, when only one MUAP is firing). In myopathic recruitment, although the number of MUAPs is normal, the interference pattern consists of short-duration, small-amplitude MUAPs, which fire with a small amount of force. In central disorders, the primary problem is the inability to fire faster (i.e., decreased activation); although the number of MUAPs is reduced, it is appropriate for the level of firing.

second MUAP should begin to fire; by 15 Hz, a third motor unit action potential should fire, and so forth. During maximal contraction, multiple MUAPs normally overlap and create an interference pattern in which no single motor unit action potential can be distinguished (Figure 15–13A). For most muscles, the maximal firing frequency is 30 to 50 Hz. Important exceptions include quick ballistic contractions, in which the firing frequency may transiently reach 100 Hz, and muscles that are predominantly slow twitch (e.g., soleus), in which the maximal firing frequency is approximately 15 Hz.

One of the key questions to answer in assessing MUAPs is the following: *Are the number of different MUAPs firing appropriate for the firing rate*? That is, is the ratio of firing rate to MUAPs approximately 5:1? To answer that question, one must understand that increasing force depends on two processes: activation and recruitment. *Activation* refers to the ability to increase firing rate. This is a central process. Poor activation may be seen in diseases of the central nervous system (CNS) or as a manifestation of pain, poor cooperation, or functional disorders. *Recruitment* refers to the ability to add motor unit action potentials as the firing rate increases. Recruitment is reduced primarily in neuropathic diseases, although rarely it may also be reduced in severe end-stage myopathy.

An incomplete interference pattern may be due to either poor activation or poor recruitment. Consider the two different incomplete interference patterns shown in Figure 15–14. In both cases, the patient has been asked to maximally contract the muscle of interest. In the first case (top trace), note that the same MUAP is firing rapidly at 30 Hz. Thus, although the firing rate is maximal, only one MUAP is seen firing at 30 Hz (30:1 ratio). In a normal muscle, by the time the firing rate reaches 30 Hz, one should see five or six different MUAPs firing (a ratio of approximately 5:1). Thus, in this case, the interference pattern is reduced because of decreased recruitment, but activation (firing rate) is normal. Decreased recruitment occurs when there has been loss of MUAPs, usually through axonal loss or conduction block. In the unusual situation of end-stage myopathy, if every muscle fiber of an MUAP is lost, the number of MUAPs also will effectively decrease, leading to reduced recruitment.

Contrast this with the pattern of the second patient (bottom trace), in which one also sees a single MUAP firing. In this case, however, the single MUAP is firing at 5 Hz. Thus, the firing rate (activation) is clearly submaximal, although the number of MUAPs firing (recruitment) is normal for the firing rate (a ratio of approximately 5:1). In this case, the interference pattern is reduced primarily because of decreased activation, but recruitment (i.e., the number of different MUAPs) is appropriate for the level of firing. The patient's weakness is reflected in the decreased activation of motor unit action potentials, judged by the

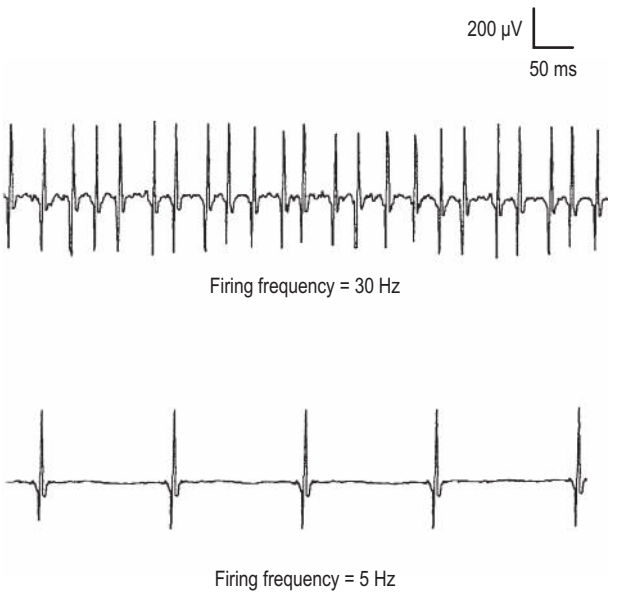

FIGURE 15–14 Incomplete interference patterns. In both traces, the patient is asked to contract the muscle maximally with the electromyography needle in place. The **top trace** demonstrates an incomplete interference pattern due to reduced recruitment. The **bottom trace** demonstrates an incomplete interference pattern due to reduced activation (see text for details).

submaximal sustained firing rate. This pattern of reduced activation may be seen if a patient cannot fully cooperate, perhaps because of pain, or has a CNS lesion (e.g., stroke, multiple sclerosis).

Of course, both decreased activation (i.e., an upper motor neuron disorder) and decreased recruitment (i.e., a lower motor neuron disorder) may be present in the same patient. This situation occurs most classically in amyotrophic lateral sclerosis, a disorder of both upper and lower motor neurons. More commonly, though, it occurs in patients with neuropathic disorders who also have difficulty moving a limb because of pain (e.g., abducting the hip in a painful L5 radiculopathy). In this latter situation, there is decreased recruitment due to loss of L5 nerve root fibers, and decreased activation due to pain.

The last concept to understand is "early recruitment." In diseases in which there is dropout of individual muscle fibers from a motor unit (e.g., myopathies or NMJ diseases with block), the motor unit becomes smaller and subsequently can generate less force. Because each motor unit generates less force, many motor units must fire to generate even a small amount of force. *This is known as early recruitment, which refers to the inappropriate firing of many motor unit action potentials to generate a small amount of force*. On the monitor, many MUAPs will appear to fire almost simultaneously, with small amounts of force. Usually, only the electromyographer performing the study can assess early recruitment; it requires knowledge of how much force is being generated. To reiterate, early recruitment refers to the inappropriate (i.e., increased) number of MUAPs firing for the degree of force generated; it does not refer to the number of MUAPs firing for the level of activation or for the firing rate. An early recruitment pattern is typically seen in muscle disorders and in some disorders of the NMJ.

Many electromyographers will judge recruitment only during maximal contraction, by examining the interference pattern. However, not as well appreciated is that recruitment is more easily evaluated during moderate levels of contraction. Remember, the key question that must be answered is the same: Are the number of different MUAPs firing appropriate for the level of activation (firing rate)? If only one MUAP is seen firing at 15 to 20 Hz (medium level of activation), recruitment is decreased, regardless of the interference pattern. There is no need to increase the firing rate using maximal contraction in order to make this determination. Maximal contraction with the EMG needle in the muscle often is perceived as more painful by the patient, and is best avoided or at least minimized. Indeed, during maximal contraction, judging the relationship between the number of MUAPs firing and the firing rate can actually be more difficult.

PATTERNS OF MOTOR UNIT ABNORMALITIES

MUAP morphology and firing patterns usually can discriminate among the various disorders affecting the motor unit. No single parameter identifies an MUAP as myopathic, neuropathic, or associated with an NMJ disorder. Specific patterns of abnormalities in MUAP morphology and firing rate reflect whether the underlying disorder is (1) acute, chronic, or end stage; (2) neuropathic, myopathic, or associated with an NMJ transmission defect; and, if neuropathic, (3) whether the primary pathophysiology is axonal loss or demyelination (Table 15–2).

Neuropathic

Acute Axonal Loss

After an acute axonal injury to a nerve, the process of wallerian degeneration occurs in motor nerve fibers within the first 3 to 5 days, followed by denervation of the distal muscle fibers of the involved motor units. Reinnervation normally occurs as surviving nearby axons form sprouts that grow and eventually reinnervate the denervated fibers. When this occurs, the number of muscle fibers in the reinnervated MUAP is larger than normal, leading to an MUAP with increased duration, amplitude, and number of phases (Figure 15–15). However, this process takes time, usually many weeks to months. *In the acute setting, MUAP morphology remains normal. The only abnormality seen on EMG in an acute neuropathic lesion is a decreased recruitment pattern in weak muscles due to the initial loss of motor units. Thus, in acute axonal loss lesions on needle EMG, there is a pattern of decreased recruitment of MUAPs with normal morphologies*. This pattern does not occur in slowly progressive or chronic conditions (e.g., most polyneuropathies). In those conditions, changes in MUAP morphology are always present by the time the patient

Table 15–2. MUAP Patterns and Pathophysiology

	MUAP Morphology			MUAP Firing Pattern	
	Duration	Amplitude	Phases	Activation	Recruitment
Acute neuropathic – axonal	NL	NL	NL	NL	↓
Chronic neuropathic – axonal	↑	↑	↑	NL	↓
Neuropathic – demyelinating (CV slowing alone)	NL	NL	NL	NL	NL
Neuropathic – demyelinating (conduction block)	NL	NL	NL	NL	↓
Early reinnervation after severe denervation (nascent units)	↓	↓	↑	NL	↓↓
Acute myopathic	↓	↓	↑	NL	NL/EARLY
Chronic myopathic	↓/↑	↓/↑	↑	NL	NL/EARLY
Myopathic – endstage	↓/↑	↓/↑	↑	NL	↓↓
NMJ disorders – increased jitter	NL	NL	NL	NL	NL
NMJ disorders – intermittent block	NL/↓*	NL/↓*	NL/↑*	NL	NL/EARLY
NMJ disorders – severe block	↓	↓	↑	NL	↓↓
CNS disorders	NL	NL	NL	↓↓	NL

CNS, central nervous system; CV, conduction velocity; MUAP, motor unit action potential; NL, normal; NMJ, neuromuscular junction. ↑ increased; ↓ decreased; ↓/↑ may be decreased and/or increased; ↓↓ usually markedly decreased; * may vary from potential to potential (unstable MUAPs)

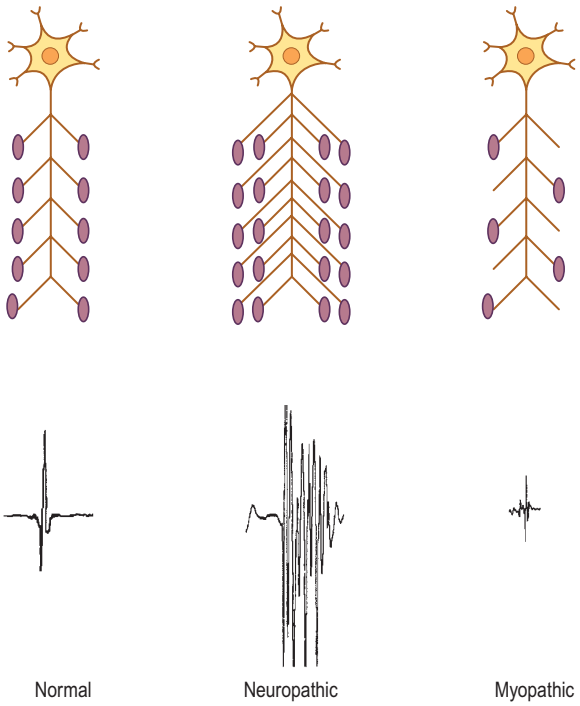

FIGURE 15–15 Motor unit action potential (MUAP) morphologies. Normal MUAPs have two to four phases. In chronic neuropathic lesions that occur after reinnervation, the number of muscle fibers per motor unit increases, resulting in long-duration, high-amplitude, and polyphasic MUAPs. In myopathies or in neuromuscular junction disorders with block, the number of functional muscle fibers in the motor unit decreases. This leads to short-duration, small-amplitude, and polyphasic MUAPs.

presents with symptoms. The acute neuropathic pattern associated with axonal loss characteristically occurs in the first several weeks after trauma, compression, or nerve infarction. The only other situation in which a similar pattern is seen is in pure demyelinating lesions with conduction block (discussed in section on Neuropathic: Demyelinating).

Chronic Axonal Loss

After axonal loss and denervation, the process of reinnervation can occur by one of two mechanisms. If there has been complete denervation, the only possible mechanism for reinnervation is axonal regrowth from the point of injury (see section on Early Reinnervation Following Severe or Complete Denervation). Typically, this regrowth is quite slow (no more than 1 mm per day) and may take months to years, depending on the length of the nerve. For the regrowth to occur, however, the anterior horn cells must remain intact. For example, the original nerve fibers can regrow following transection of a nerve, but not after poliomyelitis, which results in the death of anterior horn cells.

In contrast, in cases of partial or gradual denervation, reinnervation usually occurs through collateral sprouting by adjacent surviving motor units (Figure 15–5). As the number of muscle fibers per motor unit increases, MUAPs become prolonged in duration, with a high amplitude, and polyphasic. *These MUAP changes, in conjunction with decreased recruitment, are the hallmarks of reinnervated motor unit action potentials and nearly always imply chronic neuropathic disease (i.e., disorders of the anterior horn cell, nerve root, or peripheral nerve). Similar to other neuropathic conditions, during maximal contraction, the interference pattern will not be full, secondary to decreased recruitment*

of MUAPs (Figure 15–13B). Long-duration, high-amplitude, polyphasic MUAPs are never seen in acute conditions. When present, they always imply that the process has been present for at least several weeks and more often for months or years.

Demyelinating

Loss of axons results in denervation and ultimately reinnervation, with resultant changes in MUAP morphology. If, however, the pathology is purely or predominantly demyelinating, the underlying axon remains intact. Thus, there is neither denervation nor subsequent reinnervation. *In pure demyelinating lesions, MUAP morphology remains normal.* If demyelination results in conduction velocity slowing alone, the nerve action potential will still reach the muscle, albeit more slowly, and the number of functioning motor units will remain normal. Accordingly, there will be no change in either MUAP morphology or recruitment pattern on needle EMG. If demyelination results in conduction block, however, the number of available MUAPs effectively decreases. Although the MUAP morphology remains normal, the firing pattern shows decreased recruitment. This pattern of reduced recruitment with normal MUAP morphology is seen only in demyelinating lesions with conduction block (e.g., some cases of Guillain–Barré syndrome, carpal tunnel syndrome) or in cases of acute axonal loss before enough time has passed for reinnervation to occur.

Myopathic

Acute

In myopathies, the number of functioning muscle fibers in a motor unit decreases. Because there are fewer muscle fibers per motor unit, this results in MUAPs of shorter duration and smaller amplitude (Figure 15–15). In addition, there is less synchronous firing and consequently polyphasia of MUAPs due to dysfunction of the remaining muscle fibers. However, the actual number of functioning motor units (i.e., the number of anterior horn cells and axons) remains normal. Thus, the recruitment pattern remains normal for the level of activation. Because each motor unit contains fewer muscle fibers, however, it cannot generate as much force as a normal motor unit. To compensate, more MUAPs will fire than are normally needed for a certain level of force, resulting in early recruitment. The interference pattern will fill easily with a small amount of force from the patient (Figure 15–13C). *Consequently, the pattern associated with an acute myopathy is short-duration, small-amplitude, polyphasic MUAPs with normal or early recruitment.*

Chronic

In chronic myopathies, especially those with necrotic or inflammatory features (e.g., polymyositis, dystrophies), some denervation and subsequent reinnervation commonly occur. Consequently, long-duration, high-amplitude, polyphasic MUAPs can develop, although such MUAPs are most commonly seen in chronic neuropathic disease. In many chronic myopathies, two populations of MUAPs are often seen: both long-duration, high-amplitude, polyphasic MUAPs and short-duration, small-amplitude, polyphasic MUAPs, often in the same muscle. Rarely, only long, large, polyphasic MUAPs are seen. *The key to differentiating chronic myopathic from chronic neuropathic MUAPs is the assessment of the recruitment pattern.* In chronic myopathies, recruitment usually is normal or early. If an early recruitment pattern is not seen, at the very least the recruitment pattern appears better than what would be expected based on the chronic MUAP changes. In some cases of very chronic myopathy (especially inclusion body myositis), the EMG pattern may resemble that of active motor neuron disease (fibrillation potentials; long-duration, high-amplitude, polyphasic MUAPs), except for the recruitment pattern that appears "too good" for the apparent amount of reinnervation.

Endstage

In the very late stages of some dystrophies, periodic paralysis, and unusual, very chronic focal myopathies (e.g., inclusion body myositis), endstage muscle may occur. In such situations, the actual number of motor units may effectively decrease if every fiber of some motor units dies or becomes dysfunctional. The result is an unusual pattern of reduced recruitment of short-duration, small-amplitude, polyphasic MUAPs either alone or in combination with long-duration, high-amplitude, polyphasic MUAPs. Although decreased recruitment nearly always signifies neuropathic disease, the rare exception arises in endstage muscle from myopathy.

Early Reinnervation following Severe or Complete Denervation

Reinnervation most often occurs from collateral sprouting by adjacent surviving motor units. If there is severe or complete denervation, with no nearby surviving axons, the only possible mechanism for reinnervation is regrowth of the axon from the site of injury. As the axon regrows, at some point in time it will reinnervate some, but not all, of the original muscle fibers. At that point, the MUAP will be short duration, small amplitude, and polyphasic, similar to an acute myopathic motor unit action potential (Figure 15–16). Early reinnervated motor unit action potentials following severe denervation are known as *nascent motor units*. *The key factor that differentiates nascent motor unit action potentials from myopathic motor unit action potentials is the recruitment pattern. Nascent MUAPs are always seen in the context of markedly reduced recruitment, whereas myopathic MUAPs are seen in the context of normal or early recruitment.* Although nascent motor units are uncommon, they emphasize that not all short-duration, small-amplitude, polyphasic MUAPs are myopathic.

Neuromuscular Junction Disorders

MUAP morphology and firing patterns in NMJ disorders depend on the severity of the disorder. If the NMJ

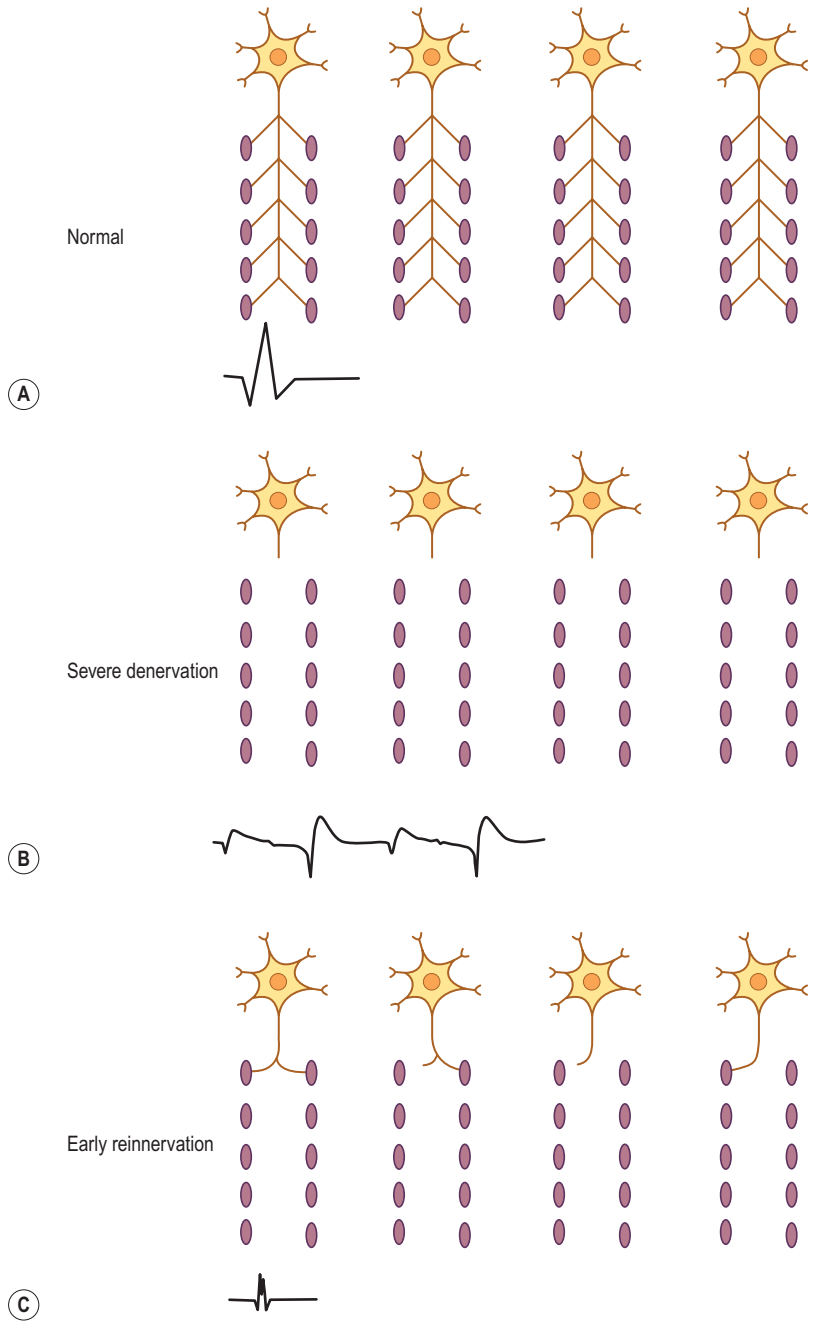

FIGURE 15–16 Nascent motor units. After a severe axonal loss lesion, wallerian degeneration occurs distal to the injury, resulting in denervation **B**. If there are no surviving nearby axons, reinnervation can occur only from axonal regrowth from the terminal stump. Early in this reinnervation process, there will be a point at which some but not all of the muscle fibers are reinnervated **C**. At that point, motor unit action potentials (MUAPs) will be short duration, small amplitude, and polyphasic, resembling myopathic units. Compare the nascent MUAP **C** with the normal MUAP **A**. Nascent MUAPs are differentiated from myopathic MUAPs by the reduced recruitment pattern compared with normal or early recruitment seen in myopathy.

disorder is mild, resulting in only slight variation of the firing of muscle fibers within the motor unit, both the morphology and recruitment of the MUAP will be normal. If the disorder is more severe, resulting in the intermittent blocking of some muscle fibers within the motor unit, the MUAP will become unstable. The morphology (amplitude, number of phases, or both) will vary from potential to potential. With greater and more persistent block, there will effectively be loss of individual muscle fibers within a motor unit. Thus, the MUAP will become short, small, and polyphasic, similar to a myopathic MUAP. Similarly, recruitment remains normal, or it may become early as each motor unit is able to generate less force. To reemphasize, both myopathies and severe NMJ disorders may result in short, small and polyphasic MUAPs with normal or early recruitment. Finally, in cases of severe NMJ block, such as botulism, all the fibers in some motor units may be blocked, effectively resulting in the loss of motor units. In these cases, the remaining MUAPs are short duration, small amplitude, and polyphasic, but with decreased recruitment, reflecting the reduced number of available motor units. This latter unusual pattern also can be seen in endstage myopathy and in nascent motor units.

Central Nervous System Disorders

In CNS disorders, normally there is no loss of anterior horn cells and, accordingly, no denervation or reinnervation. MUAP morphology and recruitment remain normal. On needle EMG, weakness is demonstrated as the inability to fire motor unit action potentials rapidly (i.e., reduced activation). Thus, although the interference pattern is incomplete, with a reduced number of motor unit action potentials firing, the actual number of motor unit action potentials (i.e., recruitment) is appropriate for the reduced level of activation (Figure 15–13D).

Occasionally, other patterns may be seen with CNS disorders. In spinal cord lesions, motor units may be lost at the level of the lesion because of segmental loss of anterior horn cells. For example, in a C6 spinal cord lesion, denervation, reinnervation, and decreased recruitment of MUAPs may be seen in the C6-innervated muscles. In the weak lower extremities, however, only decreased activation, but not decreased recruitment, of MUAPs will be seen. In those muscles that receive partial innervation from C6 (e.g., pronator teres, C6–C7 innervated), there may be a combination of decreased recruitment and decreased activation of MUAPs.

Only rarely are other EMG abnormalities seen in CNS disorders. In some reported patients with multiple sclerosis, signs of denervation and reinnervation have been seen, presumably due to involvement of motor fibers as they leave the anterior horn cell in the spinal cord prior to exiting and becoming motor roots. Whether EMG abnormalities can be seen in other CNS disorders, especially stroke, remains controversial. Stroke patients are susceptible to entrapment and compression palsies because of poor mobility, which more often explains any EMG abnormalities.

Tremor may occur in some CNS disorders and can complicate the interpretation of both spontaneous activity (see Chapter 14) and MUAP morphology. Tremor is recognized as a bursting pattern of voluntary MUAPs separated by relative silence. When tremor occurs at rest (e.g., in Parkinson's disease), the spontaneous bursting discharges may be mistaken for myokymic discharges. Although both tremor and myokymia result in a bursting pattern of MUAPs, the major difference is that in myokymia the same MUAP fires repetitively in a burst, whereas in tremor the burst is composed of many different MUAPs. In addition, most patients can voluntarily alter their tremor by changing their limb position or action, whereas myokymia cannot be voluntarily influenced by the patient. Most tremors, however, worsen with activation. Because multiple MUAPs fire simultaneously in tremor, the morphology of individual MUAPs may be difficult to assess, and polyphasia may appear to be increased. In general, it is very difficult to accurately judge MUAP morphology, stability, or recruitment if the patient has a tremor when activating their muscles.

Lastly, persistent involuntary contraction can be seen during the needle EMG as the result of central disorders, including dystonia, stiff-person syndrome, and tetanus. In all of these disorders, MUAP morphology will be normal, and the EMG pattern will be one of involuntary persistent firing of MUAPs, characterized by delayed relaxation and co-contraction of muscles. Normally, individuals can easily relax their muscles and stop contracting. In these CNS disorders, however, this often is not possible. In addition, co-contraction of agonist and antagonist muscles occurs. Normally, antagonist muscles are quiet while agonists are contracting (e.g., the triceps is relaxed while the biceps is contracting and flexing the elbow). In dystonia, MUAP firing often actually increases in the antagonist muscle when the patient is instructed to move the agonist muscle (e.g., increased firing in the tibialis anterior when the patient plantar flexes the ankle) (Figure 15–17).

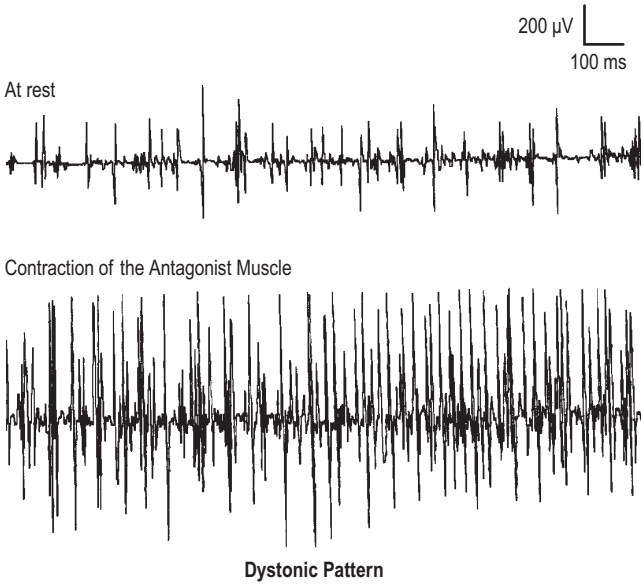

FIGURE 15–17 Dystonic firing pattern. Recording from the tibialis anterior muscle in a patient with dystonia. **Top trace:** At rest. Note the persistent firing of motor unit action potentials. **Bottom trace:** The patient is asked to plantar flex the ankle (i.e., activate an antagonist muscle). Note that the firing markedly increases. This pattern of co-contraction of agonist and antagonist muscles occurs in dystonia and other central nervous system disorders.

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16 Clinical–Electrophysiologic Correlations:

Overview and Common Patterns

The value of information gained from electrodiagnostic (EDX) studies relies on correct data collection and, even more importantly, correct data interpretation. Mastering the technical aspects of routine nerve conduction studies (NCSs) and electromyography (EMG) usually can be accomplished within several months to one year. However, if appropriate studies have not been chosen for the particular clinical situation or if interpretation of any of the studies is faulty, accurate data may be of little value. Every study must be individualized based on the differential diagnosis and clinical information. Equally important, subsequent modification often is required as a study proceeds and new information is gathered. It cannot be overemphasized that each study can be properly interpreted only alongside the clinical information. The same nerve conduction and EMG data may have a very different meaning in a different clinical setting.

Recognizing the *combined pattern* of abnormalities on NCSs (motor, sensory, late responses, repetitive nerve stimulation [RNS]) and needle EMG (spontaneous activity, motor unit potential morphology, recruitment, and activation) is the first step toward achieving an electrophysiologic diagnosis. The pattern of abnormalities usually can mark the underlying pathology as neuropathic, myopathic, or secondary to a neuromuscular junction (NMJ) disorder. Furthermore, in neuropathic lesions, the underlying primary nerve pathophysiology – axonal loss or demyelination – usually can be determined. In addition, it usually is possible to assess the temporal course (hyperacute, acute, subacute, or chronic) and severity of the underlying disorder. Localization of the disorder then is determined from the distribution of abnormalities. *In the interpretation of a study, no single piece of information leads to a diagnosis*. A final electrodiagnosis can be reached only when the overall pattern of NCS–EMG findings is analyzed and then interpreted in light of the clinical information.

NEUROPATHIC LESIONS

Neuropathic lesions result from loss or dysfunction of peripheral nerve fibers, their primary nerve cells, or both. Accordingly, polyneuropathy, plexopathy, radiculopathy, and mononeuropathy all are neuropathic lesions, as are disorders primarily affecting the motor neurons or the dorsal root ganglia. Peripheral nerve lesions may primarily affect the axon, resulting in axonal loss, or the myelin, resulting in demyelination. Both axonal loss and demyelination are neuropathic, although they result in different patterns of findings on NCSs and EMG.

Axonal Loss Lesions

Understanding the pattern of changes that takes place over time (*time-related changes*) is essential in the interpretation of neuropathic lesions. With an axonal loss lesion, an orderly pattern of abnormalities develops over time on NCSs and EMG (Table 16–1). Immediately after an axonal loss lesion (e.g., partial transection of a nerve), clinical weakness and numbness develop. However, wallerian degeneration of the nerve does not occur until days 3 to 5 for motor fibers and days 6 to 10 for sensory fibers (Figure 16–1). Before that time, distal NCSs remain normal. Thus, when the nerve is both stimulated and recorded distal to the lesion, it can still conduct well despite being effectively disconnected from its proximal segment. After wallerian degeneration occurs, NCSs become abnormal, showing changes consistent with axonal loss: amplitudes decrease, with relative preservation of conduction velocities (CVs) and distal latencies (DLs). Amplitudes for motor studies decline slightly earlier than for sensory nerves; this likely occurs due to failure first at the NMJs. If the largest and fastest axons have also been lost, there may be some slowing of CV and DL, but never into the demyelinating range (i.e., CV <75% of lower limit of normal; DL >130% of upper limit of normal).

On needle EMG, decreased recruitment of motor unit action potentials (MUAPs) occurs in weak muscles immediately with the onset of the lesion. Because some axons and their motor units have been lost, the only way to increase force is to fire the remaining available motor units faster, resulting in a pattern of decreased recruitment. No abnormal spontaneous activity or change in MUAP morphology is seen with the onset of the lesion; those changes take time to develop.

Within the next several weeks, abnormal spontaneous activity (i.e., denervating potentials – fibrillation potentials and positive sharp waves) develops. *It is well recognized that the time it takes for denervating potentials to develop depends on the length of nerve between the muscle being studied and the site of the lesion*. Consider these examples at both extremes of nerve length:

1. Lesion of the L5–S1 nerve roots (i.e., the longest distance between a lesion and the muscle). Fibrillation

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Table 16–1. Time-Related Changes in Axonal Loss

	Immediate	Hyperacute <3 Days	Acute >1 Week <3–6 Weeks	Subacute >3–6 Weeks <2–3 Months	Subacute–Chronic >2–3 Months <Many Months/Years	Chronic >Several Months/Years
Clinical findings	Abnormal	Abnormal	Abnormal	Abnormal	Abnormal	Normal/ abnormal
Nerve conductions	Normal	Normal	Abnormal	Abnormal	Abnormal	Normal/ abnormal
MUAP recruitment	Decreased	Decreased	Decreased	Decreased	Decreased	Decreased
Spontaneous activity	Normal	Normal	Normal	Abnormal	Abnormal	Normal
MUAP morphology	Normal	Normal	Normal	Normal	Reinnervated	Reinnervated

MUAP: Motor unit action potential

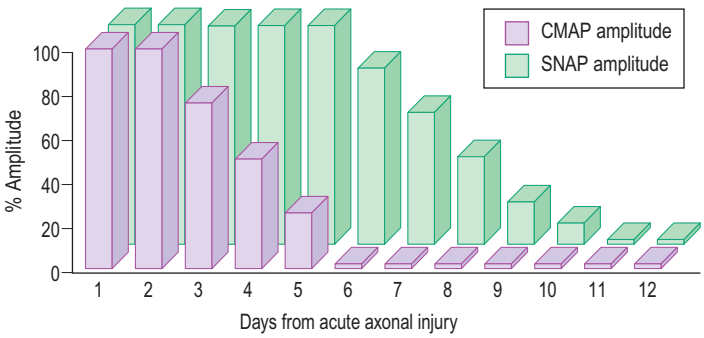

FIGURE 16–1 Effect on compound muscle action potential and sensory nerve action potential amplitudes following wallerian degeneration. Following an axonal loss lesion, the distal nerve degenerates over the next several days, with an accompanying decrease in motor and sensory amplitudes. If NCSs are performed immediately after an axonal loss injury, they will be normal, provided both the stimulation and recording sites are distal to the injury. Note in the figure that the amplitude declines earlier for motor than sensory nerves; this likely occurs due to failure first at the neuromuscular junctions.
(From Katirji, B., 1998. Electromyography in clinical practice: a case study approach. St. Louis, Mosby.)

potentials and positive sharp waves take 10 to 14 days to develop in the paraspinal muscles, 2 to 3 weeks in the proximal thigh, 3 to 4 weeks in the leg, and 5 to 6 weeks in the distal leg and foot.

2. Lesion in the distal nerve or near the NMJ (i.e., the shortest distance between a lesion and the muscle, as occurs in botulism). Fibrillation potentials develop in just a few days.

By extrapolating from these values, one can estimate the time it takes for denervating potentials to develop in other axonal loss lesions of nerves of different lengths.

Finally, in the chronic stages of axonal loss lesions, reinnervation follows denervation, which typically takes several months. Reinnervation results in changes in MUAP morphology. MUAPs become longer in duration, higher in amplitude, and polyphasic, reflecting increased numbers of muscle fibers per motor unit. If reinnervation is successful, months to years later spontaneous activity disappears, leaving only reinnervated MUAPs with decreased recruitment on needle EMG. In addition, motor and sensory amplitudes may improve on NCSs after successful reinnervation.

Thus, by looking at the combination of NCS findings (normal or abnormal), spontaneous activity (present or absent), MUAP morphology (normal or reinnervated), and recruitment (normal or decreased), one can estimate the time course of any neuropathic lesion associated with axonal loss.

Demyelinating Lesions

In pure demyelinating lesions (Figure 16–2), the pattern of abnormalities is different from that of axonal loss lesions, and depends on the degree of demyelination. Myelin is essential to maintain the speed of nerve conduction. Accordingly, demyelination first results in marked slowing of CV, as well as prolongation of DLs and late responses. If demyelination is more severe, frank conduction block occurs, with its clinical correlates of sensory loss and weakness associated with blocking of sensory and motor fibers, respectively. Slowing alone, without conduction block, still allows the nerve action potential to reach its destination, albeit more slowly than normal. Pure slowing therefore does not result in any fixed weakness. On the sensory side, pure slowing may result in depressed or absent reflexes and a perception of altered sensation, but not in fixed numbness.

The presence of conduction block has special importance in patients with demyelination. First, it implies that the

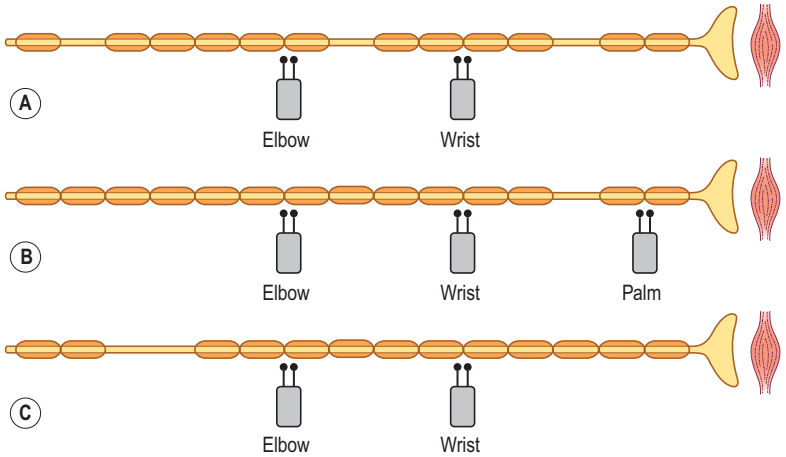

FIGURE 16–2 Demyelination and nerve conduction studies. Demyelination results in marked slowing of conduction velocity and, if severe enough, conduction block. The underlying axon remains intact, however, and wallerian degeneration does not occur. Nerve conduction parameters vary in demyelination, depending on the site(s) of demyelination. **A:** Demyelination affecting proximal, intermediate, and distal segments of nerve. This distribution results in conduction velocity slowing, prolonged distal latencies (DLs), prolonged late responses, reduced distal amplitudes, and conduction block between distal and proximal stimulation sites. **B:** Demyelination affecting only distal nerve segments. This distribution results in prolonged DLs and reduced distal amplitudes, when the nerve is stimulated at the wrist and elbow. Because late responses also travel through the distal segment, they are prolonged as well. Conduction velocities are normal, however, and no conduction block is seen between the usual distal and proximal stimulation sites. If a more distal site can be stimulated (e.g., the palm), then a conduction block pattern may be seen between the more distal stimulation site (palm) and the usual distal stimulation site (wrist). **C:** Demyelination affecting only proximal nerve segments. In this pattern, DLs, amplitudes, and conduction velocities are normal. The only abnormality on routine studies may be prolongation of late responses. If it is possible to stimulate a very proximal site, a conduction block pattern may be seen between the very proximal stimulation site and the usual proximal stimulation site (elbow).

clinical deficit (weakness, numbness) is secondary to demyelination and, accordingly, that recovery can occur with remyelination. Second, when present in entrapment neuropathies (e.g., radial neuropathy at the spiral groove, median neuropathy at the carpal tunnel), *the finding of conduction block can be used to localize the lesion*. Finally, in the evaluation of patients with demyelinating polyneuropathy, the presence of conduction block at nonentrapment sites has additional diagnostic significance because it differentiates acquired from inherited conditions. Conduction block characteristically occurs at nonentrapment sites in acquired demyelinating neuropathies, such as Guillain–Barré syndrome or chronic inflammatory demyelinating polyneuropathy (CIDP), but it is not seen in the various inherited demyelinating neuropathies (e.g., Charcot–Marie–Tooth type I) in which demyelination results only in uniform slowing.

When a demyelinating lesion results in conduction block, clinical numbness and weakness develop acutely. Distal to the conduction block, the nerve continues to conduct normally, although it is effectively disconnected from its proximal segment. Accordingly, distal NCSs remain normal, as in acute axonal loss lesions. However, in contrast to axonal loss lesions, the underlying axon remains intact, and wallerian degeneration never occurs. NCSs remain normal distally. However, if the nerve is stimulated above the lesion, electrophysiologic evidence of focal demyelination (i.e., marked CV slowing, conduction block, or both) will be seen.

Conduction block nearly always means demyelination; however, in one unusual situation, conduction block may be seen in an axonal loss lesion. If, following a transection, nerve conduction studies are performed above and below the lesion during the first several days, before wallerian degeneration has occurred, a conduction block-like pattern will be seen (Figure 16–3). If the studies are repeated after one week, however, the distal nerve will have degenerated and the apparent block will no longer be present. Some refer to this as a *pseudo-conduction block*.

On needle EMG, recruitment decreases in a demyelinating lesion associated with conduction block because the number of available motor units has been reduced. Because the underlying axon remains intact, however, no wallerian degeneration occurs. Therefore, no denervation or subsequent reinnervation occurs. *Reduced recruitment remains the only abnormality on needle EMG in a pure demyelinating lesion with conduction block*. In cases in which demyelination results only in slowing, without conduction block, clinical muscle strength and its EMG correlate, recruitment, are normal. Thus, in cases where there is only slowing, without conduction block or any axonal loss, the entire needle EMG remains normal.

Pure demyelinating lesions are uncommon. Most demyelinating lesions have some secondary axonal loss, regardless of whether they are inherited or acquired, associated with conduction block or with slowing alone. Such cases will demonstrate a combination of axonal and demyelinating changes on nerve conduction and needle EMG studies. However, usually it still is possible to determine if the primary underlying pathophysiology is demyelination or axonal loss.

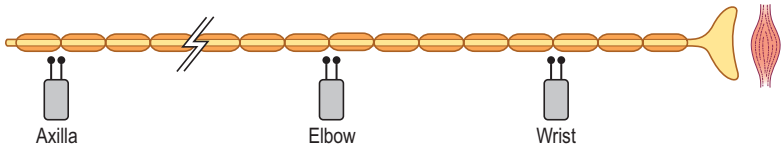

FIGURE 16–3 Hyperacute axonal loss and "conduction block." After an axonal loss injury (e.g., transection), wallerian degeneration occurs in motor fibers 3 to 5 days later. Before that time, the nerve can still be stimulated and recorded distal to the injury, despite being disconnected from its proximal segment. If the nerve is stimulated proximal to the injury, however, a conduction block pattern will be present, a finding usually associated with demyelination. If the study is repeated after 1 week's time, the nerve will have degenerated. All amplitudes will be reduced, and the previously noted "conduction block" will no longer be present. In the figure above, stimulating at the wrist and elbow immediately after a proximal axonal loss injury results in normal amplitudes, conduction velocity, and latencies. If the nerve is stimulated at the axilla, an apparent conduction block will be present.

IMPORTANT NEUROPATHIC PATTERNS

There are several important neuropathic patterns that each electromyographer must be able to recognize. These patterns vary depending on (1) the time course of the lesion, (2) whether the underlying primary pathology is axonal loss or demyelination, and, if it is demyelination, (3) whether demyelination is associated with conduction block or with CV slowing alone. These patterns are the building blocks that, when analyzed together with the distribution of the abnormalities and the clinical information, allow a final electrodiagnosis to be reached.

Axonal Loss: Hyperacute

NCS		Needle EMG			
Motor	**Sensory**	**Spontaneous Activity**	**Activation**	**Recruitment**	**MUAP Morphology**
Normal	Normal	Normal	Normal	↓	Normal

↓ = reduced

The pattern of hyperacute axonal loss occurs in axonal loss lesions less than 3 days old, prior to the beginning of wallerian degeneration. The result is an unusual combination of normal motor and sensory conductions distal to the lesion, despite clinical weakness and sensory loss. Late responses are also usually normal, unless the nerve has been completely transected proximally. If stimulation can be performed proximal to the lesion during this period, a marked drop in amplitude will be seen, mimicking conduction block, a finding usually associated with demyelination. On needle EMG, reduced MUAP recruitment in weak muscles is the only abnormality seen. Insufficient time has elapsed for either spontaneous activity or changes in MUAP morphology to have developed.

Hyperacute axonal loss is an unusual pattern, typically seen after trauma or nerve infarction. It can be difficult to differentiate this pattern from that seen with an acute demyelinating lesion associated with conduction block; the two are quite similar. Often it is necessary to repeat the study after 1 week's time. If the underlying pathology is axonal loss, wallerian degeneration will occur after about a week. Distal NCSs become abnormal, and the proximal "conduction block" disappears. Making this differentiation is important for determining the etiology of the lesion, as well as the prognosis (axonal loss has a much worse prognosis than demyelination).

Axonal Loss: Acute

NCS		Needle EMG			
Motor	**Sensory**	**Spontaneous Activity**	**Activation**	**Recruitment**	**MUAP Morphology**
Amplitude: ↓ CV: Normal/↓ DL: Normal↑	Amplitude: ↓ CV: Normal/↓ DL: Normal/↑	Normal	Normal	↓	Normal

↓ = reduced; ↑ = increased

The pattern of acute axonal loss occurs in lesions that are more than several days but less than several weeks old. Enough time has passed for wallerian degeneration to have occurred. Accordingly, NCSs are abnormal, showing evidence consistent with axonal loss. Amplitudes are decreased, with relatively normal CVs and DLs, unless some of the

largest and fastest axons have been lost, in which case some slowing of CV and latency occurs. On needle EMG, decreased recruitment remains the only abnormality. Not enough time has elapsed for denervation potentials to develop (usually 2–6 weeks, depending on the length of the nerve between the lesion and the muscle tested). Again, acute axonal loss is an unusual pattern, typically seen after an event such as trauma or nerve infarction.

Axonal Loss: Subacute

NCS		Needle EMG			
Motor	**Sensory**	**Spontaneous Activity**	**Activation**	**Recruitment**	**MUAP Morphology**
Amplitude: ↓ CV: Normal/↓ DL: Normal/↑	Amplitude: ↓ CV: Normal/↓ DL: Normal/↑	Fibrillation potentials Positive waves	Normal	↓	Normal

↓ = reduced; ↑ = increased

The pattern of subacute axonal loss lesions occurs after several weeks, but not months. Compared with the hyperacute and acute patterns, enough time has elapsed to see spontaneous denervating potentials on needle EMG. Reinnervation has not yet occurred, however, and MUAP morphology remains normal. This pattern, similar to the acute and hyperacute axonal loss patterns, is unusual and is seen most often after trauma or nerve infarction.

Axonal Loss: Subacute–Chronic

NCS		Needle EMG			
Motor	**Sensory**	**Spontaneous Activity**	**Activation**	**Recruitment**	**MUAP Morphology**
Amplitude: ↓ CV: Normal/↓ DL: Normal/↑	Amplitude: ↓ CV: Normal/↓ DL: Normal/↑	Fibrillation potentials Positive waves	Normal	↓	Long duration High amplitude Polyphasic

↓ = reduced; ↑= increased

The pattern associated with subacute–chronic axonal loss lesions occurs after a couple of months. Enough time has passed for wallerian degeneration (abnormal NCS results) and abnormal spontaneous activity (fibrillation potentials/positive sharp waves) to be demonstrated. In addition, reinnervation now is occurring, resulting in changes in MUAP morphology. MUAPs are long in duration, high in amplitude, and/or polyphasic, with decreased recruitment. In contrast to the patterns described earlier, this pattern is quite common; it is seen in most polyneuropathies.

Axonal Loss: Chronic

NCS		Needle EMG			
Motor	**Sensory**	**Spontaneous Activity**	**Activation**	**Recruitment**	**MUAP Morphology**
Amplitude: Normal/↓ CV: Normal/↓ DL: Normal/↑	Amplitude: Normal/↓ CV: Normal/↓ DL: Normal/↑	Normal	Normal	↓	Long duration High amplitude Polyphasic

↓ = reduced; ↑= increased

The chronic axonal loss pattern is seen months to years after the occurrence of a lesion that is no longer active. Reinnervation is complete, and denervating potentials have disappeared. Successful reinnervation often results in improved or even normal motor and sensory amplitudes on NCSs. MUAP abnormalities often persist indefinitely on needle EMG as a marker of the remote injury that is no longer active (e.g., old radiculopathy).

Demyelination (Slowing and Conduction Block): Single Proximal Lesion

NCS		Needle EMG			
Motor	**Sensory**	**Spontaneous Activity**	**Activation**	**Recruitment**	**MUAP Morphology**
Amplitude: Normal CV: Normal DL: Normal Conduction block and slowing at lesion LR: ↑↑	Normal	Normal	Normal	↓	Normal

↓ = reduced; ↑↑ = moderately increased; LR = late responses

An isolated proximal demyelinating lesion with focal slowing and conduction block produces an important pattern that, if not recognized, often creates confusion. Because the underlying axon remains intact, wallerian degeneration never occurs. Thus, despite clinical findings of weakness or numbness, distal motor and sensory conductions remain normal. Late responses (i.e., F and H waves) may be abnormal, signifying proximal block and slowing. Motor studies, if performed proximally across the lesion, demonstrate conduction block and focal slowing, the electrophysiologic signs of demyelination. Although they typically are not performed proximally, sensory studies would show similar findings. On needle EMG, the only abnormality is decreased recruitment in weak muscles, reflecting that blocked motor units are no longer available to help generate force. Without axonal loss, denervation and reinnervation never occur. This type of lesion often occurs as the result of an episode of prolonged compression or trauma (e.g., radial neuropathy at the spiral groove). Note that if this pattern is seen and the clinical history indicates that the lesion is less than 4 days old, distinguishing this pattern from a hyperacute axonal loss lesion may be difficult. Both will show "conduction block" at the site of the lesion. A repeat study in 1 week may be necessary to make the differentiation. In a purely demyelinating lesion, no drop in distal amplitude should be seen after 1 week, whereas in an axonal loss lesion, distal and proximal amplitudes will both be low after 1 week.

Demyelination (Slowing Alone): Single Proximal Lesion

NCS		Needle EMG			
Motor	**Sensory**	**Spontaneous Activity**	**Activation**	**Recruitment**	**MUAP Morphology**
Amplitude: Normal CV: ↓↓ at lesion DL: Normal LR: ↑↑	Normal	Normal	Normal	Normal	Normal

↓↓ = moderately reduced; ↑↑ = moderately increased; LR = late responses

When a single proximal demyelinating lesion results only in slowing and not in conduction block, the pattern of abnormalities is not as marked. Distal NCSs remain normal. Only late responses and studies performed across the lesion will be abnormal. In such a case, stimulation across the lesion site results only in slowing of CV. With no conduction block and no loss of motor units, however, the entire needle EMG pattern remains normal. This pattern, because of its few abnormalities, can be very difficult to recognize. It is occasionally seen, for example, in ulnar neuropathy at the elbow.

Demyelination (Slowing and Conduction Block): Single Distal Lesion

NCS		Needle EMG			
Motor	**Sensory**	**Spontaneous Activity**	**Activation**	**Recruitment**	**MUAP Morphology**
Amplitude: ↓ CV: Normal DL: ↑↑ Conduction block and slowing at lesion LR: ↑↑	Amplitude: ↓ CV: ↓↓ DL: ↑↑ Conduction block and slowing at lesion	Normal	Normal	↓	Normal

↓ = reduced; ↓↓ = moderately reduced; ↑↑ = moderately increased; LR = late responses

If conduction block and slowing occur between the distal stimulation site and the recording electrodes (e.g., median nerve at the wrist), a different pattern from those previously described emerges. Both motor and sensory amplitudes are decreased, associated with marked slowing of DLs. Sensory CV, typically calculated in the distal segment, is markedly slowed. However, motor CV, which is calculated in the proximal segment since it can be calculated only between two stimulation sites, one distal and one proximal, remains normal because the prolonged DL is subtracted out in the calculation. Late responses, which must also travel through the distal segment, are also prolonged. If stimulation distal to the lesion is possible (e.g., in the palm), a conduction block pattern will be seen for both motor and sensory fibers. On needle EMG, reduced recruitment in weak muscles is the only abnormality present. This pattern of distal demyelination is quite common and occurs frequently with distal entrapment neuropathies, especially carpal tunnel syndrome.

Demyelination (Slowing Alone): Single Distal Lesion

NCS		Needle EMG			
Motor	**Sensory**	**Spontaneous Activity**	**Activation**	**Recruitment**	**MUAP Morphology**
Amplitude: Normal CV: Normal DL: ↑↑ LR:↑↑	Amplitude: ↓ CV: ↓↓ DL:↑↑	Normal	Normal	Normal	Normal

↓ = reduced; ↓↓ = moderately reduced; ↑↑ = moderately increased; LR = late responses

The pattern of distal demyelination with slowing alone differs from the one with coexistent conduction block. DLs are prolonged, and late responses are still abnormal. However, motor amplitude usually remains normal. In contrast, sensory amplitudes often decrease, not from conduction block but from the process of temporal dispersion and phase cancellation. The effects of temporal dispersion from demyelination and subsequent phase cancellation are always much more marked for sensory than for motor fibers. Sensory CV is markedly slowed. Without conduction block, the needle EMG is completely normal, including recruitment of MUAPs. This pattern also is quite common and is seen in many distal entrapment neuropathies.

Early Reinnervation after Severe Denervation

NCS		Needle EMG			
Motor	**Sensory**	**Spontaneous Activity**	**Activation**	**Recruitment**	**MUAP Morphology**
Amplitude: ↓↓↓ CV: Normal/↓ DL: Normal/↑	Amplitude ↓↓↓ CV: Normal/↓ DL: Normal/↑	Fibrillation potentials Positive waves	Normal	↓↓↓	Short duration Low amplitude Polyphasic

↓ = reduced; ↓↓ = moderately reduced; ↓↓↓ = markedly reduced; ↑ = increased

After severe or complete denervation, in which there are no nearby surviving axons, the only mechanism of reinnervation is regrowth of the axon from the site of injury. As the axon regrows, there comes a time when it reinnervates some but not all of the original muscle fibers. At that point, NCSs show a pattern consistent with marked axonal loss: very low amplitudes, with normal or mildly slowed velocities and latencies. MUAP morphology reveals short-duration, low-amplitude, polyphasic MUAPs, reflecting the reduced number of muscle fibers per motor unit. The morphology of these MUAPs is similar to those of acute myopathic motor unit action potentials, and they are known as *nascent units* (see Chapter 15). *The key factor that differentiates between nascent units and myopathic units is the recruitment pattern*. Because nascent units follow severe denervation, recruitment is markedly reduced; in contrast, myopathic motor unit action potentials are seen in the context of normal or "early" recruitment. Nascent units are uncommon but serve to reemphasize that not all small, short, polyphasic MUAPs are myopathic.

MYOPATHIC LESIONS

Myopathic lesions result from loss or dysfunction of muscle fibers. Usually, the electrodiagnosis of myopathy is based on specific needle EMG abnormalities accompanied by normal NCS findings. Sensory nerve conduction studies are always normal. Motor conduction studies are usually also normal because proximal muscles are most often affected in myopathies, whereas distal muscles are most often recorded during routine motor conduction studies. In those uncommon myopathies that preferentially affect distal muscles (e.g., myotonic dystrophy), compound muscle

action potential (CMAP) amplitudes may be decreased, but latencies and CVs are normal.

On needle EMG, myopathy usually is diagnosed by changes in MUAP morphology and recruitment. In most myopathies, there is dropout or dysfunction of individual muscle fibers, effectively decreasing the size of the motor unit. The number of motor units (i.e., the number of anterior horn cells and their axons) does not change, however, except in the unusual case of a myopathy that is so severe that every muscle fiber in a motor unit drops out, effectively decreasing the number of motor units. In myopathy, MUAPs become short in duration, low in amplitude, and polyphasic. These changes result from dropout of individual muscle fibers and less synchronous firing of the remaining fibers. MUAP recruitment usually is normal because the number of motor units remains intact. However, each motor unit contains fewer fibers than normal and can generate less force. Consequently, to generate the same amount of force, more motor units than normal must fire. This results in the pattern of early recruitment (i.e., the inappropriate firing of many motor units to generate a small amount of force).

Besides MUAP morphology and recruitment, the analysis of spontaneous activity also is important in evaluating myopathic patterns. Certain myopathies are associated with abnormal spontaneous activity, either denervation potentials (fibrillation potentials/positive sharp waves), myotonic discharges, or complex repetitive discharges (CRDs). The presence of abnormal spontaneous activity is useful in narrowing the differential diagnosis. Only a limited number of myopathies are associated with fibrillation potentials; others are associated with myotonic discharges (see Chapter 35). In those myopathies associated with denervating potentials, complex EMG patterns can develop when the myopathy is chronic, often consisting of a combination of both myopathic and neuropathic features on EMG.

Myopathy: General

NCS		Needle EMG			
Motor	**Sensory**	**Spontaneous Activity**	**Activation**	**Recruitment**	**MUAP Morphology**
Amplitude: Normal or ↓	Amplitude: Normal	Normal or fibrillation potentials/ positive waves, or myotonia	Normal	Normal/early	Short duration Low amplitude Polyphasic

↓ = reduced

The classic myopathic pattern is one in which the NCSs are normal and needle EMG shows short, small, polyphasic MUAPs with normal or early recruitment. If the myopathy affects distal muscles (which is rare), CMAP amplitudes may be decreased. Abnormal spontaneous activity may or may not be present. In myopathies with inflammatory or necrotic features (e.g., polymyositis, dystrophies), fibrillation potentials and positive sharp waves may be present. Other myopathies are associated with myotonic discharges (e.g., myotonic dystrophy, myotonia congenita).

Myopathy: Chronic with Denervating Features

NCS		Needle EMG			
Motor	**Sensory**	**Spontaneous Activity**	**Activation**	**Recruitment**	**MUAP Morphology**
Amplitude: Normal or ↓	Normal	Normal or fibrillation potentials/ positive waves/CRDs	Normal	Normal, early or slightly ↓	Short duration Low amplitude Polyphasic and/or Long duration High amplitude Polyphasic

↓ = reduced; CRD = complex repetitive discharge

Chronic myopathies, especially those associated with denervating features (e.g., polymyositis, inclusion body myositis), often create complex EMG patterns. As in other myopathies, NCSs are usually normal unless distal muscles are affected, which may result in decreased CMAP amplitudes. Needle EMG may show abnormal spontaneous activity consistent with either active denervation (i.e., fibrillation potentials, positive sharp waves) or chronic denervation (i.e., CRDs). On voluntary contraction, there often is a combination of typical myopathic MUAPs (short duration, low amplitude, polyphasic), as well as long-duration, high-amplitude, polyphasic MUAPs. Thus, these

larger MUAPs, usually associated with chronic neuropathic disease, also may be seen in chronic myopathies. Because some reinnervation does occur in myopathies with denervating features, this leads to the development of these long, large, polyphasic MUAPs. In many chronic myopathies, both neuropathic- and myopathic-type MUAPs may be seen in the same muscle. In exceptional cases only large, long polyphasic MUAPs may be seen.

The key to differentiating chronic neuropathic from chronic myopathic MUAPs is the assessment of recruitment. In myopathy, recruitment usually is normal, or "early." If the myopathy is severe enough that every muscle fiber of a motor unit is lost, the number of motor units, and hence recruitment, can actually decrease. In some cases of severe chronic myopathy (especially inclusion body myositis), the needle EMG pattern can be very close to that of active motor neuron disease (fibrillation potentials; long-duration, high-amplitude, polyphasic MUAPs, with decreased recruitment). The only clue to the true underlying myopathic pattern in this case may be that the MUAP changes (long, large, and polyphasic) often appear too abnormal for what the slightly reduced recruitment pattern would suggest.

NEUROMUSCULAR JUNCTION LESIONS

NMJ disorders often present a clinical picture similar to myopathies with proximal muscle weakness. Indeed, they may be mistaken for myopathies on EMG as well, if RNS is not performed. NMJ disorders result in different patterns, depending on whether the pathophysiology is presynaptic or postsynaptic. For all NMJ disorders, sensory conduction studies are normal. Motor studies all yield normal DLs, CVs, and late responses.

NCS		Needle EMG			
Motor	**Sensory**	**Spontaneous Activity**	**Activation**	**Recruitment**	**MUAP Morphology**
CV: Normal DL: Normal Postsynaptic: Amplitude: Normal Decrement: 3 Hz RNS Presynaptic: Amplitude: ↓ Decrement: 3 Hz RNS Increment: 50 Hz RNS	Normal	Normal or fibrillation potentials/positive waves	Normal	Normal/early	Normal or Unstable or Short duration Low amplitude Polyphasic

↓ = reduced; RNS = repetitive nerve stimulation

In postsynaptic disorders (e.g., myasthenia gravis), CMAP amplitudes usually are normal. Subsequently, 3 Hz RNS causes a decrement of >10%, which becomes more marked if RNS is repeated several minutes after prolonged exercise. Presynaptic disorders (e.g., Lambert–Eaton myasthenic syndrome, botulism) are quite different. In those disorders, CMAP amplitudes usually are reduced at rest. Although they also show a decrement with 3 Hz RNS, their unique finding is a marked increment (usually >100% above baseline) after either 50 Hz RNS or brief maximal voluntary exercise.

On needle EMG, abnormal spontaneous activity usually is not present in NMJ disorders, except for botulism. In botulism, the NMJ is so severely blocked that muscle fibers are effectively denervated, often resulting in fibrillation potentials and positive sharp waves.

MUAP morphology in NMJ disorders usually is normal, as is recruitment. However, close attention often demonstrates that MUAPs are unstable, varying in configuration from potential to potential. If the severity of the disorder is sufficient that blocking occurs, individual muscle fibers drop out, reducing the number of muscle fibers per motor unit. This results in short-duration, low-amplitude, and polyphasic MUAPs, often with early recruitment, which are the needle EMG findings usually associated with myopathy.

CENTRAL NERVOUS SYSTEM LESIONS

Patients with central nervous system (CNS) lesions (i.e., lesions of the brain or spinal cord) may present with weakness and numbness. In addition, such patients often have increased reflexes, abnormal muscle tone, and other signs that mark the lesion as central. After an acute event, however, reflexes and muscle tone may be decreased (i.e., cerebral or spinal shock), making the differentiation from a peripheral lesion more difficult. For instance, this situation often arises in patients who have undergone coronary artery bypass graft surgery and are found to have new upper extremity weakness and numbness immediately after surgery. The differential diagnosis includes a brachial plexus lesion from traction, as well as a stroke from cardiac

embolus. In the acute setting, both conditions may display depressed reflexes and decreased muscle tone, along with weakness and numbness. In such a situation, the EMG examination can easily differentiate the two.

Upper Motor Neuron Lesion

NCS		Needle EMG			
Motor	Sensory	Spontaneous Activity	Activation	Recruitment	MUAP Morphology
Normal	Normal	Normal	↓↓	Normal	Normal

↓↓ = moderately reduced

In CNS disorders, nerve conductions are normal. On needle EMG, there is no denervation or reinnervation, and MUAP morphology remains normal. On voluntary contraction, however, the interference pattern is not complete, and often an erratic or sputtering pattern of MUAP firing occurs. In central lesions, the primary problem is decreased activation (i.e., decreased firing frequency); the number of available MUAPs (i.e., recruitment) remains normal. Thus, although the number of motor unit action potentials firing is reduced in central lesions, the number (i.e., the recruitment) is appropriate for the level of activation, which is reduced.

The central lesion that can create a lot of confusion is a segmental spinal cord lesion. Muscles innervated below the level of the lesion will display the typical pattern for CNS lesions (i.e., decreased activation). At the segmental level of the lesion, however, anterior horn cells may be affected, leading to a neuropathic pattern in muscles innervated by that segment. For instance, consider a complete necrotic lesion of the spinal cord at C5–C6 resulting in quadriplegia. EMG of the leg muscles would show only decreased activation. However, EMG of C5–C6-innervated muscles (e.g., deltoid, biceps) would show decreased recruitment and other neuropathic changes, depending on the time course of the lesion. Muscles with partial innervation by these segments (e.g., pronator teres, C6–C7) show a combination of decreased activation and decreased recruitment, as well as other neuropathic abnormalities. Further below in the arm, at the C8–T1-innervated muscles, only decreased activation would be seen, as in the leg muscles.

It is important to remember that decreased activation implies a central lesion. However, although a central lesion may be due to a structural lesion in the brain or spinal cord, it can also result from pain, poor cooperation, psychiatric disease, or malingering.

CLINICAL SYNDROMES

After recognizing the underlying pattern of NCS–EMG abnormalities as neuropathic, myopathic, central, or secondary to an NMJ disorder, the next step is to identify the distribution of abnormalities (i.e., which nerves and muscles are involved and which are spared). Together, this combination of findings enables the identification of unique clinical patterns.

Mononeuropathy: Non-localizing

NCS			
Motor	Sensory	Needle EMG	Distribution
Axonal loss	Axonal loss	Neuropathic findings	Limited to one nerve

Non-localizing mononeuropathy is a familiar pattern in the EMG laboratory. Nerve conductions and needle EMG are normal everywhere, except in the distribution of one nerve. Depending on whether the involved nerve is a sensory, motor, or combination nerve, sensory and motor nerve conductions may be abnormal. In a non-localizing lesion, however, findings on nerve conductions are limited to signs of axonal loss (decreased amplitudes with normal or slightly slowed latencies and CVs). On EMG, neuropathic abnormalities are limited to the distribution of the involved nerve.

Abnormalities on sensory studies identify the lesion as one of peripheral nerve, at or distal to the dorsal root ganglion. Other than that, the mononeuropathy can be localized only at or proximal to the most proximal abnormal muscle identified on the needle EMG. In this pattern, there are no demyelinating findings (i.e., focal slowing or conduction block) on NCSs to localize the lesion definitively. In the EMG laboratory, this pattern is often seen in cases of ulnar neuropathy. In the case of non-localizing ulnar neuropathy, although the lesion most likely is at the elbow in most patients, ulnar conduction studies simply show evidence of axonal loss, without slowing or conduction block across the elbow to localize the lesion.

Mononeuropathy: Localizing

NCS			
Motor	**Sensory**	**Needle EMG**	**Distribution**
Marked slowing, conduction block, or both across the lesion Variable axonal loss	Marked slowing, conduction block, or both across the lesion Variable axonal loss	Neuropathic findings	Limited to one nerve

In a localizing mononeuropathy, nerve conduction and needle EMG abnormalities are limited to one nerve, marking the pattern as a mononeuropathy. Localization is based on electrophysiologic evidence of demyelination at the site of the lesion, either focal slowing, conduction block, or both. Coexistent axonal loss may or may not be present. This is a common pattern, frequently seen in entrapment neuropathies where the underlying primary pathophysiology is demyelination (e.g., carpal tunnel syndrome, radial neuropathy at the spiral groove, peroneal neuropathy at the fibular neck).

Polyneuropathy: Symmetric Stocking-Glove

NCS			
Motor	**Sensory**	**Needle EMG**	**Distribution**
Axonal loss, demyelination, or both	Axonal loss, demyelination, or both	Neuropathic	Distal affected more than proximal Lower extremity affected more than upper extremity Symmetric–bilateral Length dependent

Polyneuropathies are recognized by generalized abnormalities on nerve conduction studies and neuropathic findings on needle EMG. Nerve conduction abnormalities may indicate either demyelination, axonal loss, or a combination, depending on the type of the polyneuropathy. One of the most common patterns is the stocking-glove polyneuropathy, wherein abnormalities are dependent on the length of the nerve. Longer nerves are preferentially affected. Thus, on both NCSs and EMG, abnormalities are more prominent distally, worse in the legs than in the arms, and more prominent in distal than proximal segments. The vast majority of polyneuropathies, especially those due to toxic, metabolic, or genetic factors, result in symmetric nerve conduction and EMG findings. Side-to-side comparisons often are useful in this regard. Any significant asymmetry should make one question the diagnosis of a symmetric stocking-glove polyneuropathy.

Polyneuropathy: Asymmetric Axonal

NCS			
Motor	**Sensory**	**Needle EMG**	**Distribution**
Axonal loss	Axonal loss	Neuropathic findings	Asymmetric Non-length dependent Multiple mononeuropathies

The presence of any significant asymmetry in an axonal polyneuropathy may have important diagnostic significance. In some cases, asymmetry or a non-length dependent pattern is seen in typical, symmetric polyneuropathies with superimposed entrapment mononeuropathies or radiculopathies. More important, however, an asymmetric pattern may suggest underlying multiple mononeuropathies. Multiple mononeuropathies (often referred to as *mononeuritis multiplex*) produce a unique pattern in which individual peripheral nerves are affected in a stepwise manner. Most often, this pattern results from an underlying vasculitic neuropathy. If the pattern is not recognized initially, as further nerves become affected, a confluent pattern of nerve involvement will develop that is difficult to differentiate from a typical distal symmetric polyneuropathy. In such cases, the presence of any asymmetry on NCSs or needle EMG may be a clue to the true underlying mononeuritis multiplex pattern.

Chronic Demyelinating Polyneuropathy with Secondary Axonal Changes: Uniform Slowing

NCS			
Motor	**Sensory**	**Needle EMG**	**Distribution**
Amplitude: Normal or ↓ CV: ↓↓ DL: ↑↑ LR: ↑↑	Amplitude: ↓ CV: ↓↓ DL: ↑↑	Neuropathic findings	Distal affected more than proximal Lower extremity affected more than upper extremity Symmetric–bilateral

↓ = reduced; ↓↓ = moderately reduced; ↑↑ = moderately increased; LR = late responses

Chronic demyelinating polyneuropathy with secondary axonal features is an important pattern to recognize. Although axonal changes are present in all chronic polyneuropathies, few are associated with primary demyelination. The differential diagnosis of a demyelinating neuropathy is further narrowed depending on whether demyelination results in uniform slowing or in conduction block at non-entrapment sites. In neuropathies where demyelination is a uniform process, all nerve segments are equally affected. Consequently, demyelination results in marked slowing of CVs (<75% of lower limit of normal), DLs and late responses (>130% of upper limit of normal), but not conduction block. This pattern of demyelination, uniform slowing without conduction block at non-entrapment sites, is the pattern seen in the inherited demyelinating polyneuropathies (e.g., Charcot–Marie–Tooth). The cardinal features of an inherited demyelinating neuropathy are symmetry comparing side to side, and uniform CV slowing without conduction block. *The absence of conduction block at non-entrapment sites is the key feature that separates inherited from acquired demyelinating polyneuropathies.*

Chronic Demyelinating Polyneuropathy with Secondary Axonal Changes: Non-uniform Slowing and Conduction Block

NCS			
Motor	**Sensory**	**Needle EMG**	**Distribution**
Amplitude: Normal or ↓ CV: ↓↓ DL: ↑↑ LR: ↑↑ Conduction block Temporal dispersion	Amplitude: ↓ CV: ↓↓ DL: ↑↑	Neuropathic findings	Distal affected more than proximal Lower extremity affected more than upper extremity Asymmetric

↓ = reduced; ↓↓ = moderately reduced; ↑↑ = moderately increased; LR = late responses

On NCSs, the presence of conduction block at non-entrapment sites and asymmetry usually can differentiate acquired from inherited demyelinating neuropathies with secondary axonal loss. Acquired conditions (e.g., chronic inflammatory demyelinating polyneuropathy) often yield asymmetric NCSs, even when there is apparent clinical symmetry. In addition, conduction block and temporal dispersion at non-entrapment sites always mark the polyneuropathy as acquired; they are not seen in inherited demyelinating neuropathies. This differentiation leads to important implications for further evaluation, prognosis, and potential therapy.

Plexopathy

NCS			
Motor	**Sensory**	**Needle EMG**	**Distribution**
Axonal loss	Axonal loss	Neuropathic findings	Multiple nerves of one plexus

In a plexopathy, neuropathic abnormalities are present in more than one nerve but are limited to the distribution of one plexus. To recognize this pattern, it usually is necessary to compare both NCS and needle EMG findings from side to side.

Radiculopathy

NCS			
Motor	**Sensory**	**Needle EMG**	**Distribution**
Normal or axonal loss	Normal	Neuropathic findings	Limited to one myotome, including the paraspinals

Radiculopathy is one of the patterns seen most frequently in the EMG laboratory. Because the lesion is proximal to the dorsal root ganglia, *sensory conduction studies are always normal in radiculopathy*. Motor conductions also are normal, unless muscles used for recording are innervated by the involved nerve roots and the radiculopathy is fairly severe, in which case low CMAP amplitudes may be seen. This is the case in the median and ulnar motor studies for C8–T1 radiculopathy, and in the peroneal and tibial motor studies for L5–S1 radiculopathy. These motor studies may show changes consistent with axonal loss.

Each nerve root supplies a segment of paraspinal muscles before innervating limb muscles, usually by way of several different peripheral nerves. Accordingly, radiculopathy is recognized on needle EMG by a pattern of neuropathic abnormalities that share the same nerve root innervation (i.e., myotomal pattern). Abnormalities usually are expected in distal and proximal limb muscles innervated by the same nerve root but by different nerves. In addition, abnormalities in the paraspinal muscles are key in helping to recognize a radiculopathy. For example, in a C7 radiculopathy, both the flexor carpi radialis (a median-innervated C7 muscle) and triceps (a radial-innervated C7 muscle) may be abnormal, as well as the cervical paraspinal muscles. As with other axonal loss lesions, it is important to remember that the specific neuropathic abnormalities vary, depending on the time course of the radiculopathy.

Polyradiculopathy

NCS			
Motor	**Sensory**	**Needle EMG**	**Distribution**
Normal or axonal loss	Normal	Neuropathic findings	Multiple myotomes, including the paraspinals

The polyradiculopathy pattern occurs when multiple nerve roots are involved. It may be seen in diabetes, in cervical–lumbosacral stenosis, or when multiple nerve roots are infected (e.g., by cytomegalovirus) or infiltrated (e.g., by tumor or granulomatous tissue). As in an isolated radiculopathy, *sensory studies are always normal*. Motor studies may show changes consistent with axonal loss if the recorded muscles are in the distribution of the abnormal nerve roots. On needle EMG, there are neuropathic changes in the paraspinal and limb muscles in the distribution of multiple myotomes. It is important to note that there is no fundamental difference between the NCS–EMG pattern seen in polyradiculopathy and that seen in motor neuron disease. However, the differentiation is easily made on clinical grounds, because patients with motor neuron disease have no sensory complaints or findings and often have additional upper motor signs.

Motor Neuron Disease

NCS			
Motor	**Sensory**	**Needle EMG**	**Distribution**
Normal or axonal loss	Normal	Neuropathic findings	± Multiple myotomes ±Thoracic paraspinals ± Bulbar muscles

Because the sensory system is spared in motor neuron disease, sensory conduction studies are always normal. Motor studies can be normal but more often show evidence of axonal loss. Demyelinating features are not seen on motor NCSs. The absence of demyelinating features is critical because some demyelinating motor neuropathies can mimic lower motor neuron disease clinically but are associated with conduction block and other signs of demyelination on NCSs. On needle EMG, motor neuron disease is similar to polyradiculopathy: there are neuropathic abnormalities in the paraspinal muscles and in the distribution of multiple nerve roots. Bulbar and thoracic paraspinal muscles may also be abnormal. Abnormalities in these areas have special diagnostic significance because they are not involved in cervical–lumbar spondylosis (i.e., cervical–lumbar polyradiculopathy), a common condition that sometimes is confused with motor neuron disease.

Neuromuscular Junction: Post-synaptic Disorders

NCS			
Motor	**Sensory**	**Needle EMG**	**Distribution**
Normal at rest Decrement: 3 Hz RNS Increased decrement post-exercise	Normal	Normal, unstable, or "myopathic" findings	Proximal affected more than distal Bulbar Extraocular

In post-synaptic NMJ disorders (e.g., myasthenia gravis), routine motor and sensory nerve conduction studies are normal. Slow RNS (3 Hz) characteristically results in decrements of CMAP amplitude of more than 10%. Decrements become more marked if RNS is performed several minutes after 1 minute of exercise. Because weakness and fatigue predominantly affect extraocular, bulbar, and proximal muscles, decrements are seen more often with stimulation of more proximal nerves. On needle EMG, MUAPs often are normal in milder cases. With worsening disease, MUAPs become unstable, varying in configuration from potential to potential. If the NMJ disorder is severe enough that persistent blocking occurs, MUAPs become small, short, and polyphasic, with normal or early recruitment, similar to the findings seen in myopathy.

Neuromuscular Junction: Pre-synaptic Disorders

NCS			
Motor	**Sensory**	**Needle EMG**	**Distribution**
Amplitude: ↓at rest Decrement: 3 Hz RNS Increment: 50 Hz RNS Increment post-exercise	Normal	Normal, unstable, or "myopathic" findings	Proximal and distal

↓ = reduced

Pre-synaptic and post-synaptic NMJ disorders both show decremental CMAP responses on 3 Hz RNS, and they display similar findings on needle EMG studies. However, two important differences separate the two. First, CMAP amplitudes in pre-synaptic disorders usually are low at baseline compared with post-synaptic disorders, in which they are normal at rest. Second, in pre-synaptic NMJ disorders marked CMAP increments occur after brief voluntary maximal contraction or 50 Hz RNS (often >100% above baseline).

Myopathy: Proximal

NCS			
Motor	**Sensory**	**Needle EMG**	**Distribution**
Normal	Normal	Myopathic MUAPs	Proximal affected more than distal Abnormal paraspinal muscles

Proximal myopathies always result in normal sensory conductions and usually in normal motor conduction studies. Needle EMG shows myopathic findings, most prominent in the most proximal muscles, especially the paraspinal muscles.

Myopathy: Distal

NCS			
Motor	**Sensory**	**Needle EMG**	**Distribution**
Amplitude: Normal or ↓	Normal	Myopathic MUAPs	Distal affected more than proximal

↓ = reduced

Myopathies that preferentially affect distal muscles (e.g., myotonic dystrophy, inclusion body myositis, distal inherited myopathy) result in myopathic abnormalities that are more prominent in the distal muscles. In addition, motor conduction studies, in which distal muscles typically are used for recording, may show decreased CMAP amplitudes.

Myopathy with Denervating Features

NCS			
Motor	**Sensory**	**Needle EMG**	**Distribution**
Amplitude: Normal or ↓	Normal	Myopathic MUAPs Fibrillation potentials/positive waves/CRDs	Variable

↓ = reduced; CRD = complex repetitive discharge

The presence of denervating potentials (fibrillation potentials, positive sharp waves, CRDs) in the setting of myopathic MUAPs on needle EMG represents an important myopathic pattern. Denervating potentials are present most commonly in myopathies associated with inflammation or necrosis and occasionally in those due to certain toxins.

Myopathy with Denervating Features: Chronic

NCS			
Motor	**Sensory**	**Needle EMG**	**Distribution**
Amplitude: Normal or ↓	Normal	Fibrillation potentials/positive waves/CRDs Myopathic findings/neuropathic findings or both Recruitment relatively spared	Variable

↓ = reduced; CRD = complex repetitive discharge

A chronic myopathy with denervating features is one of the most difficult patterns to recognize. Clinically, this pattern is seen most often in inclusion body myositis, which now is the most common inflammatory myopathy occurring in individuals older than 50 years. After denervation, some reinnervation normally occurs. As the condition becomes chronic, this can lead to complex needle EMG patterns of both myopathic and neuropathic MUAPs, often in the same muscle. However, the degree of neuropathic MUAP changes (large, long, and polyphasic) often appears too abnormal for the mild reduction in recruitment pattern, an important clue to a possible chronic myopathy.

Myopathy with Myotonic Discharges

NCS			
Motor	**Sensory**	**Needle EMG**	**Distribution**
Amplitude: Normal or ↓	Normal	Myotonic discharges +/– Myopathic MUAPs	Proximal, distal or both

The presence of myotonic discharges on EMG in the setting of myopathic MUAPs has important diagnostic significance. Myotonic discharges with distal predominant myopathic MUAPs are characteristic of myotonic dystrophy. Myotonic discharges are characteristically seen in the paraspinal muscles and very proximal muscles in acid maltase deficiency myopathy. Sparse myotonic discharges in the paraspinal muscles, along with denervating potentials and myopathic MUAPs in the proximal limb muscles, may be seen in polymyositis. Widespread myotonic discharges in the presence of normal MUAPs is characteristic of myotonia congenita and several other genetic disorders.

OTHER IMPORTANT LOCALIZATION PATTERNS

Sensory Loss with Normal Sensory Nerve Action Potentials

When performing a sensory NCS, occasionally the electromyographer is presented with an apparent paradox: the sensory nerve action potential (SNAP) is normal, yet the patient has clear sensory loss in the distribution of the sensory response being recorded. It is important to remember that there are only three possible situations in which this can occur (Figure 16–4):

1. *The lesion is proximal to the dorsal root ganglion.* This category includes structural or infiltrating lesions of the nerve roots, spinal cord, or brain, as well as psychiatric or factitious disorders. Because the dorsal root ganglion and peripheral nerve are intact, sensory responses remain normal on conduction studies.
2. *There is a proximal demyelinating lesion.* With pure demyelination, the underlying axon remains intact, and wallerian degeneration does not occur. Thus, the distal nerve continues to conduct normally, although effectively it is disconnected from its proximal segment. This pattern occurs if both the stimulation and recording sites are distal to demyelinating lesion.
3. *There is a hyperacute axonal loss lesion.* Immediately after an axonal loss lesion, the distal nerve continues to conduct normally for the first several days before wallerian degeneration occurs. During that time, distal NCSs remain normal. This underscores the need for the electromyographer to know the patient's clinical history, and particularly the temporal course of the condition, before interpreting a study.

Pure Motor Loss on Nerve Conduction Studies

During routine studies, motor nerve conductions usually are performed before sensory nerve conductions. If a pattern of diffusely low motor amplitudes emerges, along with normal latencies, CVs, and late responses, one usually thinks first of axonal loss and polyneuropathy. If sensory studies are subsequently normal, however, the unusual pattern of pure motor nerve conduction abnormalities occurs. In such a situation, axonal polyneuropathy is very unlikely because of the normal sensory potentials. This pattern can occur in the following conditions:

- Motor neuron disease
- Radiculopathy/polyradiculopathy
- NMJ disorders (especially presynaptic)
- Myopathy

The needle EMG then can be used to differentiate the neuropathic disorders (motor neuron disease, polyradiculopathy) from the myopathic disorders (NMJ disorders and myopathy). The differentiation between motor neuron disease and polyradiculopathy is easily made clinically, usually based on whether sensory symptoms or pain is present and, in the case of amyotrophic lateral sclerosis (both upper and lower motor neuron involvement), whether increased reflexes or other upper motor neuron signs are present. To differentiate NMJ disorders from myopathy may require the use of RNS and, depending on the clinical situation, possibly single-fiber EMG.

Localizing a Mononeuropathy by Needle EMG: Issues and Limitations

Both NCSs and needle EMG are important in localizing a lesion site, including localizing a mononeuropathy. On

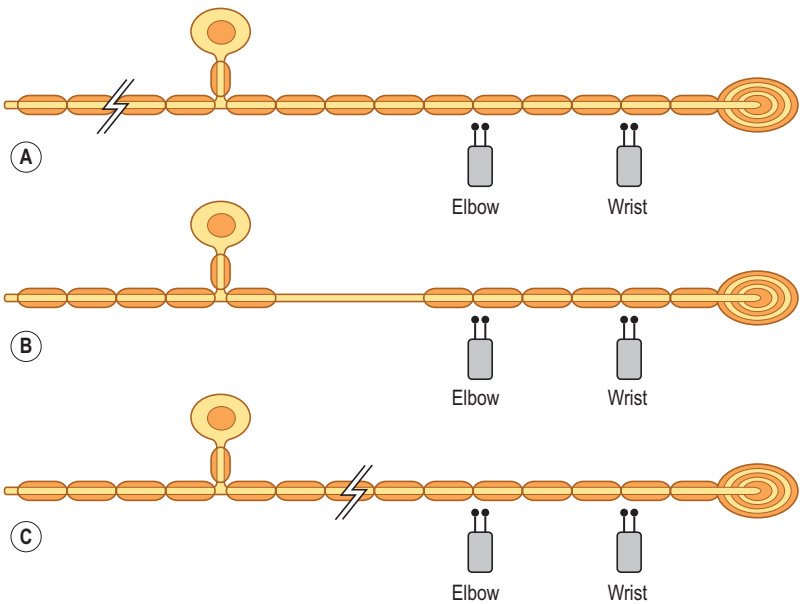

FIGURE 16–4 Sensory loss and normal sensory nerve action potentials (SNAPs). In the case of a patient with sensory loss but with normal SNAPs in the distribution of the sensory loss, there are only three possible explanations. **A:** The lesion is proximal to the dorsal root ganglion (DRG). Because the DRG and peripheral nerve remain intact, SNAPs will be normal. This occurs in lesions of the brain (structural and psychiatric) and spinal cord, as well as lesions of the nerve roots. In nerve root lesions, wallerian degeneration occurs centrally into the spinal cord and peripherally to the level of the DRG, leaving the DRG intact. **B:** There is proximal demyelination. Demyelination leaves the underlying axon intact, and subsequent wallerian degeneration does not occur. If demyelination is proximal to the stimulation and recording sites, the SNAPs will be normal. **C:** There is a hyperacute axonal loss injury. All peripheral axonal loss injuries result in abnormal SNAPs after wallerian degeneration. If sensory studies are performed distal to the injury and sooner than 6 to 10 days, before wallerian degeneration has occurred for sensory fibers, the SNAPs also will be normal.

NCSs, if abnormalities are limited to one nerve with other nearby nerves being normal, one can often determine that a neuropathy is present in the distribution of one nerve. In addition, if there is evidence of demyelination (i.e., conduction block and/or focal slowing), then the exact segment of nerve that is responsible can be determined. Likewise, needle EMG can be used to localize a mononeuropathy when the needle EMG changes (either denervation and/or reinnervation) are limited to muscles supplied by one nerve with other nearby muscles supplied by different nerves being normal. However, to localize the exact site of the lesion is often not possible by needle EMG, with a few exceptions. Consider the following examples.

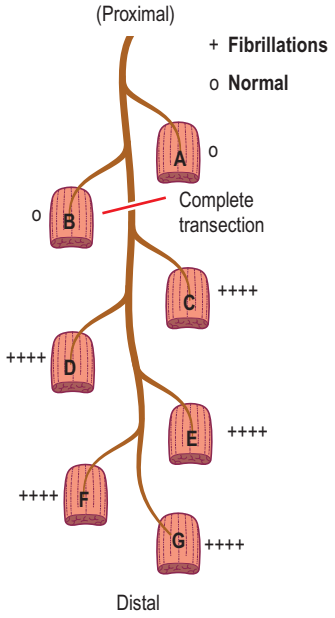

FIGURE 16–5 Needle EMG findings: complete transection of a nerve. See text for details.
(Adapted with permission from Wilbourn, A.J., 2002. Nerve conduction studies. Types, components, abnormalities, and value in localization. Neurol Clin 20 (2), 305–338.)

Example 1: There is a complete transection of a nerve (Figure 16–5). Given sufficient time, there will be florid active denervation (fibrillation potentials and positive sharp waves) and no MUAPs in muscles supplied below the transection (muscles C, D, E, F, G) with completely normal muscles above the transection (A, B). In such a case, one can be fairly certain that the localization of the lesion is in the nerve segment between muscles B and C.

Example 2: There is a severe axonal injury of a nerve (Figure 16–6, left). Given sufficient time, there will be marked active denervation (fibrillation potentials and positive sharp waves) and none or few MUAPs in muscles supplied below the injury (muscles C, D, E, F, G) with completely normal muscles above (A, B). In such a case, one usually thinks that the lesion localizes to the nerve segment between muscles B and C. One is usually (but not always) correct because there is such a marked difference in the findings between the normal and abnormal muscles. However, even in this situation, it is still best to describe the lesion site by needle EMG as "at or above the take-off to the most proximal abnormal muscle" (in this example, at or proximal to the take-off to muscle C).

Example 3: There is a severe axonal injury of a nerve (Figure 16–6, right). However, now several months have passed. Reinnervation is occurring, and reinnervation, like denervation, occurs first in the muscles closest to the lesion. Thus, one encounters a situation

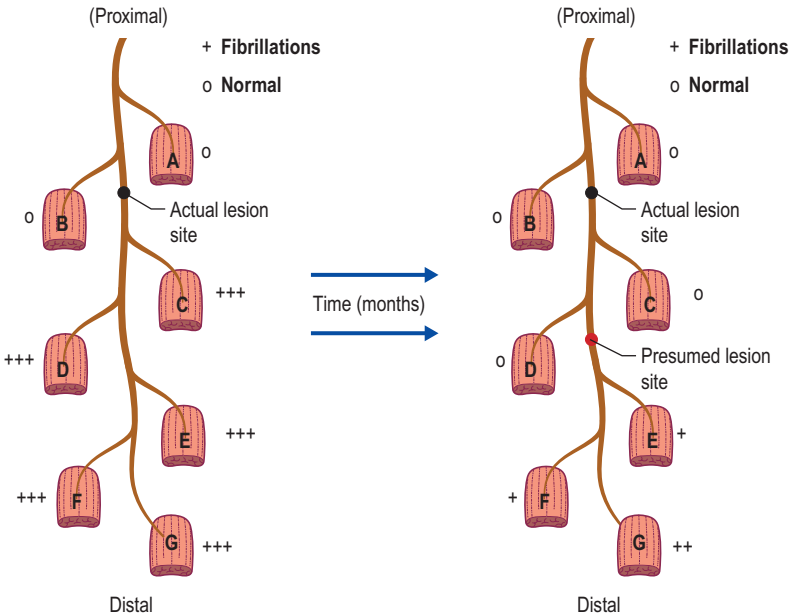

FIGURE 16–6 Needle EMG findings: severe axonal injury of a nerve (**Left:** acute; **Right:** subacute – chronic). See text for details.
(Adapted with permission from Wilbourn, A.J., 2002. Nerve conduction studies. Types, components, abnormalities, and value in localization. Neurol Clin 20 (2), 305–338.)

wherein the muscles closest to the nerve injury have fully recovered, whereas the more distal muscles are still denervated. In this situation, it is very hazardous to define the lesion localization as occurring between the most proximal abnormal muscle and a more proximal normal muscle. Here, one might incorrectly assume that the lesion is between muscles D and E, whereas the actual lesion is between muscles A and B. Thus, whenever this situation is encountered, one should properly describe the lesion site by needle EMG as "at or proximal to the take-off to the most proximal abnormal muscle" (in this example, at or proximal to the take-off to muscle E).

Example 4: Fascicular Lesion within a Nerve (Figure 16–7). One usually thinks of a nerve as being similar to a wire, but in reality, a nerve is more correctly thought of as bundles of hundreds of wires. Nerve fibers are arranged as bundles (fascicles) with the nerve trunk. Figure 16–7 (top right) represents a hypothetical nerve that contains seven fascicles, with each fascicle supplying one muscle respectively (A, B, C, D, E, F, G). One can see in this example that with external compression (Figure 16–7, bottom right), only those fascicles adjacent to the compression site are affected (in this example, fascicles D and F). The other fascicles (A, B, C, E, G) remain intact, as they are not close to the site of compression. In such a scenario, only muscles D and F, which are innervated by nerve fascicles D and F respectively, will show active denervation (Figure 16–7, left). Again, one might assume (incorrectly) that the lesion site is between muscles C and D, resulting in denervation of more distal muscles. However, one can see in this case why such reasoning is faulty. The actual lesion site is above muscle A. In such cases, one should properly describe the lesion site by needle EMG as "at or above the take-off to the most proximal abnormal muscle" (in this example, at or proximal to the take-off to muscle D). Such a scenario is quite common clinically wherein certain fascicles are involved and others are spared. Indeed, this is seen in many common entrapment neuropathies, and radiculopathies, among other neuropathic conditions.

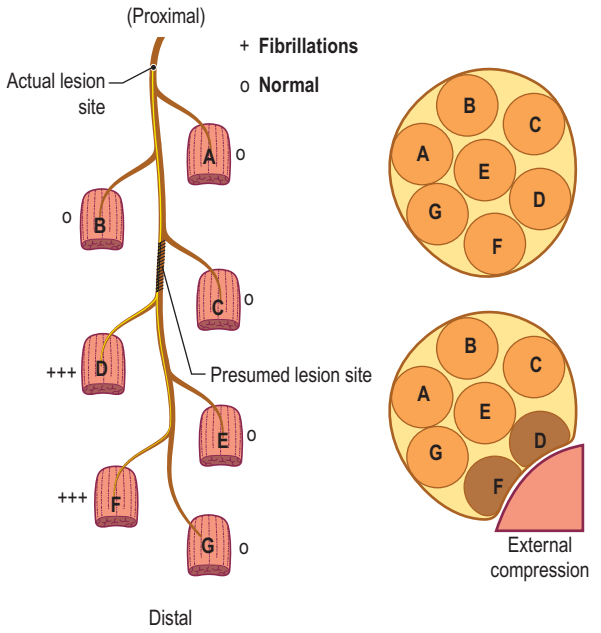

FIGURE 16–7 Needle EMG findings: fascicular lesion within a nerve. See text for details.
(Adapted with permission from Wilbourn, A.J., 2002. Nerve conduction studies. Types, components, abnormalities, and value in localization. Neurol Clin 20 (2), 305–338.)

The examples above demonstrate the following: it is not possible to localize the exact site of a lesion by EMG. The best that can be done is to find that the lesion is at or proximal to the take-off of the most proximal abnormal muscle. Only in cases where there is a dramatic difference between two sequential muscles supplied by a nerve (i.e., typically a nerve transection), can one say with almost total certainty that the lesion is between those two muscles, and be correct.

17 Median Neuropathy at the Wrist

Median nerve entrapment at the wrist is the most common of all entrapment neuropathies and, consequently, is one of the most frequent reasons for referral for an electrodiagnostic (EDX) study. In nearly all patients, the usual site of compression occurs in the carpal tunnel and results in a constellation of symptoms and signs known as the *carpal tunnel syndrome* (CTS). Lesions of the C6–C7 nerve roots or, less often, the brachial plexus and the proximal median nerve may be confused clinically with median neuropathy at the wrist, especially in early or mild cases.

For an electromyographer, familiarity with the various nerve conduction and electromyographic patterns associated with CTS is essential. It has long been recognized that in any individual patient with CTS, there may be little correlation between the degree or frequency of clinical symptoms or signs and the abnormalities seen on nerve conduction studies. For example, an occasional patient will have only mild or trivial clinical symptoms yet will have clear signs on physical examination (e.g., dense numbness, wasting of thenar muscles) and evidence of severe axonal loss on nerve conduction and needle electromyography (EMG) studies. On the other hand, there are patients whose clinical history clearly indicates CTS but who show few or no abnormalities on neurologic examination or on routine median motor and sensory nerve conduction studies. It is in these latter patients with early or electrically mild CTS that additional more sensitive nerve conduction studies must be performed in order to demonstrate median nerve slowing at the wrist. By appropriately applying the various electrophysiologic techniques available to study the median nerve, a definite diagnosis can usually be reached, and lesions of the nerve roots, proximal median nerve, or brachial plexus can be excluded.

ANATOMY

Understanding the anatomy of the median nerve is the first step toward being able to differentiate entrapment of the median nerve at the wrist from lesions of the proximal median nerve, brachial plexus, and cervical nerve roots, on both clinical and electrophysiologic grounds. The median nerve is formed by a combination of the *lateral and medial cords* of the brachial plexus (Table 17–1, Figure 17–1). The lateral cord is made up of C6–C7 fibers and supplies median sensory fibers to the thenar eminence, thumb, index, and middle fingers, and motor fibers to the proximal median forearm muscles. The medial cord, composed of C8–T1

Table 17–1. Median Nerve Innervation

	Median Branch	Cord	Trunk	Root
Muscle				
Pronator teres	(Main median nerve)	Lateral	Upper/middle	C6–C7
Flexor carpi radialis	(Main median nerve)	Lateral	Upper/middle	C6–C7
Flexor digitorum sublimis	(Main median nerve)	Lateral/medial	Middle/lower	C7–C8
Flexor digitorum profundus (2,3)	Anterior interosseous	Lateral/medial	Middle/lower	C7–C8
Flexor pollicis longus	Anterior interosseous	Lateral/medial	Middle/lower	C7–C8–T1
Pronator quadratus	Anterior interosseous	Lateral/medial	Middle/lower	C7–C8–T1
Abductor pollicis brevis	Recurrent thenar	Medial	Lower	C8–T1
Opponens pollicis	Recurrent thenar	Medial	Lower	C8–T1
Flexor pollicis brevis (superficial head)	Recurrent thenar	Medial	Lower	C8–T1
Sensory area				
Thenar eminence	Palmar cutaneous	Lateral	Upper	C6
Medial thumb	Digital branch	Lateral	Upper	C6
Index finger	Digital branches	Lateral	Upper/middle	C6–C7
Middle finger	Digital branches	Lateral	Middle	C7
Lateral ring finger	Digital branch	Lateral/medial	Middle/lower	C7–C8

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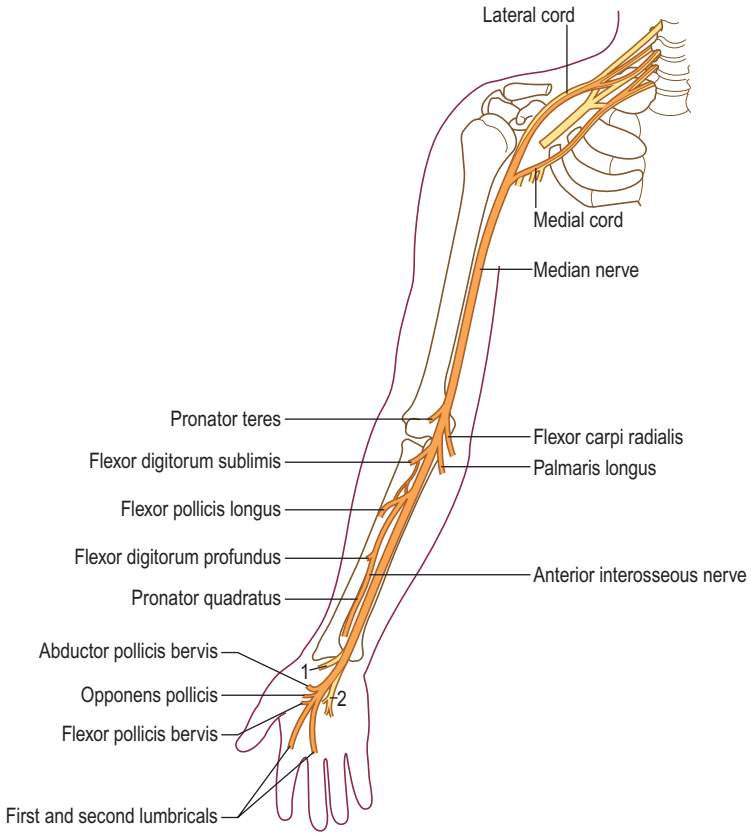

FIGURE 17–1 Anatomy of the median nerve. The median nerve is derived from a combination of the lateral and medial cords of the brachial plexus. Motor innervation is supplied to forearm muscles and to muscles of the thenar eminence. Sensation is supplied to the thenar eminence by the palmar cutaneous sensory branch (1) and to the first three and one-half digits by several digital sensory branches (2). (Adapted with permission from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia.)

fibers, supplies motor fibers to the median muscles of the distal forearm and hand, as well as sensory fibers to the lateral half of the ring finger.

The median nerve descends in the upper arm, giving off no muscular branches. In the antecubital fossa, the nerve lies adjacent to the brachial artery. As it passes into the forearm, the median nerve runs between the two heads of the pronator teres (PT) before giving off muscular branches to the PT, flexor carpi radialis (FCR), flexor digitorum sublimis (FDS), and, in some individuals, the palmaris longus muscles. The *anterior interosseous nerve* is given off next in the proximal forearm, innervating the flexor pollicis longus (FPL), the medial head of the flexor digitorum profundus (FDP) to the index and middle fingers, and the pronator quadratus (PQ) muscles. The anterior interosseous nerve is considered a pure motor nerve clinically because it carries no cutaneous sensory fibers. However, deep sensory fibers are carried in the anterior interosseous nerve, supplying the wrist joint and interosseous membrane.

Just proximal to the wrist and carpal tunnel, the *palmar cutaneous sensory branch* arises next, running subcutaneously to supply sensation over the thenar eminence. The median nerve then enters the wrist through the carpal tunnel. Carpal bones make up the floor and sides of the carpal tunnel, and the *thick transverse carpal ligament* forms the roof (Figure 17–2). In addition to the median nerve, nine flexor tendons traverse the carpal tunnel as

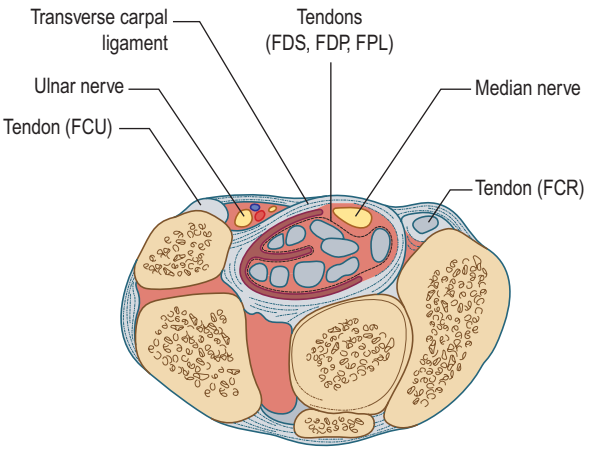

FIGURE 17–2 Anatomy of the median nerve at the carpal tunnel. At the wrist, the median nerve runs through the carpal tunnel, along with nine flexor tendons. Carpal bones form the floor and sides of the carpal tunnel; the thick transverse carpal ligament forms the roof. FCR, flexor carpi radialis; FCU, flexor carpi ulnaris; FDP, flexor digitorum profundus; FDS, flexor digitorum sublimis; FPL, flexor pollicis longus. (Reprinted with permission from Pecina, M.M., Krmpotic, Nemanic, J., Markiewitz, A.D., 1991. Tunnel syndromes. CRC Press, Boca Raton, FL.)

well (FDP: four tendons; FDS: four tendons; FPL: one tendon). In the palm, the median nerve divides into motor and sensory divisions. The motor division travels distally into the palm, supplying the first and second lumbricals (1L, 2L). In addition, the *recurrent thenar motor branch* is given off. This branch turns around (hence, recurrent) to supply muscular branches to most of the thenar eminence, including the opponens pollicis (OP), abductor pollicis brevis (APB), and superficial head of the flexor pollicis brevis (FPB). The sensory fibers of the median nerve that course though the carpal tunnel supply the medial thumb, index finger, middle finger, and lateral half of the ring finger. The index and middle fingers are each supplied by two digital branches (one lateral and one medial); the thumb and ring fingers receive only one branch each (Figure 17–3).

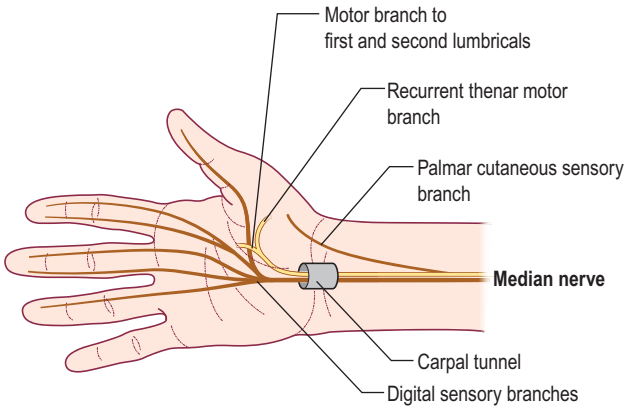

FIGURE 17–3 Distal motor and sensory branches of the median nerve. Proximal to the carpal tunnel, the palmar cutaneous sensory branch arises to supply sensation to the thenar eminence. Distal to the carpal tunnel, the median nerve divides into sensory and motor branches. Digital sensory branches supply the index and middle fingers and part of the thumb and fourth finger. Motor fibers supply the first and second lumbricals, while the recurrent thenar motor branch innervates most muscles of the thenar eminence.

CLINICAL

Patients with CTS may present with a variety of symptoms and signs (Table 17–2). Women are affected more often than men. Although CTS usually is bilateral both clinically and electrically, the dominant hand usually is more severely affected, especially in idiopathic cases. Patients complain of wrist and arm pain associated with paresthesias in the hand. The pain may be localized to the wrist or may radiate to the forearm, arm, or, rarely, the shoulder; *the neck is not affected*. Some patients may describe a diffuse, poorly localized ache involving the entire arm. Paresthesias are frequently present in the median nerve distribution (medial thumb, index, middle, and lateral ring fingers). Although many patients report that the entire hand falls asleep, if asked directly about little finger involvement, most will subsequently note that the little finger is spared.

Symptoms often are provoked when either a flexed or extended wrist posture is assumed. Most commonly, this occurs during ordinary activities, such as driving a car or holding a phone, book, or newspaper. *Nocturnal paresthesias are particularly common*. During sleep, persistent wrist flexion or extension leads to increased carpal tunnel pressure, nerve ischemia, and subsequent paresthesias. Patients frequently will awaken from sleep and shake or wring their hands out or hold them under warm running water.

Sensory fibers are involved early in the majority of patients. Pain and paresthesias usually bring patients to medical attention. Motor fibers may become involved in more advanced cases. Weakness of thumb abduction and opposition may develop, followed by frank atrophy of the thenar eminence. Some patients describe difficulty buttoning shirts, opening jars, or turning doorknobs. However, development of significant functional impairment from loss of median motor function in the hand is unusual.

The sensory examination may disclose hypesthesia in the median distribution. Comparing sensation over the lateral ring finger (median innervated) to that over the medial

Table 17–2. Clinical Symptoms and Signs

Highly Suggestive of Carpal Tunnel Syndrome	Possible Carpal Tunnel Syndrome	Inconsistent with Carpal Tunnel Syndrome
Nocturnal paresthesias awakening patient from sleep	Hand, wrist, forearm, arm, and/or shoulder pain	Neck pain
Shaking or ringing the hands		
Pain/paresthesias associated with driving or holding a phone, book, or newspaper	Perception of paresthesias involving all five digits	Paresthesias radiating from neck and shoulder down the arm
Sensory disturbance of digits 1,2, 3, and 4, splitting the fourth digit	No fixed sensory disturbance, or sensory disturbance of digits 1, 2, 3, and/or 4	Unequivocal numbness over the thenar eminence
Weakness/wasting of thenar eminence	Decreased hand dexterity	Weakness/wasting of hypothenar muscles, thumb flexion (interphalangeal joint), arm pronation, and/or elbow flexion/extension
Phalen's maneuver reproduces symptoms	Tinel's sign over the median nerve at the wrist	Reduced biceps or triceps reflexes

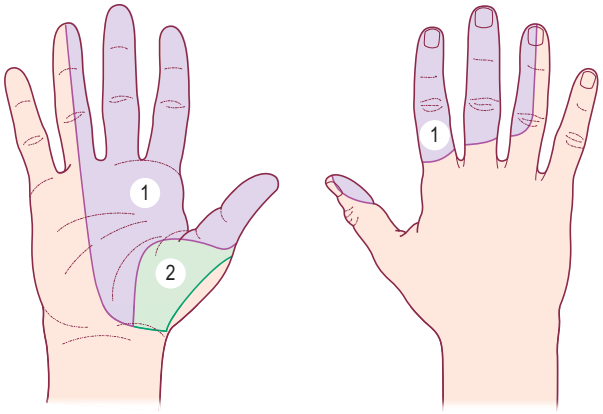

FIGURE 17–4 Typical median sensory territory. The median sensory territory is innervated by the palmar digital sensory branches (1) and the palmar cutaneous sensory branch (2). In most individuals, digit 4 is innervated by median and ulnar nerves; rarely, digit 4 may be all median or all ulnar. Only the digital sensory branches travel through the carpal tunnel resulting in the pattern of sensory loss seen in carpal tunnel syndrome (1). In contrast, sensation over the thenar area is normal in carpal tunnel syndrome (2).

FIGURE 17–5 Provocative test for carpal tunnel syndrome: Tinel's sign. The Tinel's sign is elicited by tapping over the median nerve in the center of the wrist. If abnormal, the patient will report paresthesias radiating into one or more median-innervated digits.

FIGURE 17–6 Provocative test for carpal tunnel syndrome: Phalen's maneuver. The Phalen's maneuver is performed by placing the wrist in a flexed posture **(top).** This position increases pressure within the carpal tunnel and may provoke paresthesias radiating into median-innervated digits (especially digit 3) in patients with carpal tunnel syndrome. The pressure also increases and median paresthesias may result if the wrist is placed in an extended posture **(bottom),** sometimes known as the "reverse Phalen's maneuver."

ring finger (ulnar innervated) is often helpful. *Sensation over the thenar area is spared because this area is innervated by the palmar cutaneous sensory branch, which arises proximal to the carpal tunnel* (Figure 17–4). The *Tinel's sign* is often present when tapping over the median nerve at the wrist, which results in paresthesias in the median-innervated fingers (Figure 17–5). The *Phalen's maneuver*, whereby the wrist is held passively flexed, may also provoke symptoms (Figure 17–6, top). A wide range of sensitivities and specificities for the Tinel's sign and Phalen's maneuver have been reported in the literature. A Tinel's sign is present in more than half of CTS cases; however, false-positive Tinel's signs are common in the general population. A Phalen's maneuver usually produces paresthesias within 30 seconds to 2 minutes in CTS; it is more sensitive than the Tinel's sign and has fewer false-positive results. Most commonly, the Phalen's maneuver will produce paresthesias in the middle or index fingers. It should be noted, however, that because the Phalen's maneuver often is performed with the elbow flexed as well (a provocative maneuver for ulnar neuropathy at the cubital tunnel), this position occasionally may produce ulnar paresthesias in patients with ulnar neuropathy.

The motor examination involves inspection of the hand, looking for wasting of the thenar eminence (severe cases), and testing the strength of thumb abduction and opposition (Figure 17–7). Isolating the actions of the APB and OP (median-innervated muscles distal to the carpal tunnel) may be difficult because thumb abduction is also served by the abductor pollicis longus (radial nerve) and thumb opposition by a combination of the deep head of the FPB

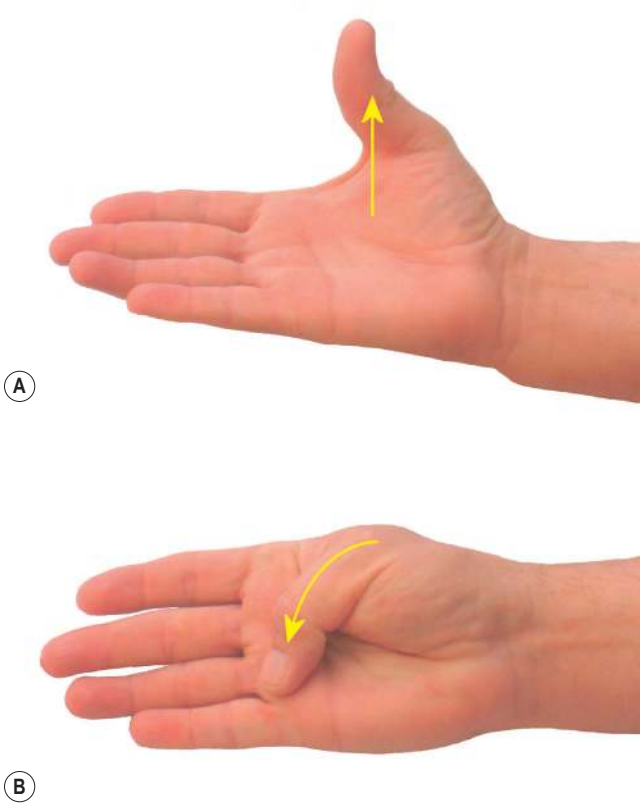

FIGURE 17–7 Muscle testing in carpal tunnel syndrome. Thumb abduction **(A)** and opposition **(B)** may be weak in more advanced cases of carpal tunnel syndrome.

(innervated by the ulnar nerve) and the FPL (innervated by the anterior interosseous nerve).

It is important to emphasize that CTS is a clinical diagnosis. It represents a constellation of clinical symptoms and signs caused by compression and slowing of the median nerve at the wrist. However, there are patients who have median nerve slowing at the wrist on nerve conductions but who have no clinical signs or symptoms. Such patients do not have CTS *per se* and do not need directed therapy. This situation is encountered most often in patients with an underlying polyneuropathy in whom preferential slowing at common sites of compression is not unusual. Often, patients with an underlying polyneuropathy may be found to have incidental slowing at several entrapment sites, including the median nerve at the wrist, ulnar nerve at the elbow, and peroneal nerve at the fibular neck. For example, a patient with numbness and tingling of both feet from a mild alcohol-induced or diabetic polyneuropathy may have relative slowing of the median nerve across the wrist on nerve conduction studies yet may have no complaints of pain, paresthesias, or weakness in the hands. According to the EDX studies, such a patient has a median neuropathy at the wrist superimposed on an underlying polyneuropathy, but the patient does not have CTS. This distinction is important, because in this case treatment with splinting, injection, or surgery is not appropriate. The point is again underscored that *nerve conduction and EMG studies can be properly performed and interpreted only with knowledge of the clinical history and physical examination.*

Box 17–1. Conditions Associated with Carpal Tunnel Syndrome

- Idiopathic disorders
  - Repetitive stress
  - Occupational
- Endocrine disorders
  - Hypothyroidism
  - Acromegaly
  - Diabetes
- Connective tissue disease
  - Rheumatoid arthritis
- Tumors
  - Ganglia
  - Lipoma
  - Schwannoma
  - Neurofibroma
  - Hemangioma
- Congenital disorders
  - Persistent median artery
  - Congenital small carpal tunnel
  - Anomalous muscles (palmaris longus, flexor digitorum sublimis)
- Infectious/inflammatory
  - Sarcoid
  - Histoplasmosis
  - Septic arthritis
  - Lyme
  - Tuberculosis
- Trauma
  - Fractures (especially Colles' fracture)
  - Hemorrhage (including anticoagulation)
- Other
  - Spasticity (persistent wrist flexion)
  - Hemodialysis
  - Amyloidosis (familial and acquired)
  - Pregnancy
  - Any condition that increases edema or total body fluid

ETIOLOGY

The reported causes of CTS are numerous (Box 17–1). *Despite this exhaustive list, most cases are idiopathic.* Indeed, idiopathic cases present with the same signs and symptoms as CTS caused by the other conditions listed in Box 17–1. Although the etiology of idiopathic cases was long considered to be tenosynovitis of the transverse carpal ligament, pathologic evaluation typically shows little evidence of inflammation. In most cases, edema, vascular sclerosis, and fibrosis are seen, findings consistent with repeated stress to connective tissue. Compression results in symptoms by way of ischemia and demyelination and, if it is severe enough, wallerian degeneration and axonal loss.

Occupations or activities that involve repetitive hand use clearly increase the risk of CTS (e.g., typists, data entry workers, mechanics, and carpenters). From the exhaustive list given in Box 17–1, the conditions most often associated with CTS, other than idiopathic, are diabetes, hypothyroidism, rheumatoid arthritis, amyloidosis, and pregnancy.

One important clue to an underlying cause, other than idiopathic, is the presence of CTS in the non-dominant hand. In idiopathic cases, the dominant hand is nearly always the affected hand; if symptoms are bilateral, then the dominant hand is more affected than the contralateral hand. CTS that is significantly worse in the non-dominant hand should raise a red flag to a specific underlying cause other than idiopathic CTS.

DIFFERENTIAL DIAGNOSIS

There are several peripheral as well as central nervous system (CNS) lesions that may result in symptoms similar to CTS. The peripheral lesions that enter into the differential diagnosis include median neuropathy in the region of the elbow, brachial plexopathy, and cervical radiculopathy. The most common among the disorders that may be confused with CTS is cervical radiculopathy, especially lesions of the C6 or C7 root, which may cause both pain in the arm and paresthesias similar to those that characterize CTS. The important clinical clues that suggest radiculopathy rather than CTS are pain in the neck, radiation from the neck to the shoulder and arm, and exacerbation of symptoms by neck motion. Key points in the physical examination that suggest radiculopathy are abnormalities of the C6–C7 reflexes (biceps, brachioradialis, triceps), diminished power in proximal muscles (especially elbow flexion, elbow extension, arm pronation), and sensory abnormalities in the palm or forearm, which are beyond the distribution of sensory loss found in CTS.

Median neuropathy at the elbow and brachial plexopathy are very uncommon, especially in comparison to the incidence of CTS. If present, however, they may easily lead to clinical confusion. Important clues on physical examination that suggest a more proximal lesion of the median nerve are sensory disturbance over the thenar eminence and weakness of median innervated muscles proximal to the carpal tunnel, especially distal thumb flexion (FPL), arm pronation (PT and PQ), and wrist flexion (FCR). In brachial plexus lesions, the neurologic examination may reveal abnormalities similar to those noted in cervical radiculopathy, although the distribution of reflex abnormalities, weakness, and sensory loss may be more widespread, beyond the distribution of one spinal segment.

As for CNS disorders, transient paresthesias may be seen in patients with focal seizures, migraine, and transient ischemic attacks and occasionally are misinterpreted as symptoms of CTS. In exceptional cases, patients referred to the EMG laboratory for suspicion of CTS will be found to have a small lacunar infarct involving the lateral thalamus and internal capsule, causing hand clumsiness and sensory disturbance predominantly affecting the median-innervated digits. In addition to the presence of other evidence of CNS dysfunction, such as limb spasticity and brisk reflexes, the major differentiating factor is the lack of pain. One should always question the diagnosis of CTS in the absence of pain.

ELECTROPHYSIOLOGIC EVALUATION

The electrophysiologic evaluation of a patient suspected of having CTS is directed toward the following:

1. Demonstrating focal slowing or conduction block of median nerve fibers across the carpal tunnel
2. Excluding median neuropathy in the region of the elbow
3. Excluding brachial plexopathy predominantly affecting the median nerve fibers
4. Excluding cervical radiculopathy, especially C6 and C7
5. If a coexistent polyneuropathy is present, ensuring that any median slowing at the wrist is out of proportion to slowing expected from the polyneuropathy alone

Nerve Conduction Studies

The nerve conduction strategy for evaluating possible CTS is outlined in Box 17–2. The pathophysiology of CTS typically is demyelination, which, depending on the severity, may be associated with secondary axonal loss. In moderate to advanced cases, the electrodiagnosis usually is straightforward. On routine median studies, a demyelinating lesion at the carpal tunnel results in slowing of the distal motor and sensory latencies. If there is either demyelination with conduction block or axonal loss, the distal compound muscle action potential (CMAP) and sensory nerve action potential (SNAP) amplitudes, stimulating the median nerve at the wrist, will be decreased as well.

In patients with typical CTS, the median distal motor and sensory latencies, and minimum F wave latencies, are moderately to markedly prolonged. However, there are a group of patients with clinical symptoms and signs of CTS in whom these routine studies are normal (approximately 10–25% of CTS patients). In such patients, the electrodiagnosis of CTS will be missed unless further testing is performed using more sensitive nerve conduction studies. Those studies usually involve a comparison of the median nerve to another nerve in the same hand. The ulnar nerve is the nerve most commonly used for comparison; less often the radial nerve is used.

The common median-versus-ulnar comparison tests are (1) median-versus-ulnar palm-to-wrist mixed nerve latencies, (2) median-versus-ulnar wrist-to-digit 4 sensory latencies, and (3) median (second lumbrical)-versus-ulnar (interossei [INT]) distal motor latencies. In each of the comparison studies, identical distances between the stimulator and recording electrodes are used for the median and ulnar nerves. These techniques create an ideal internal control in which several variables that are known to affect conduction time are held constant, including distance, temperature, age, and nerve size. Ideally, the only factor that varies in these paired median-versus-ulnar comparison studies is that the median nerve traverses the carpal tunnel, whereas the ulnar nerve does not. Thus, any

Box 17–2. Recommended Nerve Conduction Study Protocol for Carpal Tunnel Syndrome

Routine studies

1. Median motor study recording abductor pollicis brevis, stimulating wrist and antecubital fossa
2. Ulnar motor study recording abductor digiti minimi, stimulating wrist, below groove, and above groove
3. Median and ulnar F responses
4. Median sensory response, recording digit 2 or 3, stimulating wrist
5. Ulnar sensory response, recording digit 5, stimulating wrist
6. Radial sensory response, recording snuffbox, stimulating over the lateral radius

The study is highly suggestive of isolated carpal tunnel syndrome if

The median studies are abnormal, showing marked slowing across the wrist (prolonged distal motor and sensory latencies), and prolonged minimum F wave latencies. The median compound muscle action potential (CMAP) and sensory nerve action potential (SNAP) amplitudes may be diminished if there is secondary axonal loss or if demyelination has led to conduction block at the wrist

and

The ulnar motor, sensory, and F wave studies are normal and the radial sensory response is normal (making a brachial plexopathy or polyneuropathy unlikely)

No further nerve conductions are necessary, proceed to electromyography (EMG).

If the median studies are completely normal or equivocal, proceed with the median-versus-ulnar comparison tests, the median-versus-radial comparison test, or the median segmental sensory study.

Median-versus-ulnar comparison studies

1. Comparison of the median and ulnar mixed palm-to-wrist peak latencies, stimulating the median and ulnar palm one at a time 8 cm from the recording electrodes over the median and ulnar wrist, respectively
2. Comparison of the median lumbrical and ulnar interossei distal motor latencies, stimulating the median and ulnar wrist one at a time at identical distances (8–10 cm), recording with the same electrode over the 2L/interossei
3. Comparison of the median and ulnar digit 4 sensory latencies, stimulating the median and ulnar wrist one at a time at identical distances (11–13 cm) and recording digit 4

Median-versus-radial comparison study

1. Comparison of the median and radial digit 1 sensory latencies, stimulating the median nerve at the wrist and the superficial radial sensory nerve at the forearm one at a time at identical distances (10–12 cm) and recording digit 1

Median segmental sensory study

1. While recording digit 3, stimulate the median nerve at the wrist and in the palm (with the palm-to-digit distance being one-half of the wrist-to-digit distance). Then calculate the wrist-to-palm conduction velocity and compare it to the palm-to-digit conduction velocity

If two or more of the above studies are abnormal, there is a high likelihood of carpal tunnel syndrome. Proceed to EMG. If these studies are normal, consider alternative diagnoses, especially cervical radiculopathy (note: a small number of patients with CTS can have normal NCSs).

Other important considerations:

1. If there is a co-existent polyneuropathy, the case will be more challenging. The question will be: is the median nerve slowing out of proportion to the slowing associated with the polyneuropathy. It is possible that all the motor and sensory latencies may be prolonged from the polyneuropathy itself. In addition, it would not be uncommon that the sensory and mixed studies may be absent, in which case the palmar mixed, digit 4, and digit 1 comparison studies cannot be used. In this situation, the lumbrical – interosseous comparison is often the most useful internal comparison study, as these motor responses usually remain present in a polyneuropathy.
2. In the unusual situation wherein there is a co-existent ulnar neuropathy at the wrist, all of the median versus ulnar internal comparison studies may be unhelpful, as both the median and ulnar latencies may be prolonged. In this situation, the median versus radial internal comparison study or the median segmental sensory study would be most useful.
3. If there is a co-existent ulnar neuropathy at the elbow (which would not be uncommon), the ulnar mixed and sensory responses may be absent, in which case the palmar mixed and digit 4 studies cannot be used. In this situation, the median versus radial internal comparison study, the median segmental sensory study, or the lumbrical – interosseous comparison would be most useful.
4. If the distal median motor or median sensory amplitudes are low, this may denote either axonal loss or distal conduction block. The only way to differentiate between these two is to stimulate the median nerve in the palm and compare the amplitudes with wrist stimulation. Any palm/wrist ratio >1.6 for sensory and >1.2 for motor amplitudes denotes some conduction block.

preferential slowing of the median nerve compared with the ulnar nerve can be attributed to conduction slowing through the carpal tunnel. The diagnostic yield increases from approximately 75% using routine motor and sensory studies to approximately 95% using these more sensitive techniques.

These sensitive median-versus-ulnar comparison studies are considered abnormal if very small differences between the median and ulnar latencies are found (typically 0.4–0.5 ms). *Therefore, meticulous attention must be paid to all technical factors, especially distance measurement, stimulus artifact, supramaximal stimulation, and electrode placement, to obtain reliable and reproducible data.* Furthermore, it is essential to avoid overstimulation, which can cause unintentional stimulus spread to an adjacent nerve. In the three studies outlined in the following section, overstimulation with unintentional spread of current to the adjacent nerve may yield a waveform that appears perfectly normal yet obscures the true latency difference between the median and ulnar potentials.

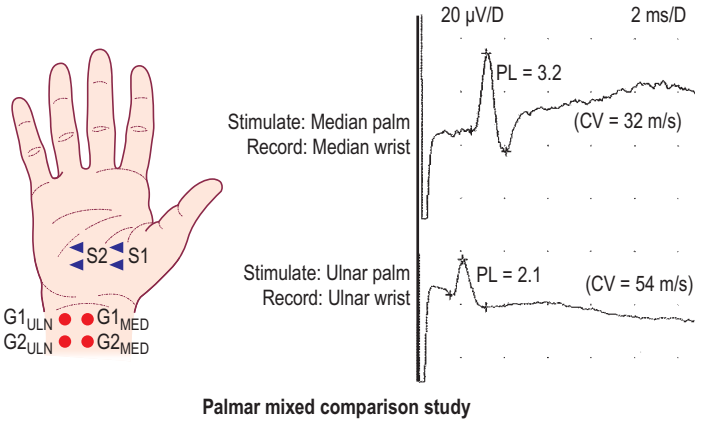

FIGURE 17–8 Palmar mixed comparison study. In this study, the median mixed nerve latency across the palm is compared to the adjacent ulnar mixed nerve latency, using identical distances between stimulation and recording sites. **Left:** G1, active recording electrode; G2, reference recording electrode; S1, median stimulation point; S2, ulnar stimulation point. In normals, there is no significant difference between the two latencies. **Right:** In carpal tunnel syndrome, the median palmar peak latency (PL) is prolonged both in an absolute sense (>2.2 ms) and in comparison to the ulnar palmar peak latency (≥0.4 ms difference).

Median-versus-Ulnar Comparison Studies

Median-versus-Ulnar Palm-to-Wrist Mixed Nerve Studies

This technique takes advantage of measuring the mixed nerve potential. Mixed nerve potentials consist of both motor and sensory fibers. The sensory fibers in the mixed nerve potential carry both cutaneous sensory fibers, which are measured in routine sensory studies, as well as muscle sensory fibers, which are not measured in routine sensory studies. This is important because the muscle sensory fibers include the Ia afferents from muscle spindles, which are the largest and fastest-conducting fibers and hence have the greatest quantity of myelin sheath. These fibers are very susceptible to demyelination, the primary pathology in CTS. The mixed nerve study also takes advantage of conducting over a very short distance of 8 cm. Because such a short distance is used, most of the conduction time is computed over the area of pathology. Only a short length of normal nerve is included that potentially could dilute any slowing present across the carpal tunnel.

The technique is performed by stimulating the median nerve in the palm, recording the median nerve at the wrist, and comparing it with the ulnar nerve stimulated in the palm and recorded over the ulnar nerve at the wrist (Figure 17–8). Each nerve is stimulated supramaximally in the palm at a distance of 8 cm from its respective recording electrodes. The median nerve is stimulated in the palm on a line connecting the median nerve in the middle of the wrist to the web space between the index and middle fingers. The ulnar nerve is stimulated in the palm on a line connecting the ulnar nerve at the medial wrist (lateral to the flexor carpi ulnaris tendon) to the web space between the ring and little fingers. Supramaximal responses are obtained for each nerve, and the difference between the onset or peak latencies is calculated.

Median-versus-Ulnar Digit 4 Sensory Latencies

The technique of comparing median-versus-ulnar digit 4 sensory latencies takes advantage of the fact that, in most individuals, the sensory innervation to the fourth digit (ring finger) is split, with the lateral half innervated by the median nerve and medial half innervated by the ulnar nerve (Figure 17–9). Thus, if identical distances are used, the latencies stimulating each nerve can be directly compared. The antidromic technique is performed by stimulating the median and ulnar nerves at the wrist, one at a time, with recording ring electrodes placed over digit 4 (G1 over the metacarpophalangeal joint and G2 over the distal interphalangeal joint). Identical distances must be used for both (range 11–13 cm). Supramaximal responses are obtained and the difference between median and ulnar onset or peak latencies recorded. The study also can be done orthodromically, stimulating with the ring electrodes over digit 4 as just described and recording the median and ulnar nerves at the wrist at identical distances. We do not recommend the latter method because with orthodromic stimulation at digit 4, co-stimulation of the median and ulnar nerves cannot be avoided, and spread of the potential from the adjacent nerve may contaminate the recorded SNAP at the wrist.

Median Second Lumbrical-versus-Ulnar Interossei Distal Motor Latencies

The technique of comparing the second lumbrical (2L)-versus-interosseous (INT) distal motor latencies takes advantage of two facts: (1) motor fibers are easy to record and more resistant to compression than sensory fibers, and (2) the median 2L muscle lies just above the ulnar INT. In some cases of generalized polyneuropathy with superimposed CTS, the SNAPs and mixed nerve potentials may be absent. In severe cases, the routine median CMAP recording the APB may also be absent, whereas the motor fibers to the second lumbrical and ulnar INT are still recordable.

CMAPs from both the median-innervated 2L and the ulnar-innervated INT can easily be recorded by placing an active electrode (G1) slightly lateral and distal to the midpoint of the third metacarpal, with the reference electrode over the proximal interphalangeal joint of the second digit, and stimulating the median and ulnar nerves at the wrist, respectively (Figure 17–10). The motor point to the 2L is

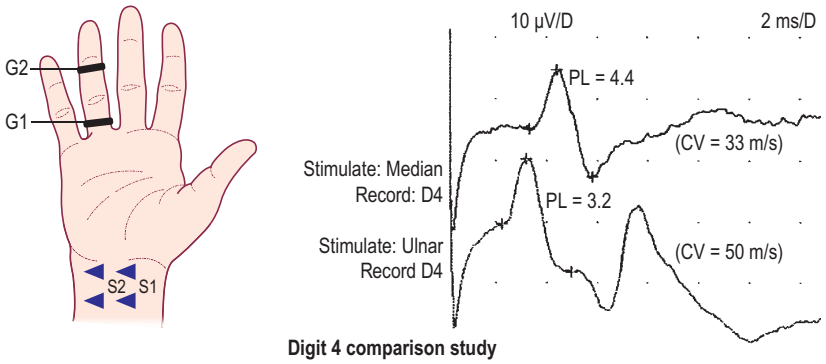

FIGURE 17–9 Digit 4 comparison study. In this study, the median sensory latency recording digit 4 is compared to the ulnar sensory latency recording digit 4, using identical distances between stimulation and recording sites. **Left:** G1, active recording electrode; G2, reference recording electrode; S1, median stimulation point; S2, ulnar stimulation point. This study takes advantage of the anatomic fact that digit 4 has a split innervation, half median and half ulnar, in most individuals. In normals, there is no significant difference between the two latencies. **Right:** In carpal tunnel syndrome, the median sensory peak latency (PL) is prolonged both in an absolute sense (>3.5 ms) and in comparison to the ulnar sensory peak latency (≥0.5 ms difference).

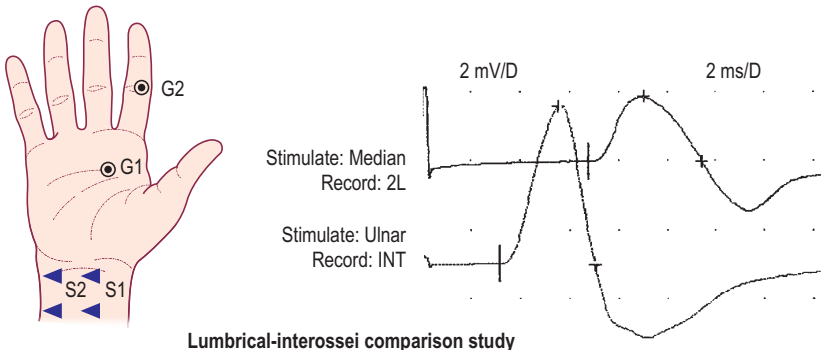

FIGURE 17–10 Lumbrical–interossei comparison study. In this study, the median motor latency recording the second lumbrical is compared to the ulnar motor latency recording the interossei, using identical distances between stimulation and recording sites. **Left:** G1, active recording electrode; G2, reference recording electrode; S1, median stimulation point; S2, ulnar stimulation point. This study takes advantage of the anatomic fact that the second lumbrical (median innervated) lies on top on the first palmar interosseous (ulnar innervated). In normals, there is no significant difference between the two latencies. **Right:** In carpal tunnel syndrome, the median motor latency is prolonged compared to the ulnar motor latency. In this case, the latency difference is about 2 ms. Any difference ≥0.5 ms is considered abnormal. The lumbrical compound muscle action potential usually has a different morphology and lower amplitude than the interossei in both patients and controls.

identified when the active recording electrode has been placed such that stimulation of the median nerve at the wrist elicits a waveform with the fastest rise time and an initial negative deflection. Because the 2L cannot be seen or palpated, moving the active electrode slightly may be necessary to ensure the electrode is optimally placed. In some individuals, if the sensitivity is increased, a small mixed nerve potential will be seen slightly before the onset of the 2L CMAP. This is a normal finding, especially in younger patients. If this small mixed nerve potential is present, the latency should be measured from the onset of the 2L CMAP, not from the onset of the mixed nerve potential. The ulnar nerve then is stimulated supramaximally at the wrist, at the same distance, *leaving the recording electrodes in place*. A CMAP from the underlying ulnar INT muscles will be easily elicited. The ulnar CMAP is generally larger than the median CMAP. Identical distances (range 8–10 cm) must be used to compare the difference between the distal latencies.

The normal values for the three median-versus-ulnar comparison studies are given in Table 17–3. In our laboratory, the palmar mixed nerve peak latency difference is the most sensitive study, followed closely by the digit 4 sensory and 2L-INT motor studies. However, there is a very high degree of correlation among the results of the three studies. In one comparison study, two of the three studies yielded abnormal results in 97% of all patients with mild CTS. In a patient in whom only one of the median-versus-ulnar comparison studies is abnormal, one should be hesitant to make a definite electrodiagnosis of CTS (see Chapter 9).

Other Useful Studies

Inching across the Wrist and Palmar Stimulation

Another technique useful in demonstrating CTS, first described by Kimura and later by others, involves segmental stimulation ("inching") of the median nerve across the carpal tunnel (Figure 17–11). One looks for an abrupt change in latency or increase in amplitude above normal control values, recording either a median CMAP at the APB or a median digital SNAP at the index or middle finger.

Kimura's method begins at 4 cm proximal to the distal wrist crease and continues to 6 cm distal to the wrist crease, with segmental stimulation at 1 cm increments. For each 1 cm increment, latency usually increases 0.2 to 0.3 ms.

Table 17–3. Median–Ulnar Comparison Studies

Study	Nerve	Stimulate	Record	Distance (cm)	Significant Difference (ms)
Palmar mixed	Median	Median palm	Median nerve at wrist	8	≥0.4
	Ulnar	Ulnar palm	Ulnar nerve at wrist	8	
Digit 4 Sensory	Median	Median nerve at wrist	Digit 4	11–13*	≥0.5
	Ulnar	Ulnar nerve at wrist	Digit 4	11–13	
Lumbrical – interossei	Median	Median nerve at wrist	Lateral to the mid third metacarpal (over the second lumbrical and interossei)	8–10*	≥0.5
	Ulnar	Ulnar nerve at wrist	Lateral to the mid third metacarpal (over the second lumbrical and interossei)	8–10	

*Must use the identical distance for median and ulnar nerve stimulation.

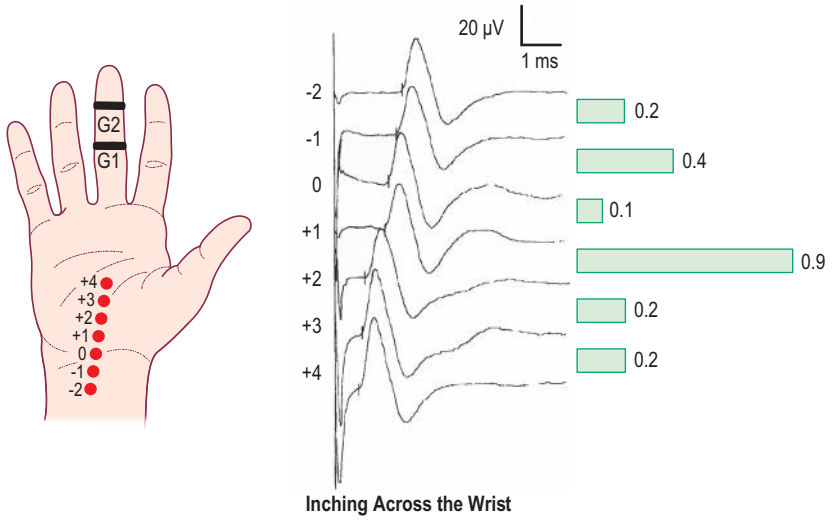

FIGURE 17–11 Inching across the wrist. **Left:** Stimulating the median nerve at 1 cm increments from 2 cm proximal to the wrist crease to 4 cm distal into the wrist crease, recording the digit 3 sensory nerve action potential. **Right:** Actual waveforms and relative change in latency between stimulation points is plotted. Note the abrupt change in latency of the sensory nerve action potential between +1 and +2 cm distal to the wrist crease, signifying the area of focal slowing.

Any abrupt change in latency is highly suggestive of focal demyelination. Although the inching technique has the advantage of showing the exact site of the lesion, its effectiveness often is limited by difficulty stimulating the nerve at the sites just distal to the wrist crease. The technique is particularly difficult to perform recording the median CMAP because stimulation of motor fibers at 1 cm increments following the course of the recurrent thenar branch of the median nerve can be quite difficult. Furthermore, stimulation in the palm often requires rotation of the anode to prevent excessive stimulus artifact (Figure 17–12).

Rather than measuring a change in latency, comparing the CMAP or SNAP *amplitudes* stimulating at the wrist and palm can be technically easier and can yield additional information about the underlying pathophysiology (Figure 17–13). Wrist and palmar stimulation can be performed for either median motor or sensory studies. Only single palm and wrist stimulations are required, whereas inching requires stimulation at multiple 1 cm increments. Several technical factors must be taken into account. First, as noted earlier for motor studies, the anatomy of the recurrent thenar motor branch is such that for stimulating the motor branch in the palm, the stimulator often must be placed beyond the thenar eminence with the anode rotated distally to prevent excessive stimulus artifact (Figure 17–12). Second, the examiner must be aware of normal values when comparing amplitudes proximal and distal to the carpal tunnel. There is always some drop in amplitude proximally compared with distally due to greater temporal dispersion and phase cancellation with proximal stimulation. The effects of normal temporal dispersion and phase cancellation are always greater for sensory fibers than for motor fibers. In normal median nerves, the ratio of the distal to proximal CMAP amplitude does not exceed 1.2, whereas the distal to proximal SNAP amplitude ratio does not exceed 1.6. Larger ratios suggest some element of conduction block (Figure 17–14). This assumption presumes that both stimulations are supramaximal, that there is no co-stimulation of adjacent nerves, and that the baseline is not obscured by shock artifact or noise that precludes an accurate amplitude measurement.

In CTS, if wrist stimulation yields a low CMAP or SNAP amplitude, there are two possible explanations: (1) there is conduction block secondary to demyelination across the

carpal tunnel with the underlying axon intact, or (2) there has been secondary axonal loss (Figure 17–15). Comparison of the amplitudes obtained with wrist and palmar stimulation can easily sort out these two possibilities. Take the following example:

	Case A	Case B
CMAP (stimulate wrist, record APB)	2 mV	2 mV
CMAP (stimulate palm, record APB)	6 mV	2 mV

In both cases, when the median nerve is stimulated at the wrist, the recorded CMAP is low (normal value >4.0 mV). When the palm is stimulated in case A, however, the CMAP amplitude increases by 200%; the distal to proximal ratio is 3.0, signifying conduction block. In contrast, there is no change in amplitude in case B, signifying that the low amplitude is secondary to axonal loss.

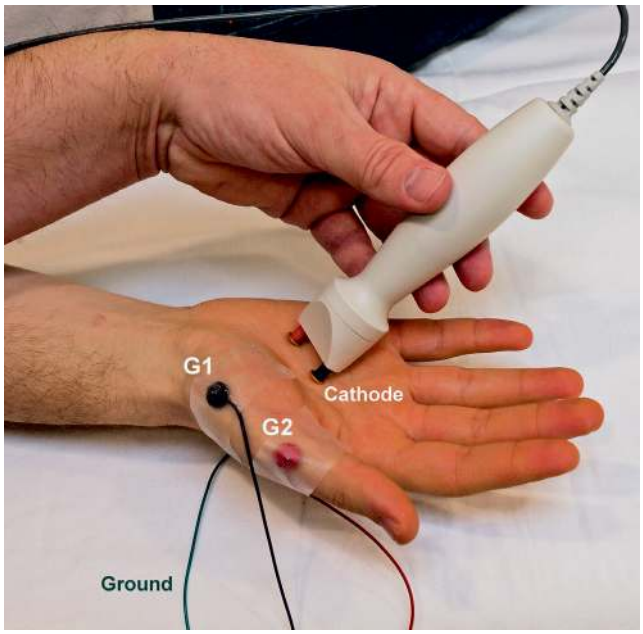

FIGURE 17–12 Stimulating the recurrent thenar motor branch in the palm. Stimulating the median nerve in the palm often is technically difficult. In many instances, the anode of the stimulator must be rotated to reduce stimulus artifact.

Median-versus-Radial Digit 1 Sensory Latencies

Comparison of the median-versus-radial digit 1 sensory latencies takes advantage of the fact that, in most individuals, digit 1 (the thumb) is innervated by both the median and radial nerves (Figure 17–16). The basic concept is the same as in the median-versus-ulnar digit 4 sensory study: the median and radial nerves are stimulated at the wrist, using identical distances, with recording ring electrodes over digit 1 (G1 over the metacarpophalangeal joint and G2 over the interphalangeal joint). The radial nerve is stimulated at the wrist along the lateral border of the radial bone. Using the same distance, the median nerve is stimulated at the wrist in the usual location. Supramaximal responses are obtained at each stimulation site, and the onset or peak latencies are compared. Although this technique is popular in some laboratories, stimulating the nerves at identical distances may be difficult because the median nerve travels to the thumb at an angle, which can hinder measurement of its true distance. Any difference between the median and radial latencies greater than or equal to 0.5 ms is considered abnormal.

Wrist-to-Palm versus Palm-to-Digit Sensory Conduction Velocity (Segmental Sensory Conduction Studies across the Wrist)

This technique compares the sensory conduction velocity along the median nerve at two segments of identical distance: the wrist-to-palm segment and the palm-to-digit segment. Digit 3 is the preferred finger to record from due to its longer length. The recording electrodes (G1, G2) are placed at the proximal and the distal interphalangeal joints, respectively. The median nerve is then stimulated at the wrist at a fixed distance to G1. The median nerve then is stimulated at the palm, with the recording ring electrodes left in place, at half the wrist-to-digit distance (Figure 17–17). Although any distances could be used for this study, making the palm-to-digit distance half that of the wrist-to-digit distance greatly simplifies the mathematical

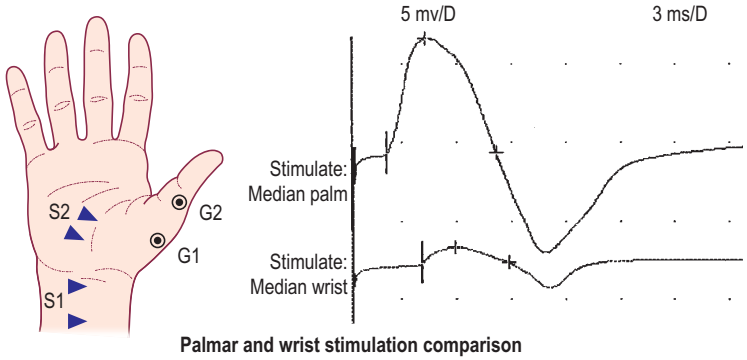

FIGURE 17–13 Palmar and wrist stimulation comparison. The median nerve is stimulated at the wrist and palm while recording the abductor pollicis brevis muscle. **Left:** G1, active recording electrode; G2, reference recording electrode; S1, stimulation at the wrist; S2, stimulation in the palm. **Right:** A significantly larger amplitude stimulating in the palm compared to the wrist signifies conduction block (i.e., demyelination) across the wrist.

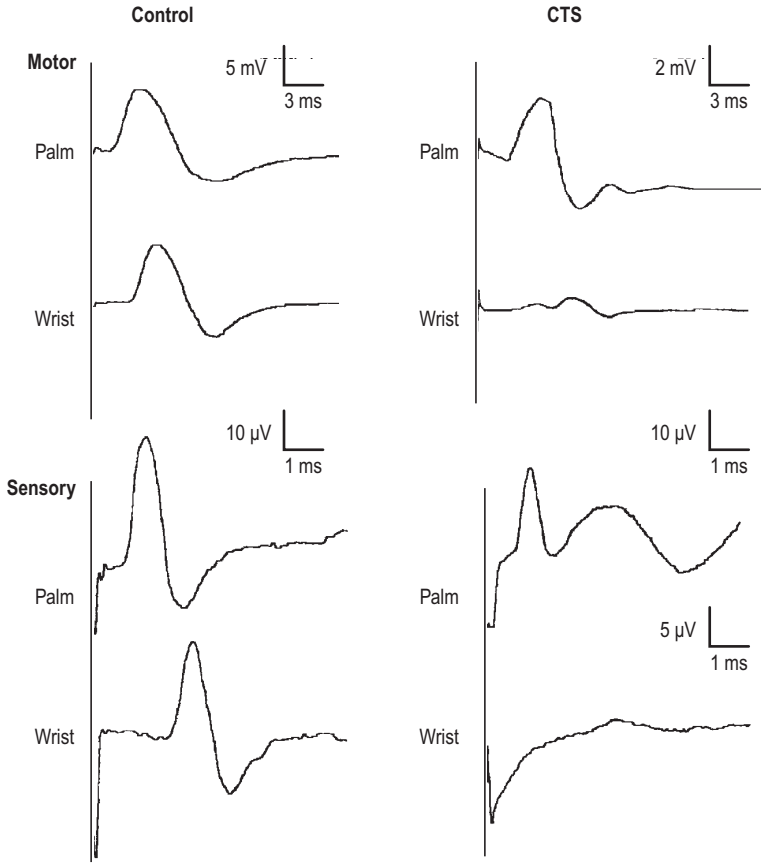

FIGURE 17–14 Change in compound muscle action potential (CMAP) and sensory nerve action potential (SNAP) amplitude across the carpal tunnel. To assess possible conduction block across the carpal tunnel, either the median CMAP or SNAP can be recorded with stimulation of the wrist and palm. Note that in normal controls, there is only a slight increase in amplitude between wrist and palm stimulation sites. A large difference in amplitude between wrist and palm sites in patients with carpal tunnel syndrome signifies conduction block. For motor studies, a normal palm to wrist amplitude ratio is ≤1.2 and for sensory studies it is ≤1.6.
(Adapted with permission from Lesser, E.A., Venkatesh, S., Preston, D.C., et al., 1995. Stimulation distal to the lesion in patients with carpal tunnel syndrome. Muscle Nerve 18, 503.)

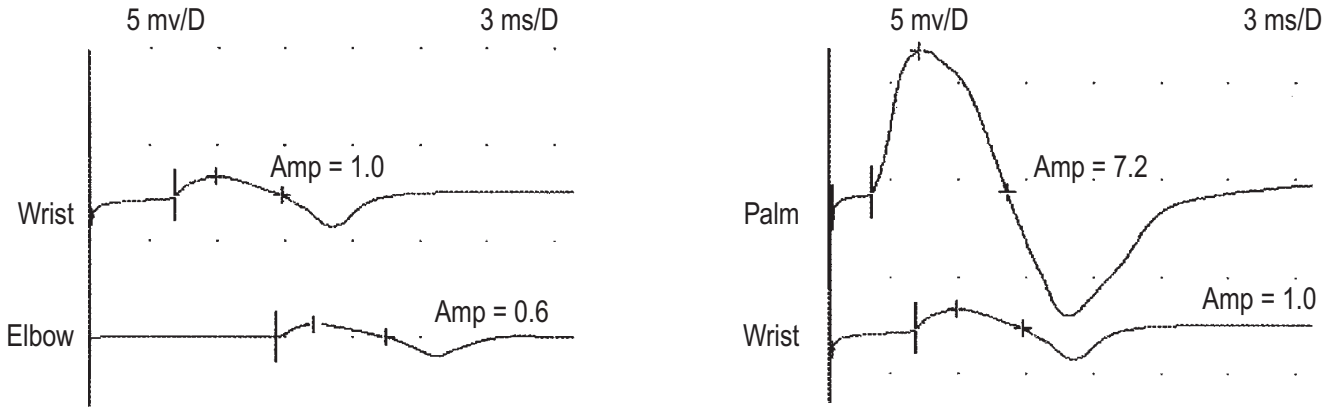

FIGURE 17–15 Distal conduction block mimicking axonal loss. Low distal amplitudes usually are attributed to axonal loss. However, if conduction block is present distal to the typical distal stimulation site, it can mimic the pattern of axonal loss. Such is often the case in carpal tunnel syndrome (CTS), where the lesion is distal to the usual distal stimulation site. **Left:** Median motor study, stimulating the wrist and antecubital fossa. Note that this appears to be a typical axonal loss pattern. **Right:** Median motor study, stimulating the palm and wrist. In this patient with CTS, a markedly higher-amplitude CMAP is evoked stimulating the palm, signifying conduction block. The identification of conduction block not only localizes the lesion, but it also denotes a much better prognosis than axonal loss. The clinical clue to the presence of conduction block in a patient with CTS is a weak thumb abduction and relatively intact muscle bulk (i.e., no atrophy) of the abductor pollicis brevis muscle, with a low median CMAP stimulating at the wrist.

equation. The wrist-to-palm conduction velocity is then computed by multiplying the palm-to-digit conduction velocity by the wrist-to-digit conduction velocity, and then dividing it by the quantity of the palm-to-digit conduction velocity times two minus the wrist-to-digit conduction velocity (Figure 17–18). In normal subjects, the wrist-to-palm segment (i.e., the segment across the carpal tunnel) is equal to or faster than the distal segment (palm-to-digit) because proximal nerve normally conducts faster than distal segments, secondary to larger nerve diameter and warmer temperatures. In CTS, there is a reversal of this normal pattern; the proximal segment (wrist-to-palm)

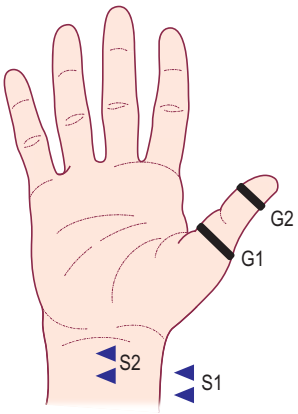

FIGURE 17–16 Median-radial sensory comparison study. In most individuals, the thumb is innervated by both the superficial radial and median sensory nerves. Using identical distances, the median and radial sensory latencies to the thumb can be compared in patients with suspected carpal tunnel syndrome, looking for preferential slowing of the median sensory fibers. G1, active recording electrode; G2, reference recording electrode; S1, radial stimulation point; S2, median stimulation point. Any difference between the median and radial latencies ≥0.5 ms is considered abnormal.

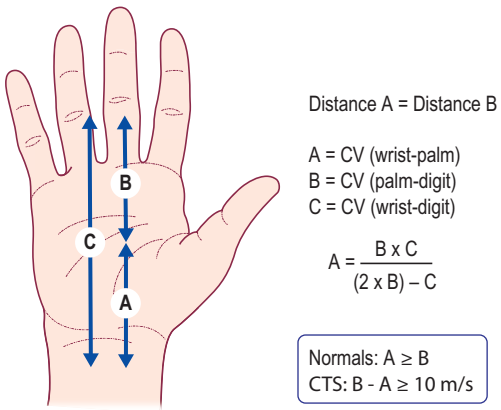

FIGURE 17–18 Calculation of the wrist-to-palm velocity in segmental sensory studies. There is no direct way to stimulate the median cutaneous sensory fibers at the wrist and record them at the palm. The wrist-to-palm conduction velocity (CV) can be calculated from knowledge of the wrist-to-digit and palm-to-digit CVs, both of which can be directly measured. If the palm-to-digit distance is half the wrist-to-digit distance, the calculation is simplified. In normal nerves, one expects the proximal segments to conduct at the same velocity or faster than the distal segments, due to larger nerve diameters and warmer temperatures (see Chapter 8). In carpal tunnel syndrome, there is a reversal of this pattern: the wrist-to-palm CV (across the carpal tunnel) is slower than the palm-to-digit CV. Any slowing ≥10 m/s is considered abnormal.

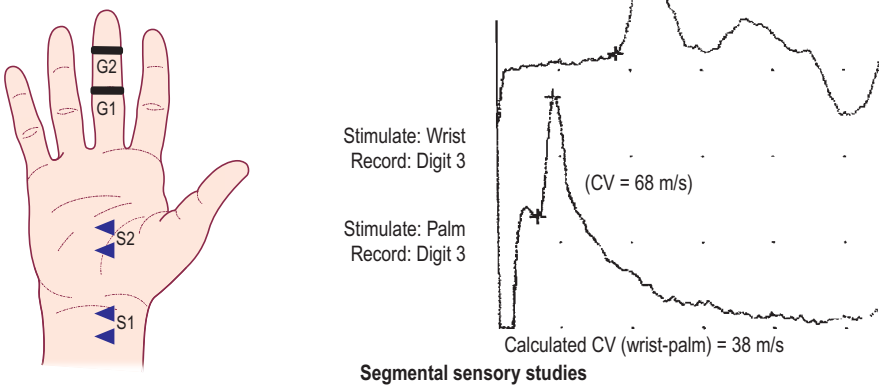

FIGURE 17–17 Segmental sensory conduction studies across the wrist. Using this technique, sensory conduction velocities (CVs) can be obtained for the wrist-to-digit and palm-to-digit segments, and then the wrist-to-palm CV can be calculated (see Figure 17–18). **Left:** The median nerve is stimulated at the wrist at a fixed distance and at the palm at half that distance, recording the median sensory nerve action potential with ring electrodes over digit 3. G1, active recording electrode; G2, reference recording electrode; S1, median stimulation point at the wrist; S2, median stimulation point in the palm. Placing the recording electrodes more distally on the finger helps reduce stimulus artifact when stimulating in the palm. **Right:** In patients with carpal tunnel syndrome, the calculated CV from wrist to palm (38 m/s) is slower than the CV from palm to digit (68 m/s).

conducts more slowly than the distal palm-to-digit segment. In general, any slowing of more than 10 m/s is considered abnormal.

Median-versus-Ulnar Minimum F Wave Latencies

This technique compares the minimum F wave latency stimulating the median and ulnar nerves at the wrist, recording the APB and abductor digiti minimi muscles, respectively. In normal individuals, the minimum F wave latency from the median nerve is approximately 1 to 2 ms shorter than the minimum F wave latency from the ulnar nerve. A reversal of this pattern is considered abnormal (Figure 17–19). This test is nonspecific, however, because the F wave measures conduction along the entire length of nerve, from the recording electrode to the spinal cord. Although this study can confirm a problem with the median nerve, it cannot localize the lesion to the wrist. It is generally used only as confirmatory evidence for a diagnosis of CTS, in conjunction with abnormalities noted using more sensitive techniques.

Electromyographic Approach

The recommended EMG approach to a patient with CTS is outlined in Box 17–3. The EMG strategy is designed with the clinical differential diagnosis in mind (i.e., proximal median neuropathy, brachial plexopathy, C6–C7 radiculopathy). The key muscle to check is the APB. In mild or early cases of CTS, the APB often is normal. In later or more severe cases, EMG may reveal secondary axonal loss resulting in denervation and reinnervation. In general, the hand muscles are best approached with a smaller-gauge needle. Because examination of the APB often is painful for patients to tolerate, it is best to begin the study with a different C8–T1 innervated muscle, such as the first dorsal interosseous (FDI). The APB can be examined next. Although some electromyographers may prefer to study the APB toward the end of the examination, there is the potential problem that the patient may quit the study before this key muscle can be studied, especially if the patient is generally intolerant of the EMG examination.

If the APB is abnormal, proximal median muscles and at least two other non-median C8–T1/lower trunk-innervated muscles should be sampled. In addition, C6–C7-innervated muscles should be sampled to exclude a cervical radiculopathy. The PT and FCR are very helpful muscles to sample because they can be used both as proximal median and C6–C7-innervated muscles. Some electromyographers have difficulty with the notion that the C6–C7-innervated muscles are important to sample, because the distal median hand muscles are innervated by the C8–T1 roots. One must remember that the distribution of numbness (not the weakness) in CTS may be very similar to the numbness noted in C6–C7 radiculopathies. Of course, because each case is different, the electromyographer must always be willing to modify each study throughout the testing, based on abnormalities noted as the study progresses.

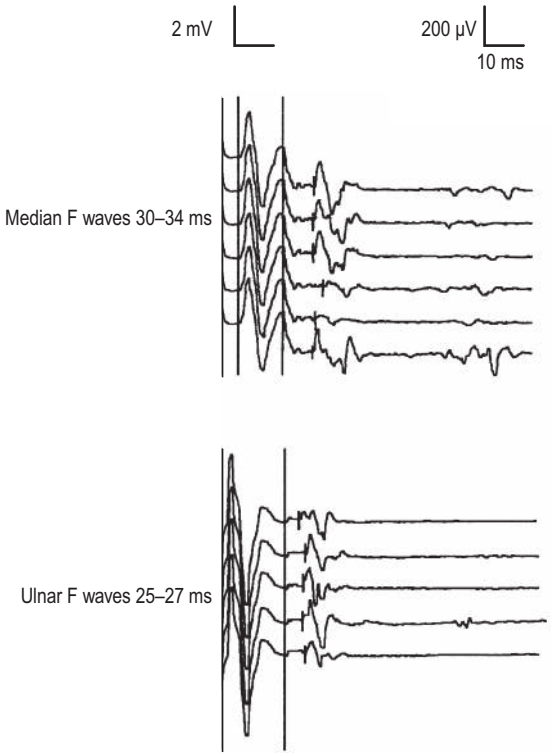

FIGURE 17–19 Inverted F waves in carpal tunnel syndrome. In normal subjects, the minimum F wave latency of the median nerve is approximately 1 to 2 ms shorter than that of the ulnar nerve. In carpal tunnel syndrome, the median F waves often are prolonged compared with the ulnar F waves, providing a useful measure to confirm median neuropathy.

Box 17–3. Recommended Electromyographic Protocol for Carpal Tunnel Syndrome

1. Abductor pollicis brevis (APB)
2. At least two C6–C7-innervated muscles (e.g., pronator teres, flexor carpi radialis, triceps brachii, extensor digitorum communis) to exclude a cervical radiculopathy

If APB is abnormal, the following additional muscles should be sampled:

1. At least one proximal median-innervated muscle (e.g., flexor carpi radialis, pronator teres, flexor pollicis longus) to exclude a proximal median neuropathy (note: the pronator teres may be spared in pronator syndrome)
2. At least two other non-median, lower trunk/C8–T1-innervated muscles (e.g., first dorsal interosseous, extensor indicis proprius) to exclude a lower trunk brachial plexopathy, polyneuropathy, or C8–T1 radiculopathy

Note: If the carpal tunnel syndrome is superimposed on another condition (e.g., polyneuropathy, plexopathy, radiculopathy), a more detailed electromyographic examination will be required.

The APB study frequently is painful and difficult for some patients to tolerate. It is best not studied first, but also best not left for the end of the electromyographic study in case the patient is unable to tolerate the entire examination.

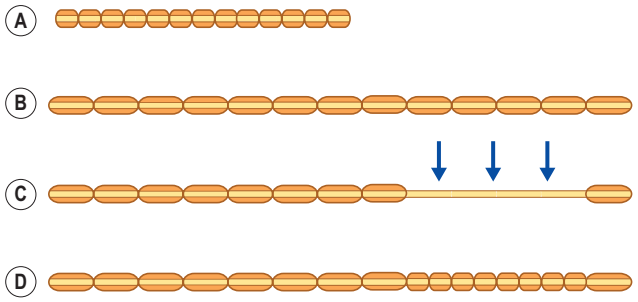

FIGURE 17–20 Persistent "slowing" following demyelination and remyelination. **A:** The process of myelination occurs at approximately age three. **B:** Between childhood and adulthood, the limb grows in length; however, the number of internodes does not change. **C:** Demyelination occurs at the site of compression (blue arrows). **D:** After the compression is successfully released, remyelination occurs. However, the new internodes are short, the same distance apart they were originally laid down as a child. Therefore more nodes are required to remyelinate the original site of compression. The greater the number of nodes of Ranvier, the more depolarizations, and hence the longer total time of depolarization. Thus, conduction velocity across the remyelinated area of compression will be slower than normal, because of the increase in number of nodes.

Special Situation: EDX Studies after Carpal Tunnel Release

It is not uncommon for a patient who has previously undergone carpal tunnel release surgery to be referred for EDX studies. The patient will either have recently undergone surgery with no clinical improvement, or will have developed recurrent symptoms a long period of time after successful carpal tunnel decompression. In some cases, the patient will not have had a pre-operative EDX study to confirm the diagnosis of CTS, which further complicates the issue. Thus, every electromyographer should be aware of what happens to nerve conduction study abnormalities after successful carpal tunnel release surgery. In general, the distal latencies and amplitudes improve both for median motor and sensory studies. However, this may take many weeks to months, and in some studies, improvement continues up to a year after surgery. However, some slowing may persist indefinitely. In the authors' experience:

1. Median distal motor latencies improve and usually return to the "normal" range. Never do distal latencies remain in the demyelinating range (i.e., >130% the upper limit of normal) after successful carpal tunnel release.
2. Median sensory latencies improve and usually return to the "normal" range. Never do conduction velocities remain in the demyelinating range (i.e., <75% the lower limit of normal) after successful carpal tunnel release.
3. Median motor amplitudes improve and return to the normal range.
4. Median sensory amplitudes may or may not improve. Many remain in a slightly reduced or borderline normal range.
5. The sensitive internal comparison studies (i.e., palmar mixed studies, digit 4 study, digit 1 study, lumbrical–interosseous study, and segmental sensory study) remain abnormal indefinitely, showing some slowing of median conduction across the carpal tunnel.

Although these findings are seen most often after carpal tunnel release surgery, similar findings are seen for other entrapments. This begs the question: after successful release surgery, why do the median conductions not return completely back to normal? The answer involves knowledge of normal myelination, demyelination, and then remyelination (Figure 17–20). As noted in Chapter 2, the process of myelination begins in utero, and full myelination of peripheral nerves does not occur until approximately age 3. Thus, by age 3, all the myelin and all the internodes have been laid down (Figure 17–20A). However, between childhood and adulthood, while the limb grows in length, resulting in longer internodes, the number of internodes does not change (Figure 17–20B). In entrapment neuropathies, such as carpal tunnel syndrome, demyelination occurs at the site of compression, resulting in interruption of the internodes at the site of compression (Figure 17–20C). When the compression is successfully released, remyelination can then occur. However, the new internodes are short, the same distance apart that they were when originally laid down as a child (Figure 17–20D). Therefore more nodes are required to remyelinate the original site of compression. When remyelination is completed, nerve impulses can once again travel successfully up and down the nerve. However, remember that the time of conduction (and hence conduction velocity) is completely dependent on the depolarization time at the nodes of Ranvier. The greater the number of nodes of Ranvier, the more depolarizations, and hence the longer total time of depolarization. Thus, conduction velocity across the remyelinated area of compression will be slower than normal, because of the increase in number of nodes. In any situation where there has been demyelination and then remyelination, sensitive techniques will always demonstrate a slightly slower conduction time across the remyelinated segment. Accordingly, one must always be cautious when interpreting any mild "slowing" on nerve conduction studies in patients who have undergone carpal tunnel release.

EXAMPLE CASES

Case 17–1

History and Examination

A 67-year-old woman was referred for clumsiness, tingling, and pain in both hands of several months' duration. Symptoms were most prominent at night, often awakening her from sleep, or during hand use such as driving. Examination showed slight wasting of both thenar eminences. Reflexes were normal. Thumb abduction was weak bilaterally. Sensation was slightly reduced over the finger pads of the thumb, index, middle, and ring fingers. There was no Tinel's sign at the wrist on either side. A Phalen's maneuver elicited tingling in the middle finger bilaterally after 30 seconds.

Summary

The history of pain and paresthesias in both hands, which was worse at night and provoked by driving, is characteristic of CTS. In addition, the examination suggests median neuropathy. Weak thumb abduction suggests dysfunction of the APB, a distally innervated median muscle. Sensation is reduced over the median-innervated digits. Although a Tinel's sign is not present at the wrist, a Phalen's maneuver causes paresthesias in the third digit. A Phalen's maneuver is thought to reproduce the situation that occurs at night when the patient is asleep and the wrist commonly assumes a flexed posture. Note that nothing in the physical examination or history suggests a radiculopathy (i.e., there is no neck pain or weakness in the C6 or C7 muscles, and the reflexes are normal). One would assume that there is a high likelihood of bilateral CTS in this patient even before proceeding to the nerve conduction and EMG studies.

Both the nerve conduction studies and EMG findings are abnormal. The median motor study on the right shows a low CMAP amplitude with a markedly prolonged distal motor latency, moderately slow conduction velocity in the forearm, and absent F responses. The left median nerve also is abnormal but not as severely as the right, with a normal CMAP amplitude, moderately prolonged distal motor latency, borderline slow conduction velocity in the forearm, and prolonged F responses. The ulnar motor study is completely normal, an important finding that indicates that the median motor abnormalities are not secondary to a more widespread polyneuropathy. The sensory studies demonstrate a similar pattern of abnormalities. The median sensory response to digit 2 is absent on the right but present on the left, with a low-amplitude, prolonged peak latency, and a correspondingly markedly slow conduction velocity. The right ulnar sensory response is completely normal. Because the median mixed potential is absent on the right, the ulnar mixed nerve study is not performed on that side; there would be nothing to compare it with. The median mixed nerve study on the left demonstrates a markedly prolonged peak latency. Furthermore, not only is the median mixed latency on the left markedly prolonged (3.8 ms) in an absolute sense, but it is clearly prolonged out of proportion to the ulnar mixed peak latency (1.7 ms), which is normal.

After completion of the nerve conduction studies, one can be fairly certain of the diagnosis of bilateral median neuropathy at the wrist, affecting both motor and sensory fibers. The localization of the lesion at the wrist, rather than more proximally, is determined by the markedly prolonged latencies with wrist stimulation. These markedly prolonged latencies signify demyelination across the wrist. There is no suggestion of a superimposed

CASE 17–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F-Wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	3.4	8.6	≥4	10.9	6.4	≤4.4				NR	33	≤31
	Antecubital fossa	APB	3.0	8.4		15.8	10.6		41	49	≥49			
Ulnar (m)	Wrist	ADM	11.2		≥6	3.0		≤3.3				25		≤32
	Below elbow	ADM	11.2			6.3			60		≥49			
	Above elbow	ADM	11.1			8.0			61		≥49			
Median (s)	Wrist	Index finger	NR	8	≥20	NR	4.9	≤3.5	NR	32	≥50			
Ulnar (s)	Wrist	Little finger	24		≥17	2.9		≤3.1	62		≥50			
Median (mixed study)	Palm	Wrist	NR	8	≥50	NR	3.8	≤2.2	NR	27	≥50			
Ulnar (mixed study)	Palm	Wrist		16	≥15		1.7	≤2.2		61	≥50			
Mixed difference							1.1	≤0.3						

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; APB = abductor pollicis brevis; ADM = abductor digiti minimi.
Note: All sensory and mixed latencies are peak latencies. All sensory and mixed-nerve conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 17–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculation Potentials	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right APB	↑	+1	0	NL	↓↓	+2	+2	+2
Right FDI	NL	0	0	NL	NL	NL	NL	NL
Right PT	NL	0	0	NL	NL	NL	NL	NL
Right triceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right FCR	NL	0	0	NL	NL	NL	NL	NL
Right C8 paraspinal muscles	NL	0	0	NL	NL	NL	NL	NL
Left APB	NL	0	0	NL	NL	NL	NL	NL

NL = normal; ↑ = increased; ↓↓ = moderately reduced; APB = abductor pollicis brevis; FDI = first dorsal interosseous; PT = pronator teres; FCR = flexor carpi radialis.

polyneuropathy because the ulnar motor, sensory, and F wave studies are completely normal.

The EMG study shows increased insertional activity and fibrillation potentials in the right APB, with decreased recruitment of long, large, polyphasic motor unit action potentials. Because the APB is abnormal on the right, the FDI and C8 paraspinal muscles are sampled to rule out the possibility of a coexistent C8–T1 radiculopathy. Note that if the clinical examination or history strongly suggests the possibility of a superimposed C8–T1 radiculopathy (e.g., weakness of other intrinsic hand muscles or pain radiating from the neck to the medial forearm), further sampling of other C8–T1-innervated muscles should be done. In addition, because the APB is abnormal, proximal median muscles (PT, FCR) must be sampled to ensure that the abnormalities seen in the APB are not secondary to a high median neuropathy. Sampling the PT muscle alone may not be sufficient because that muscle may be spared in the pronator syndrome, wherein compression of the median nerve occurs after the takeoff to the branch to the PT (see Chapter 18). Had there been a high clinical suspicion of a proximal median neuropathy, additional median-innervated proximal muscles should have been sampled.

Sampling both the PT and the FCR serves a dual purpose in that they are both proximal median and C6–C7-innervated muscles. The fact that they are normal makes the diagnosis of a superimposed C6–C7 radiculopathy, or brachial plexopathy, unlikely. The triceps brachii often is useful in this situation as well because it is very strongly innervated by C7 and typically is abnormal in C7 radiculopathy. Again, if the clinical examination or history suggests a superimposed C6–C7 radiculopathy (e.g., weakness of elbow or wrist extension, absent biceps or triceps reflex), more extensive sampling of muscles in those myotomes would have been warranted. Finally, because the symptoms are bilateral and the nerve conduction studies are abnormal bilaterally, the left APB is sampled to assess the severity of the median nerve lesion on that side. Because the APB is normal on the left and there is no clinical suspicion of a superimposed proximal median neuropathy, plexopathy, or radiculopathy, no further needle examination is needed on that side. At this point, an electrodiagnostic impression can be formed.

***IMPRESSION**: There is electrophysiologic evidence of bilateral, moderately severe (right more severe than left) median neuropathies at the wrist.*

Several questions deserve consideration.

Does the Clinical – Electromyographic Correlation Make Sense?

The answer in this case clearly is yes. The patient's history and physical examination are highly suggestive of CTS. There is nothing to suggest a superimposed radiculopathy, plexopathy, or polyneuropathy. Nerve conduction studies and EMG both confirm the clinical impression. All the electrodiagnostic abnormalities are limited to the median nerve. In addition, the markedly prolonged distal motor and sensory latencies are consistent with demyelination of the median nerve across the carpal tunnel. All findings are more severe on the right than on the left. This is the common situation in idiopathic CTS; the dominant hand is most affected. Any clearcut case of CTS in which the non-dominant hand is more severely affected should raise a red flag that there may be an unusual etiology, such as a mass lesion. In such a situation, one must go back to the clinical history and examination to look for unusual features (e.g., a palpable mass on examination). In some individuals, imaging studies of the wrist should be considered.

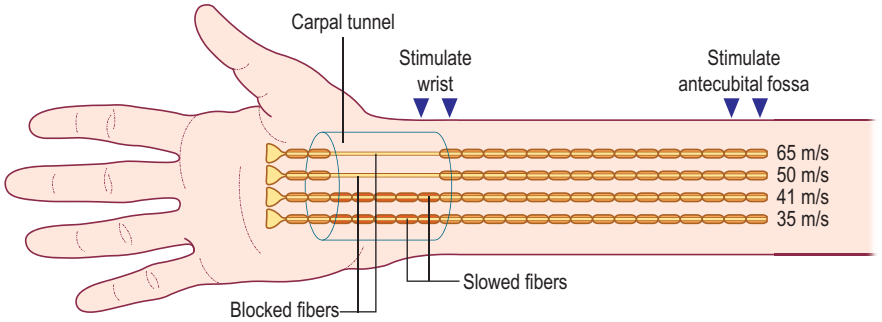

FIGURE 17–21 Slowing of forearm conduction velocity in carpal tunnel syndrome. The normal median nerve has fast-, medium-, and slow-conducting myelinated fibers. Normally, the distal latency and conduction velocity represent only the fastest fibers. In severe carpal tunnel syndrome, if the fastest fibers are blocked at the wrist or have undergone wallerian degeneration, they cannot be measured recording the median compound muscle action potential in the hand; only the normal, slower-conducting myelinated fibers can be measured, producing a spuriously low forearm conduction velocity.

Is the Lesion Demyelinating or Axonal?

In this case, there are both demyelinating and axonal features. Both distal motor latencies are markedly prolonged. The right distal motor latency (10.9 ms) is approximately 250% the upper limit of normal, and the left (6.4 ms) is approximately 145%. Any distal latency greater than approximately 130% the upper limit of normal cannot be attributed to axonal loss or dropout of the fastest fibers alone. These markedly prolonged distal latencies signify demyelination between the recording and stimulating sites (i.e., between the wrist and the APB muscle). Second, although the median sensory response is absent on the right, it is present on the left, with a demyelinating conduction velocity. The velocity of 32 m/s is less than 75% the lower limit of normal, which cannot be explained by the dropout of the fastest-conducting fibers. The lesion must be demyelinating. However, there also are axonal changes. Note that the CMAP amplitude on the right is slightly low (3.4 mV); this may be the result of either distal conduction block or axonal loss. On EMG, there are fibrillation potentials in the right APB along with long-duration, large-amplitude, polyphasic motor unit action potentials. These are EMG signs of denervation and reinnervation that signify active and chronic axonal loss. Therefore, one can say with confidence that on the right side the lesion is both demyelinating and axonal. On the left side, the EMG is normal. Thus, there is no definite evidence of axonal loss by EMG on that side.

The EMG abnormalities of denervation and reinnervation signify a more severe lesion. There is ongoing axonal loss occurring on the right side. Simple conservative treatment measures, such as a neutral wrist splint or steroid injection, likely would not be successful on the right side. This patient likely requires surgical decompression.

If the Lesion is at the Carpal Tunnel, Why is the Forearm Median Motor Conduction Velocity Slow?

The right median motor conduction velocity is slowed in the forearm segment (41 m/s). Because this value represents the speed of the median motor fibers in the forearm between the elbow and the wrist (i.e., proximal to the carpal tunnel), one might consider the possibility of an additional median nerve problem in the forearm segment. However, the finding of a slowed conduction velocity in the forearm segment is quite common in CTS, especially in severe cases. It may occur for two reasons. First, in cases of severe CTS with secondary axonal loss and wallerian degeneration, the wallerian degeneration may proceed proximally. If some of the fastest fibers are lost, then these fibers no longer contribute to the calculated conduction velocity. Second, forearm slowing may occur simply as a byproduct of the method by which the motor conduction velocity is computed (Figure 17–21). In severe CTS, demyelination may result in conduction block of the fastest and largest fibers, the fibers most prone to compression. Even though these fibers are present and their underlying axons intact, demyelination at the carpal tunnel may result in complete block. Because the blocked fibers cannot carry their impulses distally, they do not contribute to the median CMAP. As a result, the conduction velocity of these blocked fibers is not included in the calculated conduction velocity. The calculated conduction velocity will be slowed, based on the speed of the fastest of the remaining normal slower-conducting fibers. In theory, if the median motor fibers in the forearm could be selectively stimulated at the antecubital fossa and recorded at the wrist, before the conduction block at the carpal tunnel, the conduction velocity would be normal. Therefore, a slowed forearm median motor conduction velocity in a patient with severe CTS is not unusual and does not imply an additional proximal lesion.

If the Lesion is at the Carpal Tunnel, Why are the F Responses Absent or Prolonged?

In this case, both median F responses are abnormal (absent on the right, prolonged on the left), especially compared to the ulnar F responses, which typically are 1 to 2 ms longer than the median. One usually thinks of the F responses as checking the proximal nerve

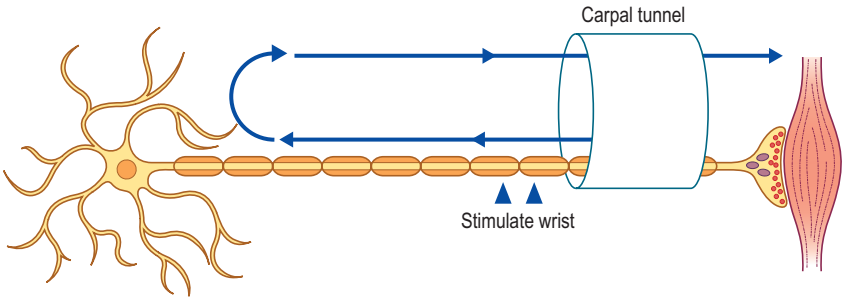

FIGURE 17–22 F wave slowing in carpal tunnel syndrome. The F wave travels antidromically to the anterior horn cell, back down to the point of stimulation, then distally through the carpal tunnel to the muscle. In the carpal tunnel, the F wave may be slowed or blocked. Prolonged or absent F waves are not unusual in carpal tunnel syndrome.

segments, and of prolonged or absent F responses as indicative of a proximal lesion. However, the F response travels the entire course of the axon. When the F response study is performed, the impulse follows a course initially up the nerve antidromically to the anterior horn cell, followed by retrograde travel down the motor nerve to the point of stimulation, and then past the point of stimulation to the distal nerve segment, across the neuromuscular junction, and into the muscle (Figure 17–22). The F response is actually a small motor response, representing approximately 5% of the motor fibers. Therefore, conduction slowing anywhere along the length of the F response circuitry will result in prolonged or absent F responses. In CTS, when the median F response is elicited stimulating at the wrist, the impulse travels antidromically up to the spinal cord and back down to the wrist and then through the carpal tunnel to the muscle, where it slows or is blocked. Prolonged or absent F responses are not unusual and should be expected in severe CTS.

Case 17–2

History and Examination

A 44-year-old woman who was diagnosed with rheumatoid arthritis 6 months previously was referred for a second opinion concerning right hand and wrist pain, paresthesias, and an abnormal cervical magnetic resonance imaging (MRI) scan. The symptoms had developed over the preceding 2 months and were associated with diffuse aching of the right arm. The patient stated that she would awaken from sleep one or two times nightly with pain and tingling in the hand. She would arise from bed and shake her right hand for several minutes or put it under running water. During the day, driving or holding a book, newspaper, or telephone would particularly exacerbate the symptoms. The symptoms slowly worsened over 2 months until nearly all activities caused pain, paresthesias, and considerable distress.

The patient initially had been referred to an outside hospital for an EMG and nerve conduction study, with a question of CTS. Bilateral median and ulnar motor, sensory, and F wave studies were normal. Needle EMG of both APB muscles was normal. The impression was that the study was normal, with no evidence of CTS.

In light of the continued symptoms and the normal nerve conduction and EMG studies, cervical radiculopathy was considered as an alternative diagnosis. A cervical MRI scan was reported to demonstrate an increased T2 signal in the center of the cervical spinal cord, consistent with a syrinx. The patient was referred for further evaluation and management of her syrinx and upper extremity symptoms.

On examination, mental state and cranial nerves were normal. Motor examination revealed normal bulk and strength testing throughout. Reflexes were normal and symmetric. Sensory examination demonstrated a patchy area of decreased light touch sensation over the finger pads of the index and middle fingers of the right hand. There was no Tinel's sign at the wrist. Phalen's maneuver after 60 seconds of wrist flexion caused paresthesias in the finger pads of the right middle finger.

Summary

In many ways, the clinical history in Case 17–2 is similar to that in Case 17–1. The history of pain and paresthesias, which awakened the patient from sleep and were exacerbated by driving or holding a book, is very characteristic of CTS. In addition, the patient has a history of rheumatoid arthritis, a condition commonly associated with CTS. Rheumatoid arthritis is associated with several other peripheral nerve disorders as well, including a distal symmetric sensorimotor polyneuropathy, a vasculitic neuropathy resulting in mononeuritis multiplex, and radiculopathies. In this case, there are no symptoms or signs suggesting any of those diagnoses.

The examination also suggests the possibility of CTS. There is a patchy decrease of light-touch sensation in the index and middle fingers (median-innervated digits). Although there is no Tinel's sign at the wrist, a Phalen's maneuver, which is more sensitive and specific for median neuropathy at the wrist, does cause paresthesias in a median-innervated digit.

Based on the history and physical examination, the suspicion of CTS should be strong. We then are confronted with the prior nerve conduction studies showing normal median and ulnar motor, sensory, and F responses, along with normal needle EMG findings of both APB muscles. This information was initially used to rule out the presence of CTS and unfortunately led to diagnostic confusion. Further investigations included a cervical MRI

CASE 17–2. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude motor = mV; sensory = μV			Latency (ms)			Conduction Velocity (m/s)			F Wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	6.2		≥4	4.2		≤4.4				29		≤31
	Antecubital fossa	APB	6.0			7.9			54		≥49			
Ulnar (m)	Wrist	ADM	9.0		≥6	2.9		≤3.3				28		≤32
	Below elbow	ADM	8.9			6.4			57		≥49			
Median (s)	Wrist	Index finger	24		≥20	3.4		≤3.5	56		≥50			
Ulnar (s)	Wrist	Little finger	22		≥17	2.9		≤3.1	62		≥50			
Median (mixed study)	Palm	Wrist	30		≥50	2.4		≤2.2	40		≥50			
Ulnar (mixed study)	Palm	Wrist	15		≥12	1.8		≤2.2	62		≥50			
Mixed difference						0.6		≤0.3						
Median (m)	Wrist	Second lumbrical	1.4		≥1.0	3.7								
Ulnar (m)	Wrist	Interosseous	4.5		≥2.5	2.9								
Lum – int difference						0.8		≤0.4						
Median (s)	Wrist	Ring finger	21		≥10	3.4			40		≥50			
Ulnar (s)	Wrist	Ring finger	23		≥10	2.8			50		≥50			
Digit 4 difference						0.6		≤0.4						

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis; ADM = abductor digiti minimi.

Note: All sensory and mixed latencies are peak latencies. All sensory and mixed-nerve conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 17–2. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right APB	NL	0	0	NL	NL	NL	NL	NL
Right FDI	NL	0	0	NL	NL	NL	NL	NL
Right triceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right FCR	NL	0	0	NL	NL	NL	NL	NL
Right PT	NL	0	0	NL	NL	NL	NL	NL

NL = normal; APB = abductor pollicis brevis; FDI = first dorsal interosseous; FCR = flexor carpi radialis; PT = pronator teres.

scan, which demonstrated an increased T2 signal in the center of the cervical spinal cord. With this new information, the patient's symptoms and signs were attributed to a syrinx.

At this point, what is the next logical step? When there is a discrepancy among the clinical history, examination, and electrophysiologic findings, one should always go back to the patient's history and physical examination. The history and physical examination clearly suggest CTS. There is nothing in the history or the examination to suggest a syrinx, despite the MRI scan result. A syrinx in the cervical cord usually is associated with a suspended, dissociated loss of pain and temperature sensation over the shoulders due to early involvement of the crossing spinothalamic fibers in the spinal cord, which lie adjacent to the central canal. In addition, there usually is asymmetric wasting and weakness of selected upper extremity muscles with reflex changes, depending on the spinal segments involved. Thus, what does one make of the initial nerve conduction and EMG studies? Despite the normal initial test results, the diagnosis of CTS should not be abandoned. There certainly is a group of patients with a history and examination very suggestive of CTS in whom the routine median motor and sensory conduction studies are normal. In this group, the more sensitive median-versus-ulnar comparison studies often are needed to make an electrodiagnosis of median neuropathy at the wrist.

Nerve conduction studies are repeated, which show normal routine median and ulnar motor and sensory

conduction studies, as were reported in the initial study. The F responses are normal in an absolute sense, although the right median F response is 1 ms longer than the ulnar F. When the three median-versus-ulnar comparison studies are performed, however, each is abnormal: (1) the median-versus-ulnar palm-to-wrist latency difference, 0.6 ms, is clearly above the upper range of normal; (2) the distal motor latencies to the median second lumbrical-versus-ulnar INT muscles at an identical distance reveal a latency difference of 0.8 ms, again clearly above the normal cutoff; and, finally, (3) the antidromic median and ulnar sensory responses recording the ring finger at identical distances reveal a peak latency difference of 0.6 ms, again above the upper limit of normal. The EMG study of the right upper extremity reveals no active denervation or reinnervation in the APB, the FDI, or in more proximal median- or C7-innervated muscles.

At this point, an electrodiagnostic impression can be formed.

IMPRESSION: *There is electrophysiologic evidence of a mild right median neuropathy at the wrist.*

What is one to make of the abnormal MRI scan showing a syrinx? In this case, a repeat MRI scan disclosed no evidence of a syrinx, and the abnormality on the original MRI scan was interpreted as an artifact from the magnetic coil.

Several questions should be considered.

Does the Clinical – Electromyographic Correlation Make Sense?

The answer clearly is yes in the case of the second set of studies performed on this patient. The patient's clinical history and physical examination were very suggestive of CTS, and she had a clear predisposing factor, rheumatoid arthritis. The important point here is that although the routine median motor and sensory conduction studies are normal, the more sensitive median-versus-ulnar comparison studies all are abnormal, demonstrating preferential median slowing across the wrist when compared with ulnar conduction across the wrist. In cases of mild CTS, abnormalities in these three comparison studies usually are closely correlated with one another. One should be hesitant to make any diagnosis based on a single abnormality. It is easy to imagine that one distance or latency measurement may be slightly in error; one would be remiss to make a diagnosis based on a single piece of abnormal data. In this case, all three median-versus-ulnar comparison studies are abnormal. Collaborating clinical evidence that supports an electrical diagnosis is always desirable.

The initial clinical–electromyographic correlation did not make sense: that of a patient with intermittent paresthesias of the second and third digits provoked by sleeping or driving, with no other neurologic signs, caused by a cervical syrinx, and with normal electrophysiologic results. This case reinforces the notion that CTS is a clinical diagnosis. Rarely, there will be a patient with clinical CTS in whom all electrodiagnostic tests are normal, even when the sensitive comparison studies are done (i.e., a false negative). In these patients, there is no demyelination or axonal loss; presumably, the symptoms are caused by intermittent compression resulting in transient ischemia. This case also reinforces the fact that incidental or erroneous test results with no clinical or electrophysiologic correlate, in this case the supposed "syrinx" seen in the cervical cord on the original MRI scan, should not take on undue meaning.

If this Patient has Carpal Tunnel Syndrome, Why are the Median Motor and Sensory Distal Latencies Normal?

This situation is not uncommon. Patient's results are commonly compared with population normal values. For example, in this patient, the distal median motor latency is 4.2 ms, which is within the normal range. However, the word range must be emphasized. There is a wide range of normal values. For instance, 1 year ago, before the onset of rheumatoid arthritis and CTS, the patient may well have had a distal median motor latency of 3.5 ms. When her distal motor latency increased from 3.5 to 4.2 ms, it became markedly prolonged in relationship to its own baseline normal. However, the value still falls within the "population normal range." It is in these cases that the median-versus-ulnar comparison studies are of greatest value because they rely on the patient's own nerves, rather than population normal values, as a control. Variables such as temperature, nerve length, size, age, and coexistent polyneuropathy all are controlled.

When the median motor and sensory latencies are normal in patients with CTS, the values often are near the upper limit of the normal range. Values near the upper limit of the normal range should be a clue that there may be an underlying abnormality. In the present case, the median distal motor latency of 4.2 ms is very close to the upper limit of normal (4.4 ms), and the median sensory peak latency of 3.4 ms is very close to the upper limit of normal (3.5 ms).

Should Electromyography and Nerve Conduction Studies be Used to Rule Out Carpal Tunnel Syndrome?

The answer is no. The value of EMG and nerve conduction studies lies in confirming the clinical impression, assessing the severity of the neuropathy, and looking for possible coexisting conditions. As already noted, patients with mild disease may have normal routine median motor and sensory studies, and rare patients will have completely normal studies, including the more sensitive median-versus-ulnar comparison studies. No laboratory test is 100% sensitive and 100% specific. CTS remains a clinical diagnosis. Once again, EDX tests can be interpreted properly only with knowledge of the clinical history and examination.

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18 Proximal Median Neuropathy

Proximal median neuropathy is distinctly uncommon compared with median entrapment at the carpal tunnel. Differentiating between median neuropathy at the wrist and more proximal entrapments can be difficult based on clinical grounds alone, especially in mild cases. Electrodiagnostic (EDX) testing plays a key role in localizing the lesion in these unusual cases, especially if the lesion results from trauma or compression.

DETAILED ANATOMY AT THE ANTECUBITAL FOSSA

As the median nerve descends in the upper arm, it runs medial to the humerus and anterior to the medial epicondyle. In a minority of individuals, a bony spur originates from the shaft of the medial humerus just cephalad to the medial epicondyle. A tendinous band known as the *ligament of Struthers* stretches between the spur and the medial humeral epicondyle. In the antecubital fossa, the median nerve travels adjacent to the brachial artery (Figure 18–1). As it enters the forearm, it runs first beneath the *lacertus fibrosus*, a thick fibrous band that runs from the medial aspect of the biceps tendon to the proximal forearm flexor musculature. In most individuals, the median nerve then runs between the two heads of the pronator teres (PT) muscle to provide innervation to that muscle. In many individuals, there are fibrous bands within the two heads of the PT muscle. The *anterior interosseous nerve* then is given off posteriorly, approximately 5 to 8 cm distal to the medial epicondyle, after the median nerve passes between the two heads of the PT. As the median nerve runs distally, it passes deep to the flexor digitorum sublimis (FDS) muscle and its proximal aponeurotic tendinous edge, known as the *sublimis bridge*.

ETIOLOGY

Median neuropathy in the region of the antecubital fossa has been described as a consequence of external compression from casting, trauma, venipuncture, and compressive mass lesions, including tumor or hematoma. Rare cases of brachial artery puncture and subsequent hematoma formation have led to compartment syndromes and subsequent injury of the proximal median nerve.

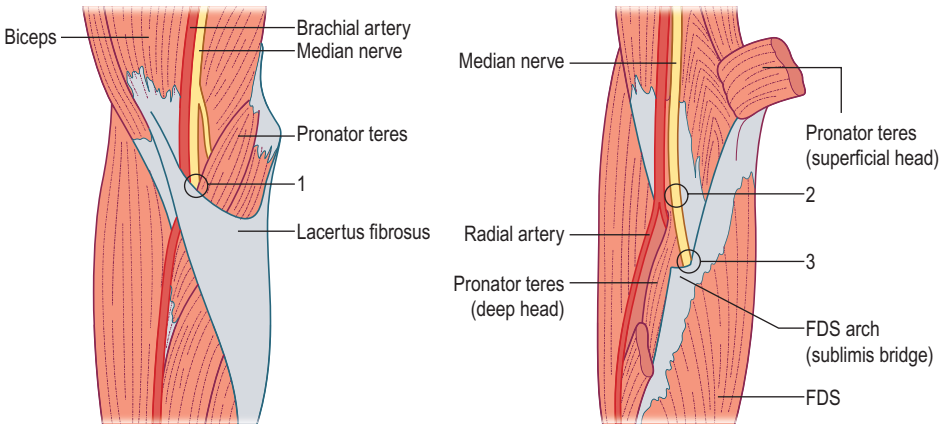

FIGURE 18–1 Median nerve anatomy in the region of the antecubital fossa, and potential sites of entrapment. **Left:** In the antecubital fossa, the median nerve travels adjacent to the brachial artery. As it enters the forearm, it runs first beneath the lacertus fibrosus, a thick fibrous band that runs from the medial aspect of the biceps tendon to the proximal forearm flexor musculature. In most individuals, the median nerve then runs between the two heads of the pronator teres. **Right:** Superficial head of the pronator teres sectioned to show the underlying median nerve. As the median nerve then runs distally, it passes deep to the flexor digitorum sublimis (FDS) muscle and its proximal aponeurotic tendinous edge, known as the sublimis bridge. The pronator syndrome refers to several potential sites of entrapment that occur in the region of the antecubital fossa: (1) lacertus fibrosus, (2) within the pronator teres muscle, and (3) the sublimis bridge. (Adapted with permission from Dang, A.C., Rodner, C.M., 2009. Unusual compression neuropathies of the forearm, part II: median nerve. J Hand Surgery (AM) 34 (10), 1915–1920.)

DOI: 10.1016/B978-1-4557-2672-1.00018-0

In addition, several sites of proximal median entrapment have been reported (Figure 18–1). All are uncommon, and some remain controversial. The four major potential sites of entrapment are as follows:

- Median nerve entrapment may occur at the ligament of Struthers in the distal upper arm, where both the median nerve and brachial artery pass between this ligament and the humerus.
- More distally in the region of the antecubital fossa, the median nerve may become entrapped beneath a hypertrophied lacertus fibrosus.
- Further distally, the median nerve may become entrapped in the substance of the PT muscle, especially in individuals who have additional fibrous bands running through that muscle.
- More distally, the median nerve may become entrapped beneath the sublimis bridge of the FDS muscle.

CLINICAL

The clinical syndromes of proximal median neuropathy depend on the underlying etiology and lesion site.

TRAUMATIC LESIONS

In patients with traumatic lesions, there usually is an obvious, acute disturbance of median motor and sensory function. Significantly, sensory disturbance in proximal median neuropathy is noted in the entire median territory, including the thenar eminence, as well as the thumb, index, middle, and lateral ring fingers. This feature clearly distinguishes proximal median neuropathy from carpal tunnel syndrome (CTS), in which sensation over the thenar eminence is spared. Sensory loss over the thenar eminence occurs as the palmar cutaneous branch, which innervates the thenar eminence, leaves the median nerve proximal to the carpal tunnel. Depending on the site of the lesion, weakness may affect some or all of the proximal median-innervated forearm muscles, including the PT, FDS, flexor digitorum profundus (FDP) to digits 2 and 3, flexor carpi radialis (FCR), flexor pollicis longus (FPL), and pronator quadratus (PQ), as well as the distal median-innervated muscles, including the abductor pollicis brevis (APB), opponens pollicis (OP), and first and second lumbricals. Weakness of the FDP to digits 2 and 3, FDS and FPL often leads to a characteristic high median neuropathy posture, whereby the individual is unable to flex the thumb, index, and middle fingers (Figure 18–2).

ENTRAPMENT SYNDROMES

The symptoms and signs in the proximal median nerve entrapment syndromes are fairly nonspecific. Typically, there is pain or discomfort in the region of the entrapment.

FIGURE 18–2 High median neuropathy hand posture. A complete high median neuropathy results in a classic hand posture when the patient attempts to make a grip: the patient is unable to flex the thumb, index, and middle fingers.

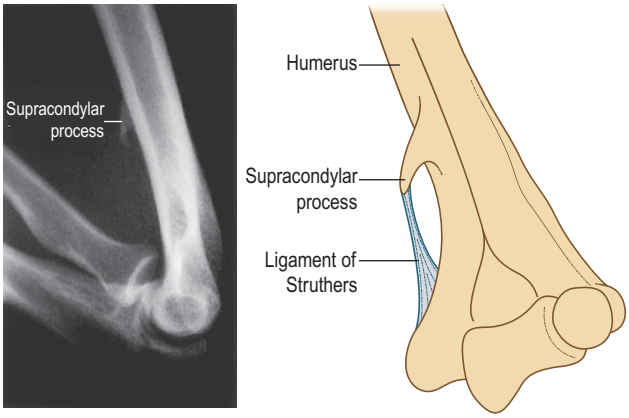

FIGURE 18–3 Ligament of Struthers. Rare individuals have a supracondylar bony spur from which a tendinous band (ligament of Struthers) runs to the medial epicondyle. The median nerve and brachial artery travel under this ligament. The supracondylar process can be demonstrated by plain bone X-ray films.
(Adapted from Struthers, J., 1854. On some points in the abnormal anatomy of the arm. Br Foreign Med Ch Rev 13, 523–533.)

Unlike CTS, the symptoms are not exacerbated at night. The two major syndromes include (1) proximal entrapment of the median nerve at the ligament of Struthers and (2) median nerve entrapment more distally, either beneath the lacertus fibrosus, in the substance of the PT, or beneath the sublimis bridge (Figure 18–1). The latter three entrapment sites usually are referred to collectively as the *pronator syndrome*. Strictly speaking, the term may be reserved for nerve entrapment within the substance of the PT muscle proper. However, entrapment at any of these last three locations usually produces a similar clinical syndrome.

Ligament of Struthers Entrapment

Entrapment at the ligament of Struthers is a very rare syndrome whereby the median nerve is entrapped by a tendinous band running from the medial epicondyle to a bony spur on the distal medial humerus (Figure 18–3). The

prevalence of such a supracondylar bony spur is approximated at 1 to 2% of the population. The syndrome is characterized by pain in the volar forearm and paresthesias in the median-innervated digits, which are exacerbated by supination of the forearm and extension of the elbow. The radial pulse also may be attenuated with these maneuvers, as the brachial artery also runs with the median nerve under the ligament of Struthers. A bony spur may be palpable at the distal humerus. Weakness of the PT and other median-innervated muscles may occur, and subtle sensory loss may be noted in the median distribution, including the thenar eminence.

Pronator Syndrome

Although rare, the pronator syndrome occurs more often than entrapment at the ligament of Struthers. The PT muscle may be enlarged or firm, with a Tinel's sign over the site of entrapment. Pain may radiate proximally and often is aggravated by using the arm, especially with repeated pronation/supination movements. Specific maneuvers that may produce symptoms of pain in the forearm and paresthesias in the median-innervated digits depend on the site of entrapment (Figure 18–4): resisted pronation with the elbow in extension (for the PT); resisted flexion of the proximal interphalangeal joint of the middle finger (for the sublimis bridge); and resisted flexion of the elbow with the forearm in supination (for the lacertus fibrosus). The sole finding of increased pain with these maneuvers is an unreliable sign, unless it is accompanied by median nerve territory paresthesias. Significant weakness or wasting of median-innervated muscles is rare, but mild weakness of the FPL and APB is not uncommon, with occasional involvement of the FDP to digits 2 and 3 and the OP. The pronator teres muscle is usually spared. There may be occasional paresthesias radiating into the median-innervated digits, with subtle impairment of sensation in the median nerve distribution, including the thenar eminence.

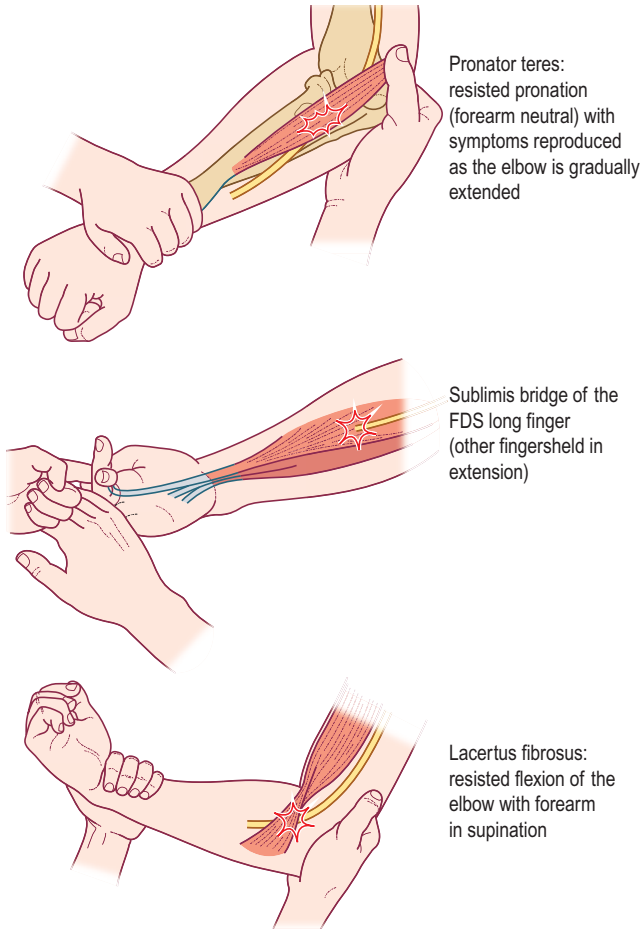

FIGURE 18–4 Provocative maneuvers for pronator syndrome. Different provocative maneuvers may reproduce symptoms associated with the pronator syndrome, depending on the site of entrapment: pronator teres, sublimis bridge (arch of the flexor digitorum sublimis [FDS]), and lacertus fibrosus. Note: many consider these maneuvers to be unreliable and nonspecific. The sole finding of increased pain with these maneuvers is especially unreliable unless the pain is accompanied by median paresthesias.
(From Omer, G.E., Spinner, M., 1980. Management of peripheral nerve problems. WB Saunders, Philadelphia.)

ANTERIOR INTEROSSEOUS NERVE SYNDROME

The anterior interosseous nerve, the largest branch of the median nerve, leaves the main trunk of the median nerve just distal to the PT to innervate three muscles: FPL, FDP to digits 2 and 3, and PQ. It carries deep sensory fibers to the wrist and interosseous membrane, but it carries no cutaneous sensory fibers. Clinically, patients present with the inability to flex the distal phalanx of the thumb, index, and middle fingers, with weakness of pronation. Weakness of the PQ is best demonstrated with the elbow flexed to avoid the contribution of the PT, which is not involved in anterior interosseous syndrome. With the elbow flexed, the PQ is the primary muscle to pronate the arm; with the elbow extended, the PT is the primary muscle to pronate the arm. There is no sensory loss. A characteristic compensatory posture occurs when the patient attempts to make an "OK" sign and is unable to flex the distal thumb and index fingers. Compensatory hyperextension of the distal interphalangeal joint of the index finger and interphalangeal joint of the thumb then occurs (Figure 18–5). Anterior interosseous neuropathy (AIN) has been reported to occur following fractures and crush injuries. In addition, it can rarely occur as an entrapment neuropathy, but more often it is a variant presentation of brachial neuritis, a full discussion of which is found in the section on brachial neuritis in Chapter 30, including the electrophysiologic evaluation.

Occasionally, it may be difficult to recognize an AIN. In some patients, the slip of the FDP to digit 3 is supplied by the ulnar nerve, leaving middle finger flexion intact despite an AIN. The situation is more complicated when an AIN occurs in combination with a Martin–Gruber anastomosis (MGA). In MGA, there is an anomalous

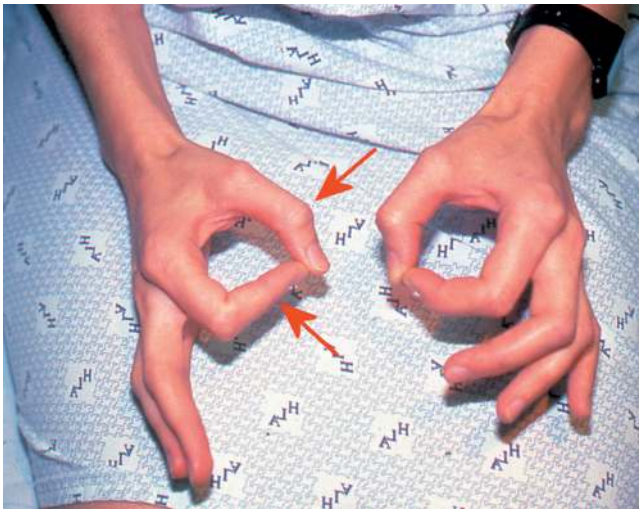

FIGURE 18–5 Anterior interosseous neuropathy. Lesions of the anterior interosseous nerve result in weakness of the flexor pollicis longus, flexor digitorum profundus (to digits 2, 3, or both), and pronator quadratus. Patients characteristically are unable to make an "OK" sign (i.e., form a circle with thumb and index finger). The thumb and index finger are unable to flex at the interphalangeal joints and the distal interphalangeal joints, respectively (arrows).

cross-over of median-to-ulnar fibers. Occasionally, the median fibers that cross over run in the anterior interosseous nerve. Thus, a patient with an AIN also can develop weakness of some ulnar-innervated intrinsic hand muscles, if an MGA is present and the cross-over fibers run in the anterior interosseous nerve.

DIFFERENTIAL DIAGNOSIS

In cases of acute trauma or injury, the clinical differential diagnosis is limited and usually straightforward. For the entrapment syndromes in the region of the antecubital fossa, however, the differential diagnosis is extensive because the symptoms often are vague. For example, local orthopedic problems may present in a similar fashion. Median neuropathy at the carpal tunnel also may give rise to diagnostic confusion. Patients with CTS can present with vague pain or heaviness in the forearm associated with median paresthesias, similar to symptoms in the proximal median entrapment syndromes. Additionally, patients with cervical radiculopathy may present with radiating pain associated with paresthesias into the hand. In cervical radiculopathy, however, there usually is a history of neck pain that radiates into the arm. Examination in cervical radiculopathy may reveal weakness outside the median territory, as well as decreased biceps, brachioradialis, or triceps reflexes.

ELECTROPHYSIOLOGIC EVALUATION

The purpose of nerve conduction studies and electromyography (EMG) in suspected proximal median neuropathy is (1) to demonstrate that median nerve abnormalities are proximal to the wrist and (2) to exclude a lesion higher in the brachial plexus or cervical nerve roots. However, the EDX evaluation may be complicated by the fact that the electrophysiology in true cases of proximal median entrapment often is normal or nonspecific, despite what one might expect on theoretical grounds.

Nerve Conduction Studies

Nerve conduction studies should include routine median motor studies stimulating the median nerve at the wrist and antecubital fossa, recording at the APB (Box 18–1). If there is a question of entrapment at the ligament of Struthers, proximal stimulation should also be performed at the axilla. Routine ulnar motor and sensory studies should also be performed to exclude a coexistent polyneuropathy. Sensory nerve conductions of median-innervated digits should always be performed, recording the most symptomatic digit(s), especially if numbness or paresthesias have been observed on clinical examination. If values are borderline or just slightly above the upper limits of normal, comparison with the contralateral side should be done. *Finally, in all suspected median neuropathies, it is imperative to perform at least one of the median-versus-ulnar comparison studies across the wrist to exclude median neuropathy at the wrist. If values are borderline or just slightly above the upper limits of normal, a second median-versus-ulnar comparison*

Box 18–1. Recommended Nerve Conduction Study Protocol for Proximal Median Neuropathy

Routine studies:

1. Median motor study recording abductor pollicis brevis, stimulating wrist, antecubital fossa, and axilla
2. Ulnar motor study recording abductor digiti minimi, stimulating wrist, below groove, and above groove
3. Median and ulnar F responses
4. Median sensory response, recording digit 2 or 3, stimulating wrist (bilateral studies suggested)
5. Ulnar sensory response, recording digit 5, stimulating wrist
6. Median and ulnar palm-to-wrist mixed nerve studies using identical distances of 8 cm

The following patterns suggest possible proximal median neuropathy:

1. Reduced median compound muscle action potential and/or sensory nerve action potential amplitudes with distal latencies that are either normal or only slightly prolonged (never in the demyelinating range) and no significant slowing of the median palm-to-wrist latency compared with the ulnar
2. Either conduction block/temporal dispersion or marked conduction velocity slowing between the wrist and antecubital fossa, or between antecubital fossa and axilla, with normal or only slightly prolonged distal latencies on median motor studies
3. Prolonged median F responses despite a relatively normal distal compound muscle action potential amplitude and distal latency

study should be done to look for median neuropathy at the wrist.

A lesion of the median nerve that results in wallerian degeneration, regardless of the lesion site, will result in decreased compound muscle action potential (CMAP) and sensory nerve action potential (SNAP) amplitudes distal to the lesion. Often the distal latencies will be slightly prolonged, and conduction velocity will be mildly slowed because of dropout of the fastest-conducting axons. However, although such findings are abnormal and indicate a median nerve lesion, they do not localize the lesion. If there is focal demyelination at the ligament of Struthers, one might expect to see either focal slowing or a drop in CMAP amplitude (i.e., conduction block or temporal dispersion) between the antecubital fossa and the axilla sites. If there is a focal lesion in the region of the antecubital fossa, there may be a conduction block between the wrist and antecubital fossa sites. Although such findings can be expected on theoretical grounds, in fact they rarely occur.

Electromyographic Approach

The EMG usually is more gratifying than the nerve conduction studies in patients with a suspected proximal median neuropathy (Box 18–2). The distal median muscles (APB) should always be studied. However, the critical part of the study consists of careful examination of several median-innervated muscles proximal to the carpal tunnel. These muscles include the PT, FCR, FDS, FDP to digits 2 and 3, FPL, and PQ. If any of these muscles are abnormal (evidence of denervation or reinnervation), the problem must be proximal to the wrist. If the lesion is at the level of the ligament of Struthers, EMG abnormalities may be noted in all the median-innervated muscles, including the PT. In the pronator syndrome, EMG abnormalities have been reported most often in the FPL and FDP to digits 2 and 3, less often in the FDS and APB, and only rarely in the PT, because the compression site most often occurs distal to its innervation. If any of the proximal median-innervated muscles are abnormal, other muscles innervated by the same myotomes as the proximal median muscles, but supplied by different nerves, should be sampled to exclude a more proximal lesion of the brachial plexus or cervical nerve roots. At a minimum, one non-median C6–C7 innervated muscle (e.g., triceps) and one non-median C8–T1 innervated muscle (e.g., first dorsal interosseous) must be checked.

A few technical points are important to keep in mind. The proximal median-innervated muscles that are most accessible and easiest to sample are the PT, FPL, and FCR. In all suspected proximal median nerve lesions, the PT and at least one of these other muscles should be sampled. Two proximal median-innervated muscles that are somewhat more difficult to study on a routine basis are the FDP to digits 2 and 3 and the PQ. The FDP has two slips: a median-innervated slip to digits 2 and 3 and an ulnar-innervated slip to digits 4 and 5. The ulnar-innervated slip is superficial and very easy to study. The median slip is deep, however, and thus is much more difficult to localize. Likewise, the PQ is a deep muscle that lies beneath the extensors to the thumb and index finger, making it technically more difficult to study.

Box 18–2. Recommended Electromyographic Protocol for Proximal Median Neuropathy

Needle examination of:

1. Median muscle distal to the carpal tunnel (abductor pollicis brevis)
2. At least two median muscles proximal to the carpal tunnel, including the pronator teres and one of the following: flexor pollicis longus, flexor carpi radialis, flexor digitorum sublimis

If the abductor pollicis brevis is abnormal:

3. Test at least two other non-median, lower trunk/C8–T1 innervated muscles (e.g., first dorsal interosseous, extensor indicis proprius, flexor digitorum profundus to digits 4 and 5) to exclude a lower brachial plexopathy, polyneuropathy, or C8–T1 radiculopathy

If the proximal median muscles are abnormal:

4. Test at least one non-median C6–C7 and C7–C8 innervated muscle (e.g., triceps, extensor digitorum communis, extensor indicis proprius) to exclude a more proximal brachial plexopathy or cervical radiculopathy

Note: If nerve conduction studies show a non-localizing median neuropathy, electromyography can only localize the lesion to at or above the take-off to the most proximally affected median-innervated muscle. For example, an abnormal flexor carpi radialis with a normal pronator teres does not necessarily localize the lesion to the median nerve between those two muscles, but only to at or proximal to the take-off to the flexor carpi radialis muscle. Although this may seem counterintuitive, remember that there are proximal lesions that spare some of the muscles distal to the lesion while affecting others.

EXAMPLE CASES

Case 18–1

History and Examination

A 24-year-old man noticed numbness of the right thumb, index, and middle fingers. The numbness was noted after removal of a cast that had been in place for 6 weeks following wrist fusion because of trauma.

Examination showed wasting of the thenar eminence. Thumb abduction was moderately weak. Wrist flexion was difficult to evaluate because of the effects of surgery. Hypesthesia was present over the thumb, index, and middle fingers, as well as over the thenar eminence.

Summary

The clinical history and examination both are suggestive of a median nerve lesion. Given the history of trauma to the wrist and subsequent surgery, median neuropathy at the wrist seems a likely diagnosis. However, the finding of hypesthesia over the thenar eminence should alert one to a more proximal lesion because that area should be spared in median nerve lesions at the carpal tunnel.

CASE 18–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = μV			Latency (ms)			Conduction Velocity (m/s)			F-wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	0.4	8.6	≥4	6.1	3.8	≤4.4				NR	28	≤31
	Antecubital fossa	APB	0.3	8.4		10.6	7.6		44	52	≥49			
Ulnar (m)	Wrist	ADM	11.2		≥6	3.0		≤3.3				27		≤32
	Below elbow	ADM	11.2			6.3			60		≥49			
	Above elbow	ADM	11.1			9.6			61		≥49			
Median (s)	Wrist	Index finger	4	22	≥20	3.1	3.0	≤3.5	54	56	≥50			
Ulnar (s)	Wrist	Little finger	24		≥17	2.9		≤3.1	62		≥50			
Median (mixed study)	Palm	Wrist	9		≥50	1.6		≤2.2	62		≥50			
Ulnar (mixed study)	Palm	Wrist	23		≥15	1.6		≤2.2	62		≥50			
Mixed difference						0.0		≤0.3						

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; APB = abductor pollicis brevis; ADM = abductor digiti minimi.
Note: All sensory and mixed latencies are peak latencies. All sensory and mixed-nerve conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 18–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right APB	↑	+3	0	NL	↓↓	+1	+1	+3
Right FDI	NL	0	0	NL	NL	NL	NL	NL
Right EIP	NL	0	0	NL	NL	NL	NL	NL
Right PT	NL	0	0	NL	↓	+1	+1	+1
Right triceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right FCR	↑	+1	0	Fair	↓	+1	+1	+1
Right FDS	↑	+1	0	NL	NL	NL	NL	NL
Right biceps brachii	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓ = slightly reduced; ↓↓ = moderately reduced; APB = abductor pollicis brevis; FDI = first dorsal interosseous; EIP = extensor indicis proprius; PT = pronator teres; FCR = flexor carpi radialis; FDS = flexor digitorum sublimis.

Proceeding to the nerve conduction studies, the right median motor study is strikingly abnormal. The amplitude is markedly decreased, with moderate prolongation of the distal motor latency and moderate slowing of conduction velocity. The distal latency of 6.1 ms strongly suggests the possibility of demyelination between the wrist and the recording site. Indeed, the distal latency of 6.1 ms is near the unequivocally demyelinating range. Although this degree of slowing might represent true demyelination, it could also represent marked dropout of the medium- and fastest-conducting fibers, secondary to severe axonal loss. If severe axonal loss is present, one would expect the distal CMAP amplitude to be very low and the needle EMG of that muscle to be strikingly abnormal. In this case, both are true. The distal median CMAP amplitude is very low at 0.4 mV, suggesting that there has been severe axonal loss. This is confirmed by the EMG of the APB, which shows prominent active denervation and reinnervation with reduced recruitment of motor unit action potentials (MUAPs), which are signs of axonal loss.

The right median F responses are absent. Theoretically, this finding could represent a proximal median lesion; however, a distal CMAP amplitude this low usually results in an absent F response, but not because of a proximal lesion. Because the F response normally is only

1 to 5% of the distal CMAP amplitude, F responses in the setting of such a low CMAP amplitude are commonly absent or difficult to obtain.

The ulnar motor study and the ulnar and radial sensory responses are completely normal, which suggests that the problem is limited to the median nerve. The median sensory and palm-to-wrist mixed-nerve studies also show a normal latency with a low amplitude. Comparison of the median and ulnar palm-to-wrist mixed latencies reveals no significant difference. These studies strongly argue against a median nerve lesion at the wrist.

In summary, the nerve conduction studies demonstrate a severe median neuropathy involving motor and sensory fibers. The neuropathy does not appear to be localized to the wrist for the following reason: although the median sensory and mixed nerve amplitudes are low, their latencies are not slowed. The distal motor latency to the APB is moderately prolonged, but that may be attributable to severe axonal loss, which cannot be localized to the wrist.

On needle EMG, the right APB is floridly fibrillating with moderately reduced recruitment of long polyphasic MUAPs. This provides additional EMG confirmation that the APB has undergone significant axonal loss. Because of the abnormal APB, the FDI is sampled next to exclude a C8–T1 radiculopathy or, more importantly, a widespread brachial plexopathy, in light of the abnormal median sensory and mixed-nerve potentials. The right extensor indicis proprius (EIP) also is checked for the same reason. The findings of a normal FDI and EIP with such an abnormal APB argue strongly against a lesion of the lower trunk of the brachial plexus or the C8–T1 roots, and suggest strongly that the problem is limited to the median nerve.

The more proximal median muscles also are denervated, including the FCR and FDS. The PT and FCR also show evidence of reinnervation. The biceps brachii and triceps brachii are sampled to exclude a C6 or C7 radiculopathy or brachial plexopathy as the cause of the changes in the proximal median-innervated muscles.

Because these muscles are normal and all of the EMG abnormalities are limited to median-innervated muscles spanning several myotomes (C6–T1), an electrophysiologic impression can be made.

IMPRESSION: *There is electrophysiologic evidence consistent with a severe right median neuropathy at or proximal to the take-off to the PT muscle.*

The etiology of the high median neuropathy in this case most likely was the cast, which was too tight for the patient and caused chronic compression of the median nerve at the antecubital fossa. Although the patient sustained significant trauma to his wrist and underwent wrist fusion surgery, there is no definite electrophysiologic evidence of focal median slowing at the carpal tunnel. If median motor, sensory, and F response studies alone had been performed, along with an EMG limited to the APB and FDI muscles, a misdiagnosis of median neuropathy at the carpal tunnel could easily have been made, perhaps leading to an inappropriate median nerve decompression at the wrist.

The clinical clues that more extensive studies were called for included (1) numbness over the thenar eminence, which is not found in CTS, and (2) the fact that the numbness was appreciated after removal of the cast for wrist fusion, and not after the initial trauma.

Case 18–2

History and Examination

A 25-year-old man was shot in the left arm two months previously. The bullet entered the posterior arm and exited anteriorly in the region of the mid biceps. The patient complained of persistent numbness of the thumb, index, and middle fingers and poor dexterity of the hand.

Examination showed marked wasting of the thenar eminence. Thumb abduction and opposition were markedly weak. There was moderate weakness of thumb, index, and middle finger flexion at both the distal interphalangeal and proximal interphalangeal joints. Arm pronation was mildly weak. The remainder of the motor examination was normal, as were the reflexes. There was sensory loss over the left thumb, index, and middle fingers and the thenar eminence.

Summary

The history and examination are consistent with a proximal median nerve lesion. Although nerve conduction studies and EMG generally are most useful in determining localization, in this case there is little doubt where the lesion is (i.e., the bullet hole). The nerve conduction studies and EMG serve additional important roles in determining the severity of the lesion and hence the prognosis in this type of case where there has been severe trauma.

There is no response from the APB muscle stimulating the left median nerve. The sensory response from the left median nerve also is absent. The left ulnar motor study and the contralateral right median motor and sensory nerve conduction studies are completely normal. These findings strongly suggest an isolated lesion of the left median nerve. Several sensory conductions, including studies of the left ulnar, radial, and lateral antebrachial cutaneous nerves, are normal. These also tend to preclude a more proximal plexus lesion. The complete absence of median motor and sensory responses makes the diagnosis of a median neuropathy inescapable; however, the nerve conduction results are of no value in localizing the lesion.

On EMG, the APB is floridly fibrillating, and no MUAPs can be activated. The nerve conduction finding of an absent median motor response and the EMG finding of florid fibrillation potentials with no MUAPs in the APB suggest that there is no axonal continuity to the distal median muscles. Assessment of the more proximal

CASE 18–2. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = μV			Latency (ms)			Conduction Velocity (m/s)			F-wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	6.2	NR	≥4	4.2	NR	≤4.4				29	NR	≤31
	Antecubital fossa	APB	6.0			7.9			54		≥49			
Ulnar (m)	Wrist	ADM		9.0	≥6		2.9	≤3.3					28	≤32
	Below elbow	ADM		8.9			6.4			57	≥49			
	Above elbow	ADM		8.7			8.1			59	≥49			
Median (s)	Wrist	Index finger	24	NR	≥20	3.4	NR	≤3.5	56	NR	≥50			
Ulnar (s)	Wrist	Little finger	22	23	≥17	2.9	3.0	≤3.1	62	64	≥50			
Radial (s)	Forearm	Snuffbox		35	≥15		2.4	≤2.9		65	≥50			
Lateral antebrachial cutaneous(s)	Elbow	Forearm		19	≥10		2.9	≤3.0		62	≥55			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; APB = abductor pollicis brevis; ADM = abductor digiti minimi.
Note: All sensory and mixed latencies are peak latencies. All sensory and mixed-nerve conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 18–2. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Left APB	↑	+3	0	None				
Left FPL	↑	+2	0	NL	↓↓↓	+3	+1	+1
Left PT	↑	+3	0	NL	↓↓	−1/+1	NL	+1
Left FCR	↑	+3	0	NL	↓↓	−1/+1	NL	+1
Left FDI	NL	0	0	NL	NL	NL	NL	NL
Left biceps brachii	NL	0	0	NL	NL	NL	NL	NL
Left triceps brachii	NL	0	0	NL	NL	NL	NL	NL

NL = normal; ↑ = increased; ↓↓ = moderately reduced; ↓↓↓ = markedly reduced; APB = abductor pollicis brevis; FPL = flexor pollicis longus; PT = pronator teres; FCR = flexor carpi radialis; FDI = first dorsal interosseous.

median muscles, including the PT, FCR, and FPL, also shows fibrillation potentials. More importantly, however, MUAPs are also present. In the PT and FCR, there is a combination of brief and long-duration MUAPs, with moderately to markedly reduced recruitment.

The biceps and triceps are also checked to exclude a coexistent C6 or C7 radiculopathy or upper/middle trunk plexopathy that could account for the abnormalities in the proximal median-innervated muscles. The FDI is checked to exclude a coexistent C8–T1 radiculopathy. These muscles are all normal.

An electrophysiologic impression now can be formed.

IMPRESSION: *There is electrophysiologic evidence consistent with a severe left median neuropathy at or proximal to the take-off to the PT muscle. No axonal continuity to the APB muscle can be demonstrated. A repeat study is recommended in 2 to 3 months to further assess axonal continuity.*

In this case, the localization of the lesion is obvious, marked by the bullet, which clearly went through the median nerve in the region of the upper arm. This is a severe lesion that has led to marked denervation in most of the median-innervated muscles. Of note, there is a combination of brief and long-duration polyphasic MUAPs in two of the proximal median-innervated muscles. The brief-duration, polyphasic motor unit potentials might lead one to question whether there is a coexistent myopathy. The answer clearly is no. These

MUAPs represent early reinnervation, or so-called nascent motor units. The key to differentiating nascent motor unit potentials from myopathic motor unit potentials is the presence of decreased recruitment in neuropathic conditions, whereas recruitment is normal or early in myopathic conditions.

The surgeon in this case was considering a tendon transfer to provide function to the left thumb. The question arises whether serial EMGs would be helpful in this regard. Although EMG is a very useful diagnostic tool, in general it has little role in following a patient's improvement. One exception to this rule includes cases in which one is trying to document axonal continuity of a nerve. In the case under consideration here, there has been a severe traumatic lesion of the median nerve with complete denervation of the APB, and no evidence of axonal continuity to the APB on the initial EMG study. A repeat study several weeks or months later would be useful to look for evidence of early reinnervation in the APB before consideration of tendon transfer surgery. After trauma and wallerian degeneration, axonal regrowth occurs at approximately 1 mm per day. Thus, a lesion in the region of the arm might not reinnervate the APB for several months to a year. In this case, if the APB were to become reinnervated, the first change on EMG would be the presence of nascent motor unit potentials that recruit poorly, along with fibrillation potentials. The appearance of nascent motor unit potentials would be a clear indication to delay the surgery and observe further in the hope that continued axonal regeneration would obviate the need for surgery.

Suggested Readings

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19 Ulnar Neuropathy at the Elbow

Ulnar neuropathy at the elbow (UNE) is second only to median nerve entrapment at the wrist (i.e., carpal tunnel syndrome [CTS]) as the most common entrapment neuropathy affecting the upper extremity. In contrast to CTS, localizing the site of the lesion by electrodiagnostic (EDX) studies often is much more difficult in patients with ulnar neuropathy. Indeed, the diagnosis of a non-localizable ulnar neuropathy is not infrequently the best that can be accomplished in the electromyography (EMG) lab. Although the elbow is the most common site of compression, the ulnar nerve is susceptible to entrapment at other sites, especially at the wrist. In addition, lesions of the lower brachial plexus or C8–T1 roots may result in symptoms similar to UNE. It is the role of the electromyographer to identify the ulnar nerve lesion, localize it as accurately as possible, and exclude other disorders that may mimic it.

ANATOMY

The ulnar nerve is essentially derived from the C8 and *T1 roots* (Figure 19–1), although some anatomic dissections have also demonstrated a minor component from C7. Accordingly, nearly all ulnar fibers travel through the *lower trunk of the brachial plexus* and then continue into the medial cord. The terminal extension of the medial cord becomes the ulnar nerve. The *medial brachial and medial antebrachial cutaneous sensory nerves and a large contribution to the median nerve* are derived from the medial cord as well. As the ulnar nerve descends through the medial arm, it does so without giving off any muscular branches. The ulnar nerve pierces the medial intermuscular septum in the mid-arm and then passes through the arcade of Struthers, which is composed of deep fascia, muscle fibers

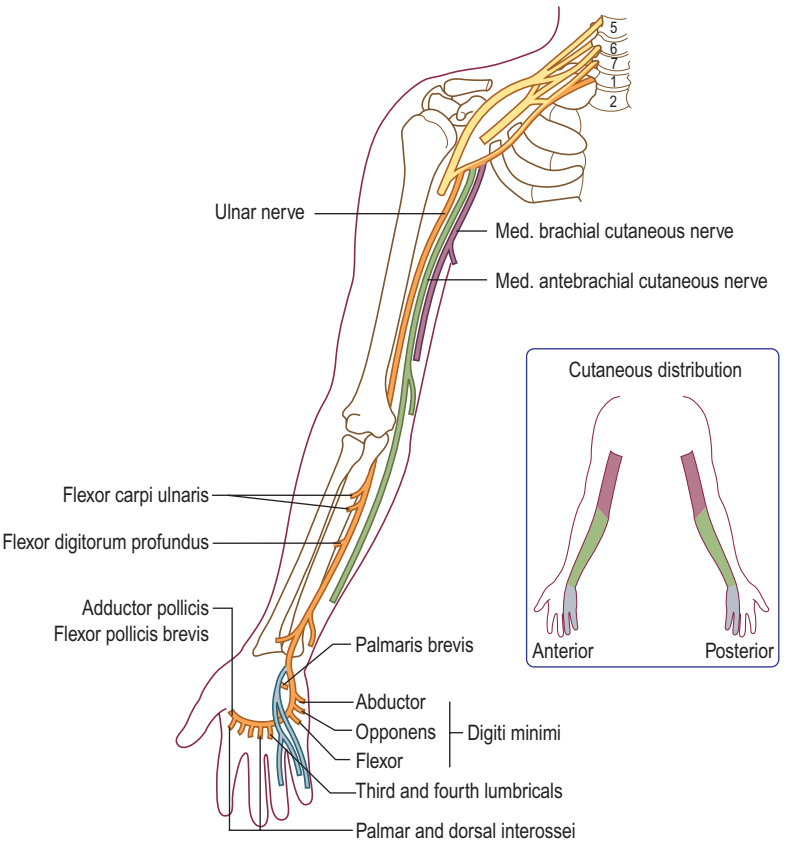

FIGURE 19–1 Ulnar nerve anatomy. The ulnar nerve, along with the medial brachial and medial antebrachial cutaneous nerves, is derived from the medial cord of the brachial plexus. **Inset:** Cutaneous distributions of the ulnar, medial antebrachial, and medial brachial cutaneous nerves.
(Reprinted with permission from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia.)

DOI: 10.1016/B978-1-4557-2672-1.00019-2

from the medial head of the triceps, and the internal brachial ligament. The ulnar nerve then travels medially and distally toward the elbow.

At the elbow, the nerve enters the ulnar groove formed between the medial epicondyle and the olecranon process. Slightly distal to the groove in the proximal forearm, the ulnar nerve travels under the tendinous arch of the two heads of the flexor carpi ulnaris (FCU) muscle, known as the humeral–ulnar aponeurosis (HUA) or cubital tunnel. Muscular branches to the FCU and the medial division (fourth and fifth digits) of the flexor digitorum profundus (FDP) are then given off.

The nerve then descends through the medial forearm, giving off no further muscular branches until after the wrist. Five to eight centimeters proximal to the wrist, the *dorsal ulnar cutaneous sensory branch* exits to supply sensation to the dorsal medial hand and the dorsal fifth and medial fourth digits. At the level of the ulnar styloid, the *palmar cutaneous sensory branch* originates to supply sensation to the proximal medial palm.

The nerve next enters the medial wrist through Guyon's canal to supply sensation to the volar fifth and medial fourth digits and muscular innervation to the hypothenar muscles, the palmar and dorsal interossei, the third and fourth lumbricals, and two muscles in the thenar eminence, the adductor pollicis and the deep head of the flexor pollicis brevis.

DETAILED ANATOMY AT THE ELBOW

As the nerve approaches the ulnar groove, it becomes quite superficial (Figure 19–2). The ulnar nerve normally runs in the groove formed by the medial epicondyle of the humerus and the olecranon process of the ulna. In some individuals, fully flexing the elbow may allow the ulnar nerve to sublux out of the groove medially over the medial epicondyle. In a small number of individuals, a dense fibrotendinous band or an accessory epitrochleoanconeus muscle (or both) may be present between the medial epicondyle and the olecranon process. Just distal to the groove is the HUA (cubital tunnel).

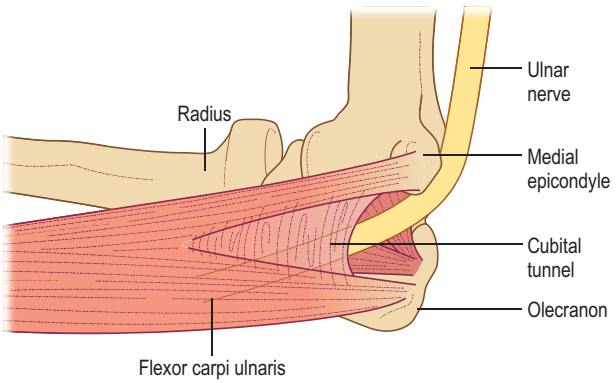

FIGURE 19–2 Detailed ulnar nerve anatomy at the elbow. Entrapment of the ulnar nerve occurs both at the groove (between the medial epicondyle and the olecranon) or distally at the cubital tunnel.
(Reprinted with permission from Kincaid, J.C., 1988. AAEE minimonograph no. 31: the electrodiagnosis of ulnar neuropathy at the elbow. Muscle Nerve 11, 1005.)

Studies have shown that the distance from the medial epicondyle to the cubital tunnel distally varies between 3 and 20 mm in cadaver dissections and from 0 to 22 mm in surgical specimens. *This variation underscores the importance of stimulating the below-elbow site at least 3 cm distal to the elbow, in routine ulnar motor studies, to ensure that the stimulation is distal to the cubital tunnel, a common site of entrapment*. In the cubital tunnel, the ulnar nerve then continues under the FCU to exit between the deep fascia separating the FCU and FDP. The location of this exit from the cubital tunnel varies from 3 to 7 cm distal to the ulnar groove, according to cadaver studies. The muscular branch to the FCU usually arises distal to the cubital tunnel in 93–95% of cadaver dissections, and always follows the same course as the main ulnar nerve.

ETIOLOGY

UNE usually occurs as a result of chronic mechanical compression or stretch, either at the groove or at the cubital tunnel. Although rare cases of ulnar neuropathy at the groove are caused by ganglia, tumors, fibrous bands, or accessory muscles, most are caused by external compression and repeated trauma. Elbow fracture, often sustained years earlier, and subsequent arthritic change of the elbow joint may result in so-called *tardy ulnar palsy*. In addition, chronic minor trauma and compression (including leaning on the elbow) can either exacerbate or cause ulnar neuropathy at the groove. Ulnar neuropathy at the groove also is common in patients who have been immobilized because of surgery or who sustain compression during anesthesia or coma. More controversial is the possibility that repeated subluxation of the ulnar nerve out of the groove (during elbow flexion) also leads to ulnar neuropathy.

Distal to the groove is the cubital tunnel, the other major site of compression of the ulnar nerve in the region of the elbow. Although some use the term *cubital tunnel syndrome* to refer to all lesions of the ulnar nerve around the elbow, it more properly denotes compression of the ulnar nerve under the HUA. Some individuals have congenitally tight cubital tunnels that predispose them to compression. Repeated and persistent flexion stretches the ulnar nerve and increases the pressure in the cubital tunnel, leading to subsequent ulnar neuropathy.

CLINICAL

UNE caused by compression at the groove or at the cubital tunnel may present in a similar manner. In contrast to CTS, in which sensory symptoms predominate, motor symptoms are more common in ulnar neuropathy, especially in chronic cases. In some patients, insidious motor

loss may occur without sensory symptoms, particularly in those with slowly worsening mechanical compression. Because most of the intrinsic hand muscles are ulnar innervated, weakness of these muscles leads to loss of dexterity and decreased grip and pinch strength. These are often the complaints that bring the patient to medical attention. There may be atrophy of both the hypothenar and thenar eminences (the ulnar-innervated adductor pollicis and deep head of the flexor pollicis brevis are in the thenar eminence). However, thumb abduction is spared (median and radial innervated).

In moderate or advanced cases, examination often shows the classic hand postures that occur with ulnar muscle weakness. The most recognized is the *Benediction posture* (Figure 19–3). The ring and little fingers are clawed, with the metacarpophalangeal joints hyperextended and the proximal and distal interphalangeal joints flexed (from third and fourth lumbrical weakness), while the fingers and thumb are held slightly abducted (from interossei and adductor pollicis weakness). The *Wartenberg's sign* is recognized as a passively abducted little finger due to weakness of the third palmar interosseous muscle (Figure 19–4). The clinical correlate to this sign is that the patient reports

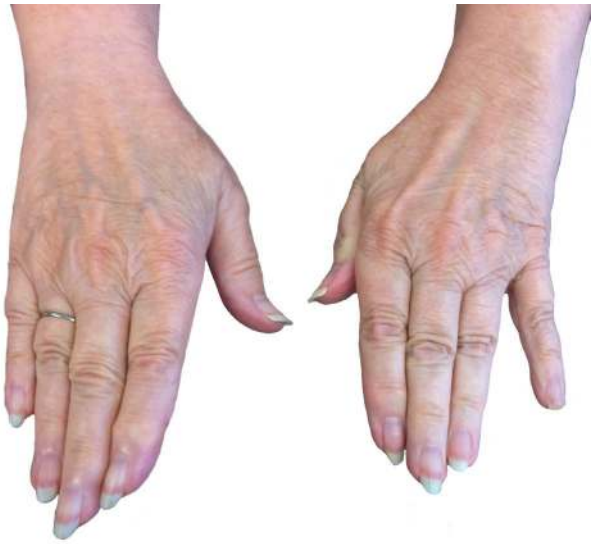

FIGURE 19–4 Wartenberg's sign. The sign results from difficulty adducting the fifth digit because of preferential weakness of the third palmar interosseous muscle. In the photo, the patient was asked to hold her fingers together. Note that the patient's left fifth finger is held abducted.

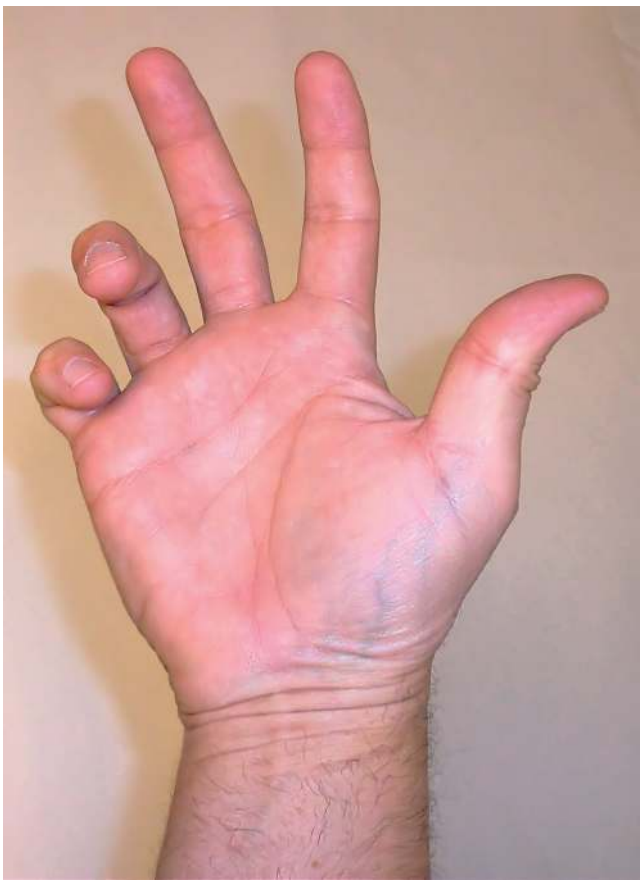

FIGURE 19–3 Benediction posture. The deformity results from a combination of finger adduction weakness (interossei) and clawing of digits 4 and 5 (extension at the metacarpophalangeal joints and flexion of the distal and proximal interphalangeal joints, from weakness of the third and fourth lumbricals).

getting the little finger caught when trying to put their hand in their pocket. The *Froment's sign* occurs when the patient attempts to pinch an object or a piece of paper (Figure 19–5). To compensate for intrinsic ulnar hand weakness, the long flexors to the thumb and index finger (median innervated) are used, creating a flexed thumb and index finger posture.

Examination of the patient's grip often reveals it to be abnormal. Weakness of the ulnar-innervated FDP will result in the inability to flex the joints of the ring and little fingers. This often can be demonstrated just by having the patient make a fist (Figure 19–6). Patients with ulnar neuropathy may not be able to flex the distal fourth and fifth fingers completely when making a grip; in contrast, the median-innervated second and third distal digits flex normally.

In UNE, sensory disturbance, when present, involves the volar and dorsal fifth and medial fourth digits and the medial hand (Figure 19–7). The sensory disturbance does not extend proximally much beyond the wrist crease. Sensory involvement extending into the medial forearm implies a higher lesion in the plexus or nerve roots (i.e., this is the territory of the medial antebrachial cutaneous sensory nerve, which arises directly from the medial cord of the brachial plexus). Another important skin territory to check is the dorsal medial hand. Sensory abnormalities here are important because they indicate that the dorsal ulnar cutaneous sensory nerve territory also is involved. This finding excludes an ulnar neuropathy at the wrist as the dorsal ulnar cutaneous sensory nerve arises proximal to the wrist.

Pain, when present, may localize to the elbow or radiate down to the medial forearm and wrist. Paresthesias may be reproduced by placing the elbow in a flexed position or by

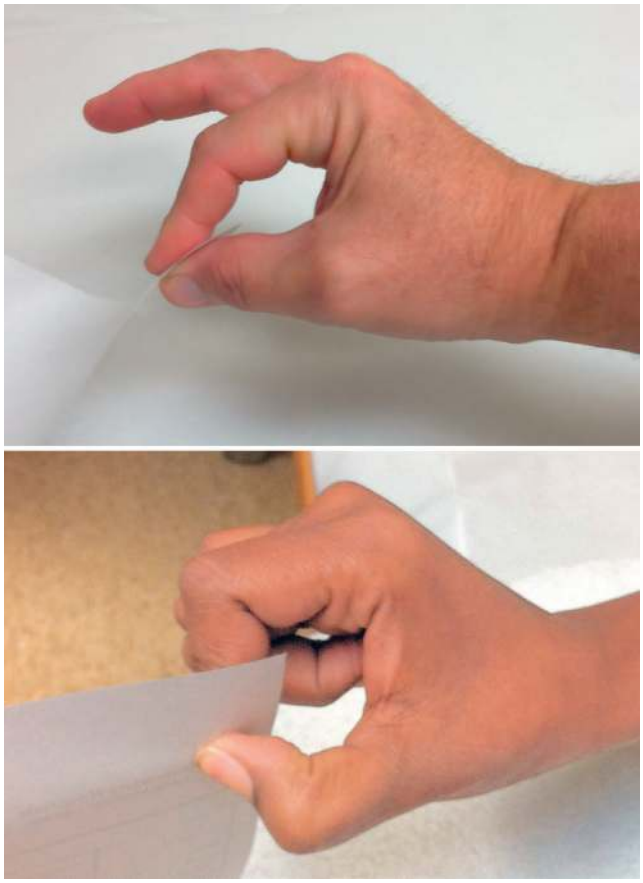

FIGURE 19–5 Froment's sign. **Top:** Normally to pinch a piece of paper, the finger pads of the thumb and index finger are brought together by the action of the ulnar-innervated adductor pollicis and first dorsal interosseous, respectively. **Bottom:** In ulnar neuropathy, weakness of these muscles results in a characteristic posture, known as the Froment's sign. To compensate, the median-innervated flexor pollicis longus and flexor digitorum profundus (digit 2) have to contract, resulting in marked flexion of the interphalangeal joints of the thumb and index finger.

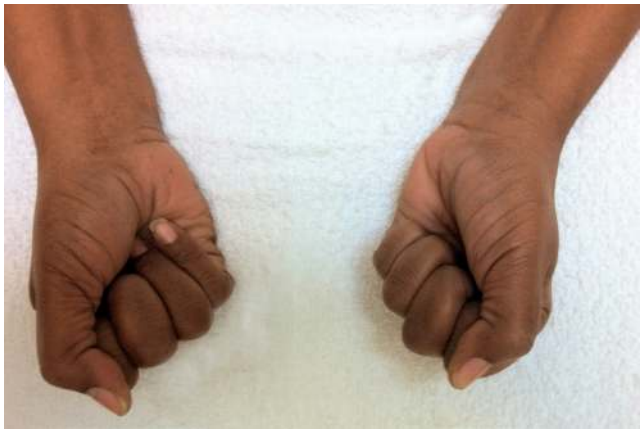

FIGURE 19–6 Weakness of ulnar flexor digitorum profundus. In ulnar neuropathy at the elbow, making a fist may result in the inability to completely flex the distal phalanx of the fourth and fifth digits due to weakness of the flexor digitorum profundus to digits 4 and 5. The median-innervated flexor digitorum profundus to digits 2 and 3 is normal (affected hand shown is the right hand – left side of the photo).

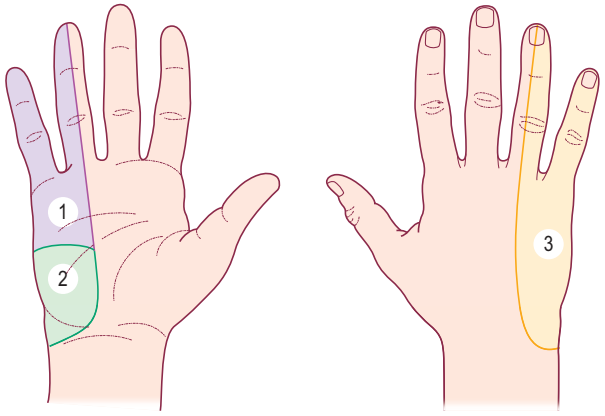

FIGURE 19–7 Sensory loss in ulnar neuropathy. The ulnar nerve contains three sensory branches: (1) ulnar digital sensory branches supply the volar fifth and medial fourth fingers; (2) palmar cutaneous branch supplies the proximal volar medial hand, arising 1 to 2 cm proximal to the wrist; and (3) dorsal ulnar cutaneous sensory branch arises 5 to 7 cm proximal to the wrist and supplies the dorsal medial hand and the dorsal medial fourth and fifth fingers. Lesions at the elbow may be associated with abnormalities in all three territories; lesions at the wrist never involve the dorsal ulnar territory (3) or the proximal volar ulnar palm (2).

applying pressure to the groove behind the medial epicondyle. The ulnar nerve may be palpably enlarged and tender. The nerve may also be palpably taut with decreased mobility, especially in patients with ulnar neuropathy at the cubital tunnel.

DIFFERENTIAL DIAGNOSIS

The differential diagnosis in a patient suspected of having UNE (Table 19–1) principally includes C8–T1 radiculopathy, lower trunk or medial cord brachial plexopathy, and ulnar neuropathy at the wrist. Very rare cases of ulnar nerve entrapment in the proximal arm and more distally in the forearm have also been reported.

A cervical radiculopathy at the C8–T1 level, although seen less frequently than radiculopathy at the C6 and C7 root levels (which are more commonly affected in cervical disc disease or spondylosis), may be difficult to differentiate clinically from ulnar neuropathy. Neck pain and radiation into the arm, sensory disturbance extending into the forearm, and weakness involving the median and radially innervated C8–T1 muscles are the major differentiating features. Of course, weakness often is minimal and sensory loss often vague in radiculopathy, making the differentiation between a mild C8–T1 radiculopathy and an ulnar neuropathy demanding, if based on clinical findings alone.

Lower trunk/medial cord brachial plexopathies are uncommon. Entrapment of the lower trunk by a fibrous band or hypertrophied muscle results in *neurogenic thoracic outlet syndrome* (see Chapter 30). Lower trunk plexopathies may also result from infiltration by neoplasm, prior radiation, or self-limited inflammatory processes (e.g.,

Table 19–1. Clinical Differentiating Factors in Suspected Ulnar Neuropathy

	UNW*	UNE	Medial Cord	Lower Trunk	C8–T1
Weakness of the interossei	X	X	X	X	X
Weakness of the hypothenar muscles	X	X	X	X	X
Weakness of the third and fourth lumbricals	X	X	X	X	X
Weakness of distal finger flexion of the little and ring fingers		X	X	X	X
Weakness of thumb abduction			X	X	X
Weakness of thumb flexion			X	X	X
Weakness of index finger extension				X	X
Sensory loss of the volar medial hand, volar little finger, and volar medial ring finger	X	X	X	X	X
Sensory loss of the dorsal medial hand, dorsal little finger, and dorsal medial ring finger		X	X	X	X
Sensory loss of the medial forearm			X	X	X
Tinel's sign at the elbow		X			
Neck pain					X

*Assumes both motor and sensory branches are involved; some cases of UNW may spare the hypothenar muscles and/or the sensory branch (for details, see Chapter 20).

X, may be present; UNE, ulnar neuropathy across the elbow; UNW, ulnar neuropathy at the wrist.

neuralgic amyotrophy). Like C8–T1 radiculopathy, lower trunk plexopathies may demonstrate weakness of non-ulnar-innervated C8–T1 muscles and sensory disturbance that extends into the medial forearm.

Other than in the region of the elbow, entrapment of the ulnar nerve in the arm or forearm is rare. In the arm proper, entrapment under the arcade of Struthers has been reported. In the forearm, infrequent cases of ulnar neuropathy occur at the exit of the cubital tunnel. The entrapping structure is the deep fascia between the FCU and FDP. Unusual cases of ulnar neuropathy in the distal forearm have also been reported due to a fibrovascular band supplying blood to a hypertrophied FCU muscle. Clinical differentiation of these unusual cases from typical UNE is difficult. They are usually discovered either by careful electrophysiologic examination, at the time of surgery, or at the time of a second surgery after a failed ulnar surgery at the elbow.

ELECTROPHYSIOLOGIC EVALUATION

Like other mononeuropathies, the goal of nerve conduction studies and electromyography (EMG) is to demonstrate abnormalities that are limited to one nerve, in this case the ulnar nerve. Although in most cases the lesion is at the elbow, entrapment at the wrist, at the medial cord or lower trunk of the brachial plexus, or at the C8–T1 nerve roots can mimic a UNE clinically. Patterns of nerve conduction and EMG abnormalities often can be used to differentiate these possibilities (Table 19–2). If the ulnar nerve lesion is demyelinating, nerve conduction studies may demonstrate conduction velocity slowing, conduction block, or both at the lesion site. Unfortunately, in many cases of UNE, the pathophysiology is that of axonal loss, and nerve conduction studies demonstrate only a non-localizable ulnar neuropathy. The EMG study, if abnormal, then can be used to localize the lesion only at or proximal to the takeoff to the most proximal muscle affected on EMG. Because there are no ulnar-innervated muscles above the elbow, the electrophysiologic impression often is one of an ulnar neuropathy at or proximal to the FCU muscle (the most proximal ulnar-innervated muscle).

Nerve Conduction Studies

The goal of nerve conduction studies in patients with UNE is to demonstrate, when possible, focal demyelination across the elbow (Box 19–1). Focal demyelinating lesions may manifest as slowing of conduction velocity or conduction block between proximal and distal stimulation sites (Figure 19–8). As for focal slowing, one needs to consider how much slowing is abnormal. In general, conduction velocities of more proximal nerve segments are the same as, or more often faster than those of, distal segments. This is due to a combination of (1) larger nerve fiber diameter and less tapering of the nerve more proximally (the reason that conduction velocities are faster in the upper than in the lower extremity) and (2) warmer temperatures in the proximal limb compared to the distal limb. In ulnar motor nerve conduction studies, however, this relationship may not hold true unless the position of the elbow is controlled.

Table 19–2. Electromyographic and Nerve Conduction Study Abnormalities Localizing the Lesion Site in Ulnar Neuropathy

	UNW	UNE	Medial Cord	Lower Trunk	C8–T1
Electromyographic Findings					
First dorsal interosseous	X	X	X	X	X
Abductor digiti minimi	X	X	X	X	X
Flexor digitorum profundus (digits 4, 5)		X	X	X	X
Flexor carpi ulnaris		X	X	X	X
Abductor pollicis brevis			X	X	X
Flexor pollicis longus			X	X	X
Extensor indicis proprius				X	X
Cervical paraspinal muscles					X
Nerve Conduction Study Findings					
Abnormal ulnar digit 5 SNAP (if axonal)	X	X	X	X	
Abnormal dorsal ulnar cutaneous SNAP (if axonal)		X	X	X	
Abnormal medial antebrachial cutaneous SNAP (if axonal)			X	X	
Low ulnar CMAP (if axonal)	X	X	X	X	X
Low median CMAP (if axonal)			X	X	X
Conduction block/slowing of ulnar nerve across elbow (if demyelinating)		X			

X, may be abnormal; UNW, ulnar neuropathy at the wrist; UNE, ulnar neuropathy across the elbow; SNAP, sensory nerve action potential; CMAP, compound muscle action potential.

Note: The table indicates classic patterns; other patterns may be seen (see text for details).

Box 19–1. Recommended Nerve Conduction Study Protocol for Ulnar Neuropathy at the Elbow

Routine studies:

1. Ulnar motor study recording abductor digiti minimi, stimulating wrist, below elbow, and above elbow in the flexed elbow position (note: the optimal site for stimulating at the below-elbow site is 3 cm distal to the medial epicondyle)
2. Median motor study recording abductor pollicis brevis, stimulating wrist and antecubital fossa
3. Median and ulnar F responses
4. Ulnar sensory response, recording digit 5, stimulating wrist
5. Median sensory response, recording digit 2 or 3, stimulating wrist
6. Radial sensory response, recording snuffbox, stimulating lateral forearm

The following patterns may result:

Ulnar neuropathy at the elbow with demyelinating and axonal features:

- Low ulnar SNAP.
- Normal or low-amplitude ulnar CMAP with normal or slightly prolonged distal latency.
- Unequivocal evidence of demyelination at the elbow (conduction block and/or slowing >10–11 m/s across the elbow compared with the forearm segment, in the flexed elbow position).

Ulnar neuropathy at the elbow with pure demyelinating features:

- Normal distal ulnar SNAP and CMAP amplitudes and latencies.
- Unequivocal evidence of demyelination at the elbow (conduction block and/or slowing >10–11 m/s across the elbow compared with the forearm segment, in the flexed elbow position).

Non-localizable ulnar neuropathy (axonal features alone):

- Low ulnar SNAP.
- Normal or low-amplitude CMAP with normal or slightly prolonged distal latency.
- No focal slowing or conduction block across the elbow.

If the ulnar neuropathy is non-localizable, the following studies should be considered:

- Repeat motor studies recording the first dorsal interosseous.
- Inching studies across the elbow.
- Sensory or mixed nerve studies across the elbow.
- Recording the dorsal ulnar cutaneous SNAP (bilateral studies) (remember that the dorsal ulnar cutaneous SNAP can be normal in some patients with ulnar neuropathy across the elbow).
- Recording the medial antebrachial cutaneous SNAP (bilateral studies) if sensory loss extends above the wrist on clinical examination or there is a suggestion of lower brachial plexus lesion by history.

CMAP, compound muscle action potential; SNAP, sensory nerve action potential.

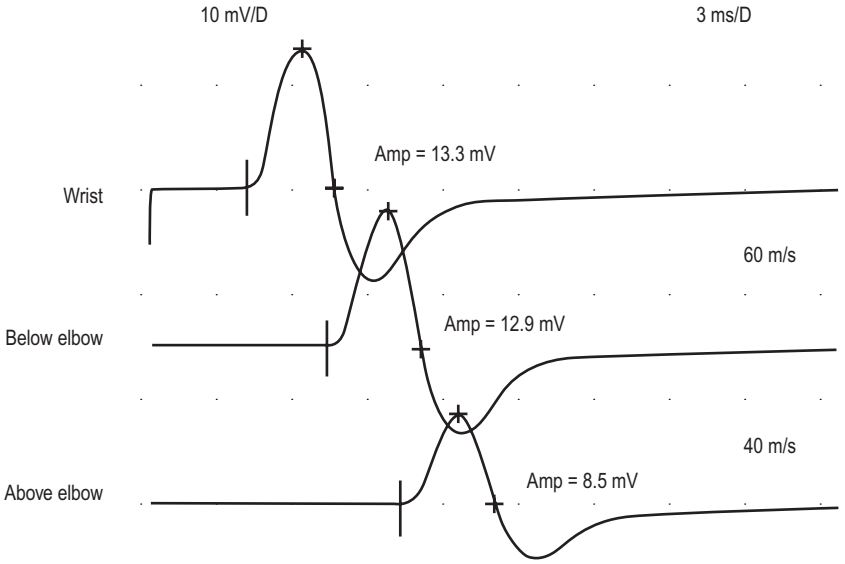

FIGURE 19–8 Focal slowing and conduction block at the elbow. The ulnar compound muscle action potential amplitude is normal at the wrist and below the elbow. Stimulation above the elbow results in a marked drop in amplitude and focal slowing between the above-elbow and below-elbow sites (40 m/s) compared to the forearm segment (60 m/s). These are the electrophysiologic markers of focal demyelination, which allow for definitive localization of ulnar neuropathy at the elbow.

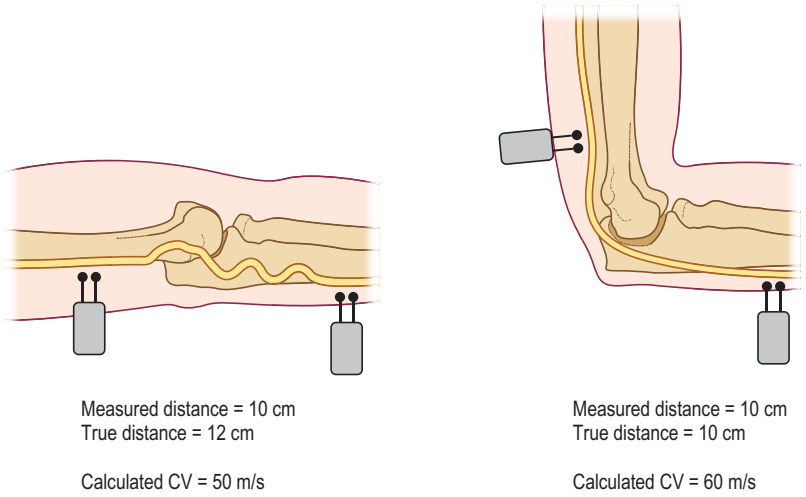

FIGURE 19–9 Extended versus straight elbow technique and measurement error. **Left:** Ulnar conduction studies performed in the extended elbow position often show artifactual slowing of conduction velocity across the elbow due to underestimation of the true nerve length. In the extended elbow position, the ulnar nerve is slack with some redundancy. **Right:** With the elbow flexed, the true length of the ulnar nerve is more accurately measured, and the resultant conduction velocity is more valid. To prevent this error, the flexed elbow is the preferred position when studying the ulnar nerve.

Differential Slowing: Flexed versus Extended Elbow Conduction Techniques

One of the more complicating factors in ulnar conduction studies is the position of the elbow and its effect on the calculated conduction velocity across the elbow. It has been well established in many studies that the position of the elbow during ulnar conduction studies strongly influences the calculated conduction velocity. Ulnar conduction studies performed in the extended (i.e., straight) elbow position often show artifactual slowing of conduction velocity across the elbow due to underestimation of the true nerve length (Figure 19–9). This is because in the extended elbow position, the ulnar nerve is slack with some redundancy. In normal subjects, this results in ulnar conduction velocities being slower in the across-the-elbow segment than in the segment above or below it, if the study is performed with the elbow in the extended position. Autopsy studies have confirmed that the length of the ulnar nerve across the elbow is measured more accurately with the elbow flexed (i.e., bent).

In several studies of normal controls, the mean differential slowing comparing the across-the-elbow conduction velocity to forearm conduction velocity in the flexed elbow position (90–135 degrees) was 0 m/s, with an upper limit

of normal of 10 to 11 m/s. In contrast, in the extended elbow position, mean slowing was 10 to 11 m/s, with an upper limit of normal in the range of 25 to 30 m/s (to reemphasize, in normal controls!). This extent of factitious conduction velocity slowing across the elbow, in the extended elbow position, is poorly appreciated in some EMG laboratories. Some laboratories arbitrarily use a value of 10 m/s differential slowing across the elbow, in the extended elbow position, to localize an ulnar neuropathy to the elbow. However, appreciation of the large range of variability in normal subjects, with the elbow in an extended position, is crucial to avoid erroneously diagnosing UNE in the normal population. An arbitrary cutoff value of 10 m/s differential slowing between the forearm and across elbow segments, in the extended elbow position, will result in many false-positive diagnoses of UNE. A patient with sensory loss in the little finger from a C8 radiculopathy would not be pleased to undergo ulnar nerve surgery simply based on a conduction velocity slowing of 10 m/s across the elbow compared to the forearm segment, if tested in the extended elbow position (as this is a normal finding in the extended elbow position).

Similar considerations apply to the absolute conduction velocity across the elbow in normal controls. The lower limit of normal for absolute conduction velocity across the elbow is 38 m/s in the extended elbow position, but never drops below 49 m/s in the flexed elbow position. Some have found that the absolute conduction velocity across the elbow is a better measure than differential conduction velocity slowing for detecting abnormalities in patients with ulnar neuropathy. Although absolute conduction velocity across the elbow may be considered a sensitive indicator of ulnar neuropathy, it does not localize the lesion. In any patient with significant axonal loss and dropout of the largest conducting fibers, conduction velocity will decrease across all nerve segments. An ulnar conduction velocity across the elbow segment of 40 m/s has little localizing value if the forearm conduction velocity is also 40 m/s.

In studies comparing the relative usefulness of the flexed versus extended elbow position in demonstrating focal slowing across the elbow, in those patients who had localizing electrophysiology, the flexed elbow position has been found to be more sensitive than the extended position. The difference in the yield between the flexed and extended positions likely is related to the greater range and variability found in normal subjects for differential and absolute conduction velocities across the elbow when tested in the extended elbow position, leading to lower cutoff values.

Thus, the flexed elbow position is considered the preferred technique when performing ulnar nerve conduction studies across the elbow. However, the flexed elbow position is more demanding in terms of measuring the curved anatomic course of the ulnar nerve around the elbow. In addition, the flexed position has the drawback of undercalling patients with UNE and subluxable ulnar nerves, which might lead to an overestimation of the true nerve length (see below). Nevertheless, it is far better to undercall UNE in this uncommon patient group, using the flexed technique, than to erroneously diagnose UNE in normal patients, using the extended position, with inappropriate low cutoff values.

Conduction Block

In addition to focal slowing, the other electrophysiologic marker of demyelination is conduction block (Figure 19–8). There is some controversy regarding how much the amplitude or area must drop between distal and proximal sites to be considered conduction block (see Chapter 3). Ulnar motor conduction studies in normal subjects have shown a maximum drop in compound muscle action potential (CMAP) amplitude of 10% comparing below and above elbow and 20 to 25% comparing wrist and above-elbow sites. Accordingly, any drop in amplitude of more than 10% between below and above the elbow, especially if associated with a very small change in stimulating electrode position (see the following section) or an abrupt drop in conduction velocity, likely represents true demyelination and is of localizing value.

The other issue that must be considered in the proper interpretation of a conduction block is to not confuse a Martin–Gruber anastomosis (MGA) with a conduction block. Almost always, an MGA is recognized on routine ulnar motor nerve conduction studies as a drop in amplitude and area between the wrist and below-elbow stimulation sites (i.e., mimicking a conduction block in the forearm). The site of the MGA is typically between 3 and 10 cm distal to the medial epicondyle, a location that is not thought to interfere with electrodiagnostic evaluation of UNE. However, there are rare reports of very proximal MGAs wherein the drop in amplitude and area occurs between the below-elbow and above-elbow stimulation sites – that is, across the elbow. Thus, in all cases of ulnar conduction block across the elbow, it is prudent also to check for an MGA (by stimulating the median nerve at the wrist and antecubital fossa, and recording the ulnar muscle) (see more below in the Nerve Conduction Pitfalls section).

Short Segment Incremental Studies ("Inching")

In a technique similar to that used for CTS, short segment incremental studies (SSIS), also known as "inching," can be performed effectively on the ulnar nerve across the elbow to try to localize the lesion, looking for an abrupt change in either latency or amplitude. The technique is performed as follows:

1. Either the abductor digiti minimi (ADM) or first dorsal interosseous (FDI) muscle is recorded. A mark is first placed halfway between the medial epicondyle and the olecranon to mark the ulnar groove. The location of the ulnar nerve is then mapped out. This process is basically identical to that of ensuring that the stimulator is directly over the nerve, as described in Chapter 3. This is accomplished by using a submaximal current (10–25% supramaximal), and stimulating medial to and lateral to the suspected nerve location in successive sites across the elbow. Several locations are tested sequentially from the

below-elbow to above-elbow sites. At each site, the location that gives the highest CMAP amplitude is the one that is closest to the nerve, and is marked with a marker pen. A line is then drawn across the elbow "connecting all the dots" to mark exactly where the nerve lies.

2. The spot between the medial epicondyle and olecranon is marked as the "zero" point along the line that was drawn across the elbow, and denotes the spot adjacent to the medial epicondyle. Next, 1 cm increments are carefully marked off, along the line that was drawn, from 4 cm below the "zero" point (medial epicondyle) to 4 or 6 cm above.
3. The ulnar nerve is stimulated supramaximally at each location at successive 1 cm intervals from below to above the medial epicondyle (Figure 19–10).

Any abrupt increase in latency or drop in amplitude between successive stimulation sites implies focal demyelination. In normal individuals, the latency between two successive 1 cm stimulation sites usually is 0.1 to 0.3 ms and rarely 0.4 ms (Figure 19–11). Any greater latency shift (i.e., ≥0.5 ms) suggests focal slowing and demyelination (Figure 19–12). The inching technique is very sensitive but technically demanding. Any error in measurement is magnified when such short distances are used. The technique has the advantage of potentially being able to directly locate the lesion either at the groove or at the cubital tunnel. This may be of more than just academic interest, because it may be of some help in deciding the best surgical technique to use (e.g., a lesion of the cubital tunnel may be best handled by a simple release rather than a transposition).

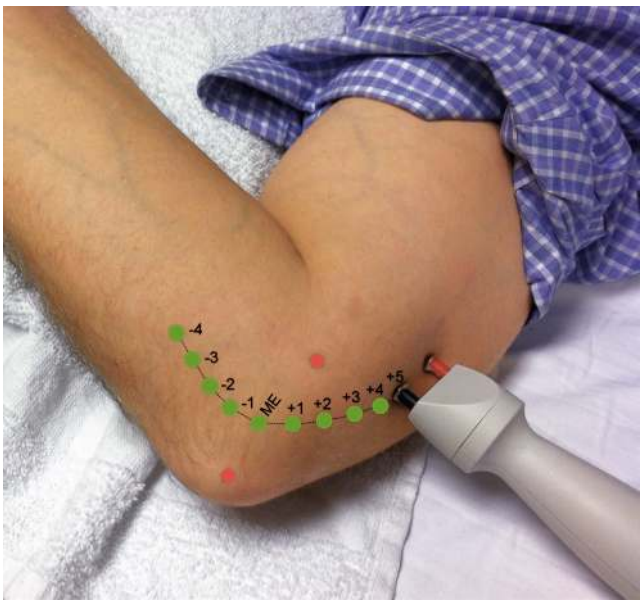

FIGURE 19–10 Short segment incremental studies. To perform these studies, a mark is first placed halfway between the medial epicondyle (ME) and the olecranon to mark the ulnar groove (the red circles are over the ME and olecranon). The location of the ulnar nerve is then mapped using a submaximal current and stimulating from the below-elbow to above-elbow sites, stimulating medial to and lateral to the suspected nerve location in successive sites across the elbow. The location that gives the highest compound muscle action potential amplitude is the one that is closest to the nerve. Several locations are tested from the below-elbow to above-elbow sites to mark exactly where the nerve lies. Then 1 cm increments are carefully marked off from 4 cm below the elbow to 4 or 6 cm above. The ulnar nerve then is stimulated supramaximally at each location at successive 1 cm intervals from below to above the elbow looking for any abrupt change in latency or drop in amplitude.

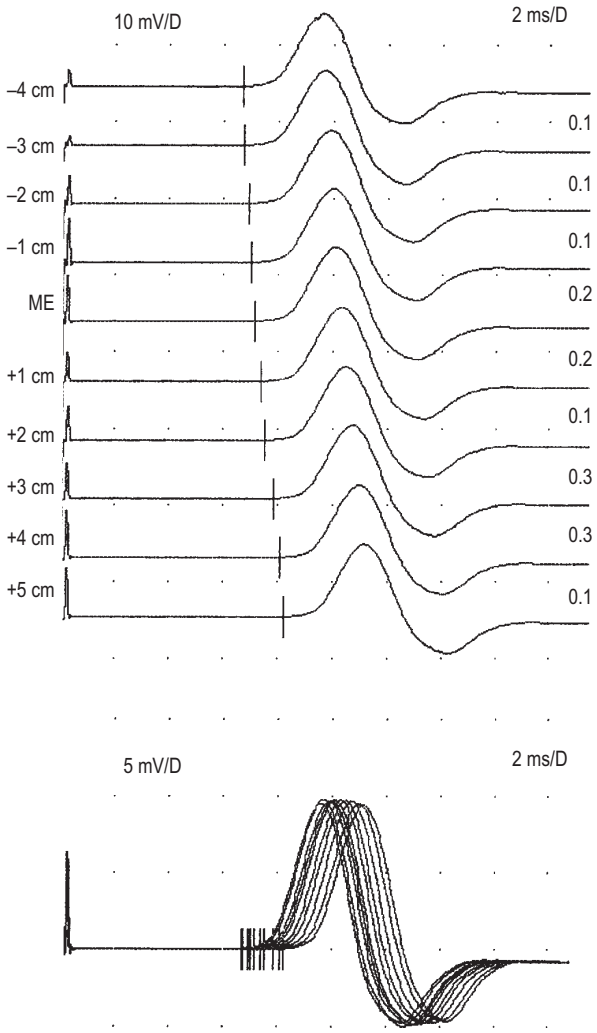

FIGURE 19–11 Inching around the elbow – normal. Ten successive traces in 1 cm increments from 4 cm below the medial epicondyle (ME) to 5 cm above. Superimposed traces are at the bottom. The numbers on the right are the latency differences in milliseconds between successive traces. Note: In normals, the amplitude of the waveform stays constant, and the latency difference between successive traces is 0.1 to 0.3 ms.

Recording the First Dorsal Interosseous

In entrapment neuropathies, it is well known that nerve fibers to certain muscles may be preferentially affected whereas others are preferentially spared. Within a nerve, bundles of nerve fibers to different muscles run in separate fascicles separated by connective tissue. External compression may preferentially affect the fibers within the fascicle

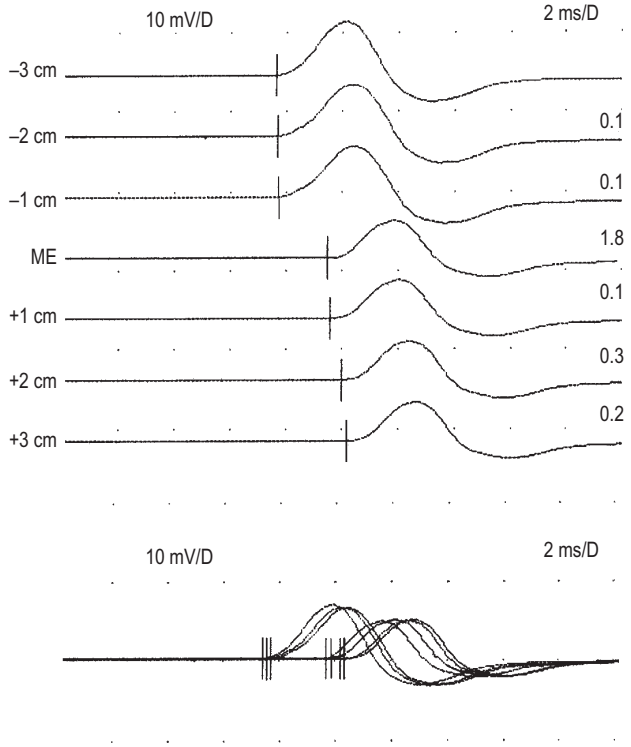

FIGURE 19–12 Inching around the elbow – cubital tunnel syndrome. Seven successive traces in 1 cm increments from 3 cm below the medial epicondyle (ME) to 3 cm above. Superimposed traces are at the bottom. The numbers on the right are the latency differences in milliseconds between successive traces. Note: Between the 1 cm below-elbow site and the ME, there is an abrupt change in latency (1.8 ms) and a drop in amplitude. In this case, inching studies not only have confirmed an ulnar neuropathy at the elbow but have precisely located the lesion at the cubital tunnel.

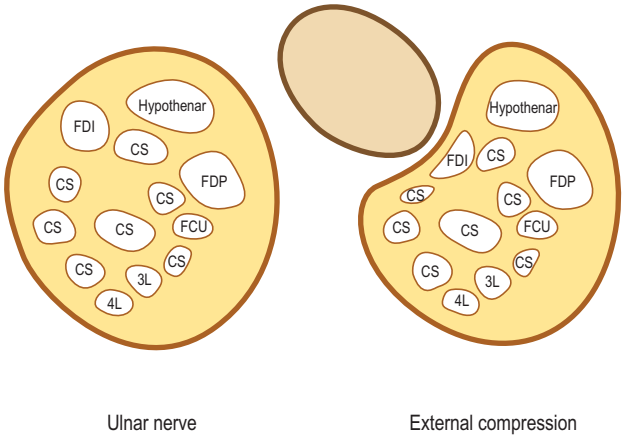

FIGURE 19–13 Fascicular involvement and sparing in entrapment neuropathies. Within a nerve, bundles of nerve fibers to different muscles run in separate fascicles separated by connective tissue. External compression may preferentially affect the fibers within the fascicle nearest to the compression, thereby preferentially affecting the muscle that those fibers innervate. Thus, recording from different muscles sometimes can increase the yield of demonstrating either focal slowing or conduction block. In this example, the fibers that supply the first dorsal interosseous (FDI) run in a fascicle closest to the site of compression. Accordingly, studying the FDI may have a higher yield of demonstrating abnormalities. 3L, third lumbrical; 4L, fourth lumbrical; FCU, flexor carpi ulnaris; FDP, flexor digitorum profundus, CS, cutaneous sensory.

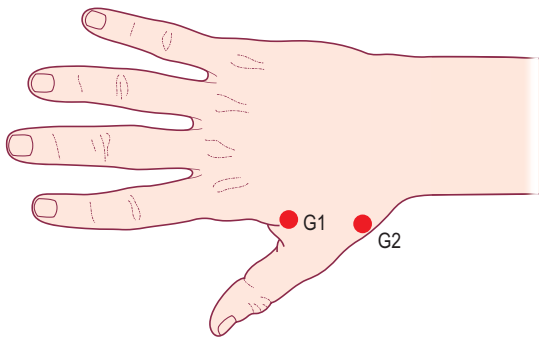

FIGURE 19–14 Recording the first dorsal interosseous muscle. The active electrode (G1) is placed over the muscle belly, and the reference electrode (G2) is placed over the metacarpophalangeal joint of the thumb. Recording the first dorsal interosseous is helpful in ulnar neuropathy at the wrist and in some cases of ulnar neuropathy at the elbow.

nearest to the compression, thereby preferentially affecting the muscle that those fibers innervate (Figure 19–13). Thus, recording from different muscles sometimes can increase the yield of demonstrating either focal slowing or conduction block. Some studies have shown that recording the first dorsal interosseous (FDI) may be a slightly more sensitive technique than recording the ADM in UNE. When recording the FDI, it is best to place the active electrode over the muscle belly and the reference over the metacarpophalangeal joint of the thumb (Figure 19–14). If the reference electrode is placed on the metacarpophalangeal joint of the index finger, an initial positive deflection often will be seen, which complicates latency measurements (Figure 19–15).

Mixed and Sensory Nerve Conductions

Mixed and sensory ulnar nerve conductions across the elbow may increase the yield of identifying focal slowing in patients with UNE. Sensory conductions can be performed antidromically or orthodromically from the fifth digit using the wrist, below-elbow, and above-elbow sites for either stimulating or recording, respectively. Likewise, a mixed nerve potential can be recorded below and above the elbow, stimulating the mixed nerve at the wrist.

Although these studies may have increased sensitivity for identifying UNE, they involve significant technical difficulties. Both sensory and mixed nerve potentials dramatically decrease in amplitude when recorded at greater distances because of the normal phenomena of temporal dispersion and phase cancellation (Figure 19–16). For instance, a normal antidromic ulnar sensory nerve action potential (SNAP) amplitude may be 20 μV when stimulated at the wrist; however, stimulating at the below-elbow site, the amplitude may fall to 5 μV and above the elbow to 2 μV. In patients with ulnar neuropathy, these potentials are often low if axonal loss has occurred. In such cases, the potential at the below-elbow and above-elbow sites may be

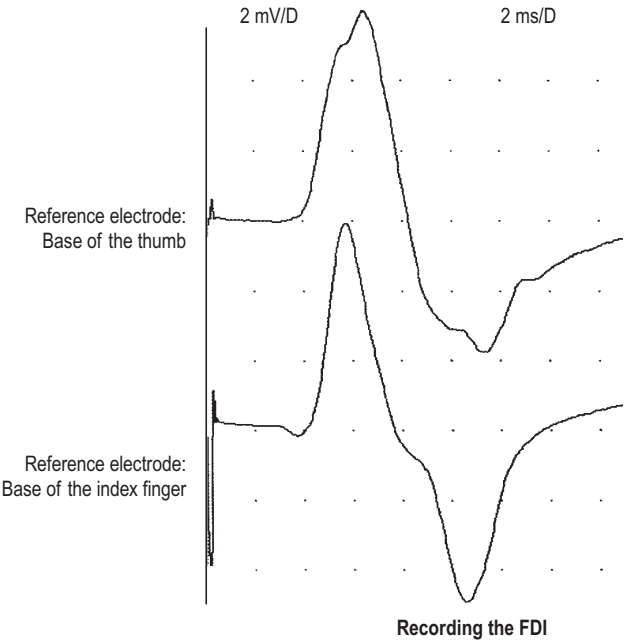

FIGURE 19–15 First dorsal interosseous muscle – compound muscle action potential morphology and placement of the reference electrode. When recording the first dorsal interosseous, it is best to place the active electrode over the muscle belly and the reference electrode over the metacarpophalangeal joint of the thumb. If the reference electrode is placed on the metacarpophalangeal joint of the index finger, an initial positive deflection often will be seen, which complicates latency measurements.

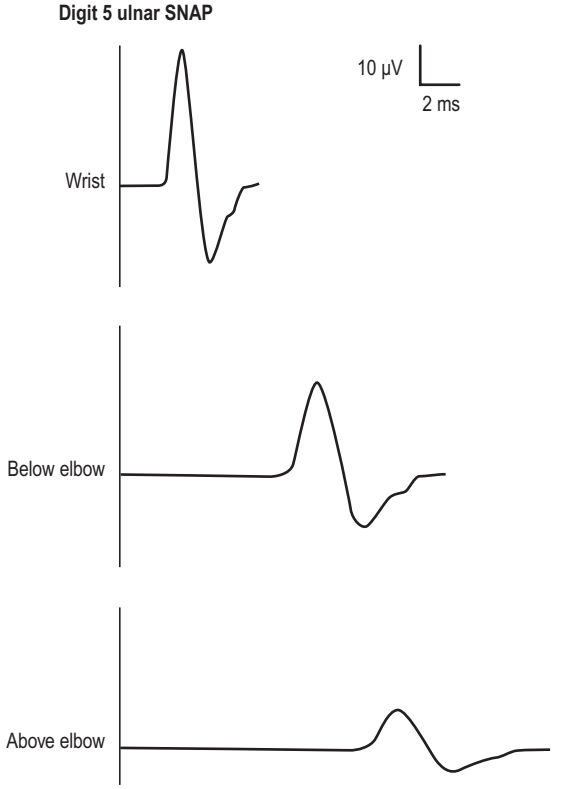

FIGURE 19–16 Ulnar sensory conduction studies: normal responses. An antidromic ulnar sensory nerve action potential can be recorded over the fifth digit, stimulating the wrist and below and above the elbow. Normal sensory responses decrease markedly in amplitude and area, whereas their duration increases at more proximal stimulation sites because of the normal processes of temporal dispersion and phase cancellation. For this reason, proximal demyelinating lesions in sensory fibers can be detected only by conduction velocity slowing and not by drop in amplitude or area.

very low or absent. Averaging is frequently required, and identification of the onset latency of these very small potentials is often difficult. These techniques may be best suited for mild cases of UNE, in which the distal sensory and mixed nerve potentials are of relatively normal amplitude. It is important to emphasize that when performing these studies, one is looking for focal slowing across the elbow and not for conduction block. Because of the normal drop in amplitude of sensory and mixed nerve fibers over distance, separating conduction block from normal temporal dispersion and phase cancellation may be very difficult (unless the stimulation sites are very close, such as the 1 cm increments used in inching across the carpal tunnel).

Dorsal Ulnar Cutaneous Sensory Study

Recording the dorsal ulnar cutaneous sensory nerve can be a useful technique to perform in patients with suspected ulnar neuropathy. The dorsal ulnar cutaneous sensory nerve arises 5 to 8 cm proximal to the wrist to supply sensation over the dorsal medial hand, as well as the dorsal fifth and medial fourth digits. The dorsal ulnar SNAP can be recorded by placing recording electrodes in the dorsal web space between the fifth and fourth digits and stimulating 8 to 10 cm proximally just below the ulnar styloid with the hand placed in a pronated position (Figure 19–17). Usually, the potential can be recorded using a small stimulating current (e.g., 5–15 mA). A normal antidromic response is

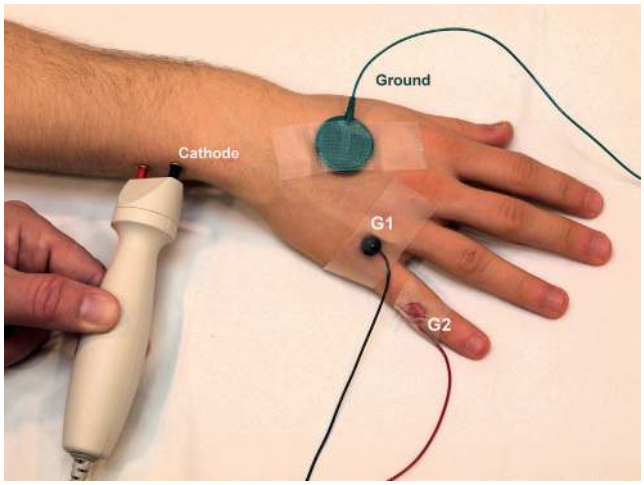

FIGURE 19–17 Dorsal ulnar cutaneous sensory study. With the hand in a pronated position, recording electrodes are placed in the dorsal web space between the fourth and fifth fingers. The stimulation site is just below the ulnar styloid, 8 to 10 cm proximal to the recording electrodes.

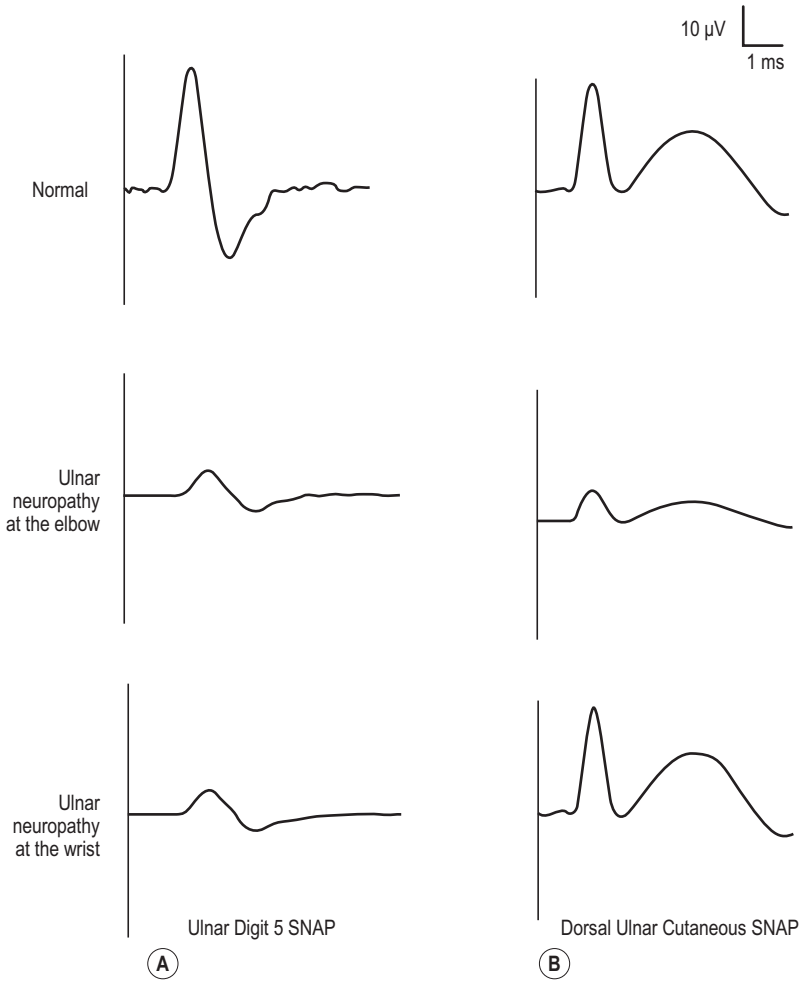

FIGURE 19–18 Ulnar sensory response patterns. The typical patterns of the routine ulnar digit 5 **(A)** and the dorsal ulnar cutaneous sensory nerve action potential (SNAP) responses **(B)** in ulnar neuropathy at the elbow and at the wrist. Both assume lesions that involve axonal loss and that there is no anomalous innervation of the dorsal ulnar cutaneous sensory nerve. However, significant exceptions to these classic patterns may occur: (1) if the ulnar neuropathy at the elbow is purely demyelinating or (2) if there is an ulnar neuropathy at the wrist that spares the sensory branch. In both of these situations, both ulnar SNAPs may be normal. In addition, some cases of mild axonal loss ulnar neuropathy at the elbow may spare the dorsal ulnar cutaneous sensory response and thus display the pattern common to ulnar neuropathy at the wrist, sparing the dorsal ulnar cutaneous SNAP.

greater than 8 μV, but, as in other uncommonly performed sensory nerve conduction studies, comparison with the contralateral asymptomatic side frequently is helpful. Any potential that is less than 50% that of the contralateral asymptomatic side likely is abnormal.*

With knowledge of the anatomy of both the routine digit 5 ulnar SNAP and the dorsal ulnar SNAP, one can predict the expected patterns of abnormalities in lesions of the ulnar nerve at the elbow and at the wrist (Figure 19–18). In patients with UNE, one would expect both SNAPs to be abnormal, provided there has been axonal loss. If the lesion is pure demyelination at the elbow, both distal sensory responses will be normal. Conversely, the presence of a normal dorsal ulnar SNAP with an abnormal digit 5 ulnar sensory response suggests that the lesion is at the wrist (the dorsal ulnar branch arises proximal to the wrist). Nevertheless, this latter pattern does not completely exclude the possibility of UNE. In some patients with definite UNE and axonal loss, the dorsal ulnar cutaneous SNAP is spared. This finding is thought to be due to preferential fascicular sparing of the dorsal ulnar cutaneous sensory fibers at the elbow. Studies of the microanatomy of the fascicle that forms the dorsal ulnar cutaneous sensory branch have shown that it commonly separates from the main ulnar trunk above the elbow and effectively travels as

*Remember that very rarely there is an anomalous innervation wherein the superficial radial sensory nerve supplies the entire dorsum of the hand, including the usual territory of the dorsal ulnar cutaneous sensory nerve. Thus, in cases where the dorsal ulnar cutaneous sensory response is absent, it is prudent to stimulate the superficial radial sensory nerve along the lateral radius with the recording electrodes in place for the dorsal ulnar cutaneous sensory study to ensure that this very rare anomalous innervation is not present.

a separate nerve next to the ulnar nerve in the forearm. Therefore, care must be taken in interpreting the findings of an abnormal digit 5 ulnar SNAP and a normal dorsal ulnar cutaneous SNAP. This pattern has limitations as a diagnostic marker and cannot be used alone to reliably localize the site of the lesion to the wrist. Electrophysiologic measurement of the dorsal ulnar SNAP is useful, but only in those cases where it is abnormal, implying localization of the lesion proximal to the wrist. *To summarize, although an abnormal dorsal ulnar cutaneous SNAP indicates that the lesion is proximal to the wrist, the converse is not necessarily true.*

Nerve Conduction Study Pitfalls

When performing routine ulnar nerve conduction studies, one must keep in mind several important technical factors:

1. When stimulating at the below-elbow site, the stimulator must be located 3 cm distal to the groove to ensure that the stimulation point is distal to the cubital tunnel.
2. Care must be taken not to stimulate too distally at the below-elbow site. The mistaken impression of UNE may occur if the below-elbow stimulation site is too distal and the patient has a coexistent high Martin–Gruber anastomosis (see Chapter 7). In this situation, one could see a drop in amplitude between the below-elbow and above-elbow stimulation sites. Thus, the optimal position to stimulate the below-elbow site is 3 cm distal to the medial epicondyle, not less, not more. In addition, as the nerve runs deep under the FCU, higher current is required at the below-elbow site, and supramaximal stimulation may be difficult to achieve.
3. The distance from the below-elbow site to the above-elbow site ideally should be 10 cm. If shorter distances are used, slight errors in measurement may create large differences in calculated conduction velocities. If longer distances are used, a longer length of normal nerve may dilute any conduction velocity slowing across the elbow, yielding normal or equivocal results.
4. The examiner should be cautious of any apparent conduction block between the wrist and below-elbow sites (Figure 19–19). Although there are very rare ulnar lesions in the forearm (e.g., exit of the cubital tunnel, fibrovascular bands in the forearm), this finding usually indicates a Martin–Gruber anastomosis, which is a normal finding. In these situations, stimulating the median nerve at the wrist and antecubital fossa, while recording the ulnar muscle (ADM or FDI), is essential to demonstrate that an anastomosis is present.
5. As noted above, a Martin–Gruber anastomosis is usually recognized on routine ulnar motor nerve conduction studies as a drop of amplitude and area between the wrist and below-elbow stimulation sites. However, there are rare reports of a very proximal MGA wherein the drop in amplitude and area occurs between the below-elbow and above-elbow stimulation sites (i.e., across the elbow), mimicking a conduction block across the elbow. The optimal site for the below-elbow stimulation site is 3 cm distal to the medial epicondyle. It should be more than 2 cm in order to be distal to the cubital tunnel, and less than 4 cm to avoid the nerve being so deep that it is difficult to stimulate. Although almost all MGAs occur in the forearm and do not interfere with electrodiagnostic determination of conduction block at the elbow, some reports have found an MGA to be as proximal as 3 cm distal to the medial epicondyle (Figure 19–20). Thus, in this very unusual situation, one could confuse an MGA (a normal finding) with an ulnar conduction block across the elbow. This underscores that the correct site to stimulate the ulnar nerve below the elbow is 3 cm distal to the medial epicondyle. In all cases where an ulnar conduction block is found across the elbow, it is prudent to check for an MGA (by stimulating the median nerve at the wrist and antecubital fossa, and recording the ulnar muscle).
6. Rarely, flexing the elbow causes the ulnar nerve to sublux out of the groove medially over the medial epicondyle. Recurrent subluxation of the ulnar nerve has been a suggested cause of repetitive ulnar trauma and UNE. Thus, in a situation where a patient does have UNE and a subluxed nerve when in the elbow flexed position, the measured distance around the groove will actually overestimate the length of the nerve, resulting in a spuriously fast conduction velocity across the elbow (see Figure 19–21). In one recent study of normal individuals with a subluxed ulnar nerve at the elbow, the average change in distance across the elbow segment was overestimated by 1.6 cm (range, 0.6 to 2.5 cm), which equated to

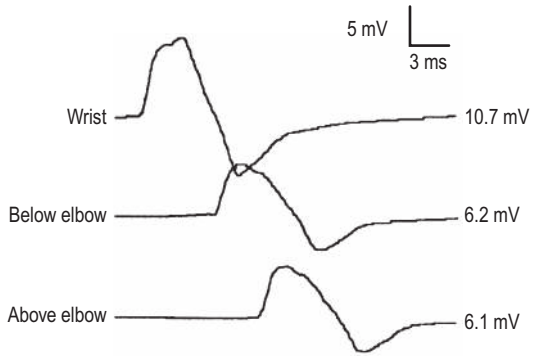

FIGURE 19–19 Martin–Gruber anastomosis mimicking conduction block of the ulnar nerve in the forearm. The most common cause of drop in amplitude between the wrist and below-elbow sites during routine ulnar motor conduction studies is not true conduction block but a Martin–Gruber anastomosis. Conduction block of the ulnar nerve in the forearm should never be diagnosed unless the median nerve has been stimulated at the wrist and antecubital fossa to exclude a Martin–Gruber anastomosis.

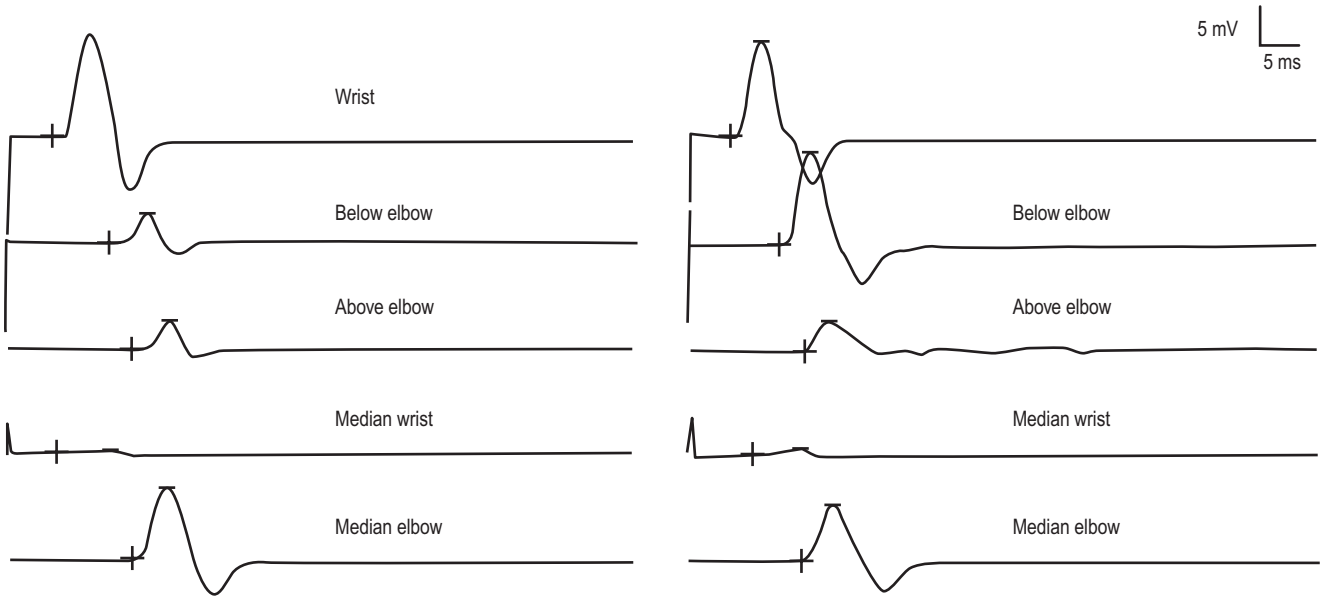

FIGURE 19–20 Martin–Gruber anastomosis: "conduction block" patterns in the forearm and across the elbow. **Left:** Recording from the first dorsal interosseous, there is a marked drop in amplitude between the wrist and below-elbow stimulation sites, suggesting a conduction block in the forearm. However, stimulating the median nerve at the wrist and antecubital fossa (elbow) while recording from the FDI confirmed an MGA, as a much larger response was present at the antecubital fossa than at the wrist. This is the common presentation of an MGA during routine ulnar motor conduction studies. **Right:** Recording from the first dorsal interosseous, there is a marked drop in amplitude between the below-elbow and above-elbow stimulation sites, which was interpreted as a conduction block across the elbow (i.e., UNE). However, stimulating the median nerve at the wrist and antecubital fossa (elbow) while recording from the FDI also demonstrated an MGA in this case. By short segment "inching studies," the site of the MGA was found to be 3 cm distal to the retrocondylar groove. This finding of an MGA mimicking an ulnar conduction block across the elbow is exceedingly rare.
(With permission from Leis, A.A., Stetkarova, I., Wells, K.J., 2010. Martin–Gruber anastomosis with anomalous superficial radial innervation to ulnar dorsum of hand: a pitfall when common variants coexist. Muscle Nerve 41, 313–317.)

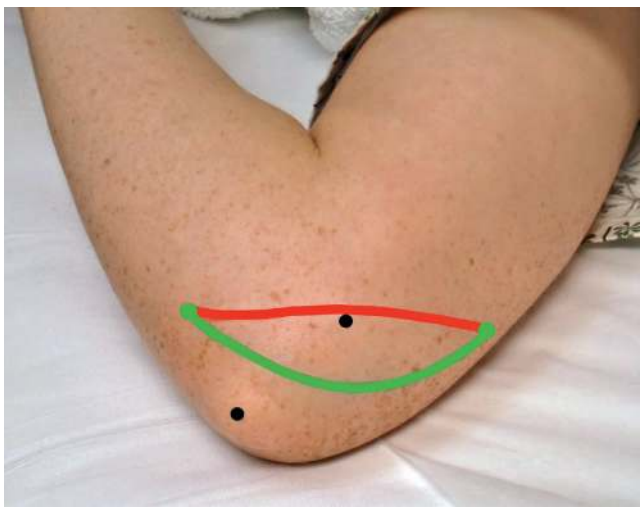

FIGURE 19–21 Ulnar nerve location at the elbow. In the vast majority of individuals, the ulnar nerve runs in a curved pattern (green line) through the ulnar groove between the medial epicondyle (upper black dot) and the olecranon (lower black dot). However, in some individuals, when the elbow is flexed the ulnar nerve will sublux out of the groove medially over the medial epicondyle (red line). In these cases, the measured distance (green line) will overestimate the true distance (red line), which then results in an overestimate of the ulnar conduction velocity across the elbow (i.e., the conduction velocity will be spuriously fast). Accordingly, in some cases of true UNE, this could result in a false-negative study.

an overestimated ulnar conduction velocity across the elbow an average of 7.9 m/s (range, 3.0 to 13.0 m/s). One can see how this could result in a false-negative study in a person with UNE, if the conduction velocity across the elbow were overestimated, and did not meet the cutoff criteria for absolute and differential focal slowing across the elbow. It is important to emphasize that a subluxed ulnar nerve interferes with determination of the true conduction velocity across the elbow, but not conduction block across the elbow. These cases emphasize the value of SSIS ("inching") in suspected UNE, as this technique maps out the exact location of the ulnar nerve, and is able to detect the precise area of slowing.

Electromyographic Approach

The strategy in the EMG examination of UNE is directed toward identifying denervation or reinnervation limited to the ulnar-innervated muscles of the hand and forearm (Box 19–2). Useful muscles to check are the FDI, FDP (to digit 4 or 5), and FCU. Of the intrinsic ulnar hand muscles, testing of the FDI is usually tolerated best by patients. Testing of the ADM often is perceived as more painful, similar to the abductor pollicis brevis (APB). Median- and radial-innervated C8 muscles are screened to rule out

Box 19–2. Recommended Electromyographic Protocol for Ulnar Neuropathy at the Elbow

Routine muscles:

1. Ulnar muscle distal to the wrist (first dorsal interosseous or abductor digiti minimi)
2. Ulnar muscles in the forearm (FDP 5 and flexor carpi ulnaris)

If any of the ulnar muscles are abnormal, test the following additional muscles:

1. At least two non-ulnar lower trunk/C8–T1-innervated muscles (e.g., abductor pollicis brevis, flexor pollicis longus, extensor indicis proprius) to exclude a lower brachial plexopathy, polyneuropathy, or C8–T1 radiculopathy
2. C8 and T1 paraspinals

Special considerations:

- If the ulnar neuropathy is superimposed on another condition (e.g., polyneuropathy, plexopathy, radiculopathy), a more detailed electromyographic examination will be required.
- The abductor digiti minimi frequently is painful and more difficult for some patients to tolerate than the first dorsal interosseous.
- In ulnar neuropathy at the elbow, the flexor carpi ulnaris may be spared even when the FDP 5 is abnormal.
- If no evidence of ulnar neuropathy is found on nerve conduction studies, electromyographic study should focus on evaluation for lower trunk brachial plexopathy or C8–T1 radiculopathy if clinically indicated.

FDP, flexor digitorum profundus.

evidence of a C8 radiculopathy or lower trunk brachial plexopathy. Useful muscles to check are the APB, flexor pollicis longus, and extensor indicis proprius. If a cervical radiculopathy is suggested based on clinical history, then sampling the cervical paraspinal muscles is also indicated.

Of interest, the FCU is either normal or minimally affected in many surgically proven cases of UNE. Overall, involvement of the FCU correlates with the severity of the ulnar neuropathy both clinically and electrically. The finding of FCU involvement is slightly more common in lesions at the groove than at the cubital tunnel. Although sparing of the FCU was classically thought to be due to the muscular branch to the FCU arising proximal to the groove, cadaver anatomic studies have found this not to be the case. The true etiology of FCU sparing likely is related to either *differential fascicular susceptibility* (i.e., different fascicles are involved or spared depending on their position within the nerve trunk in relationship to the compression site) or the "dying back" concept of nerve lesions (i.e., the most distal muscles are maximally affected and the proximal ones are relatively preserved). This EMG pattern of an abnormal FDI and FDP to digits 4 and 5, but a spared FCU, is important to recognize in patients with UNE.

Unfortunately, there is no ulnar-innervated muscle above the elbow. If all ulnar-innervated muscles, including the FCU, are abnormal and the nerve conduction studies do not identify any focal slowing or conduction block around the elbow, the best electrophysiologic diagnosis that can be reached is one of an ulnar neuropathy that can only be localized at or proximal to the takeoff to the FCU muscle. Although most such cases will in fact be cases of UNE, the electrophysiologic examination cannot exclude an unusual ulnar neuropathy in the proximal arm or a lower brachial plexopathy that selectively involves ulnar fibers. Examination of the medial antebrachial cutaneous sensory nerve, which comes directly off the medial cord of the brachial plexus, may help identify a lower brachial plexus lesion.

EXAMPLE CASES

Case 19–1

History and Physical Examination

A 44-year-old man was referred for numbness and pain in his right arm and hand. The patient described several months of numbness involving his right fourth and fifth digits, accompanied by pain in the right elbow, shoulder, and neck. Examination showed hypesthesia in the right ulnar distribution. There was slight weakness of all intrinsic hand muscles. Reflexes were normal. There was no tenderness of the ulnar nerve in the groove.

Summary

The clinical history and examination suggest dysfunction in the ulnar nerve distribution. The fourth and fifth fingers are innervated by the ulnar nerve, as are most of the intrinsic hand muscles, which are described as slightly weak. There is nothing further in the history or examination to suggest a more specific localization. Indeed, the patient has some pain in the elbow, shoulder, and neck but no tenderness in the ulnar groove. This complicates the case further because the differential diagnosis of dysfunction of the ulnar nerve includes ulnar neuropathy at the wrist, UNE, a lower brachial plexopathy, and a lesion of the C8–T1 nerve roots. Occasionally, patients with UNE have pain that radiates more proximally into the arm and shoulder but not into the neck. Pain into the neck associated with more distal numbness and weakness usually suggests a cervical radiculopathy.

The nerve conduction studies begin with a routine median motor conduction study recording the APB. Although the CMAP amplitude is normal with a normal conduction velocity, the distal motor latency is slightly prolonged. This mild prolongation of distal latency may be due to a median nerve lesion at the wrist. However, it may also simply suggest loss of the fastest conducting axons from any axonal loss lesion involving the median-innervated C8–T1 fibers from the anterior horn cells in the spinal cord on down. Further studies will be required to make this distinction. The routine ulnar motor conduction study recording the ADM muscle shows a marked decrease in motor amplitude but with a normal distal latency. The conduction velocity in the forearm is normal, but the conduction around the elbow is markedly reduced at 34 m/s. Correspondingly, the F responses are prolonged, compared both with normal controls and with

CASE 19–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F Wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	6.4		≥4	4.6		≤4.4				31		≤31
Median (m)	Antecubital fossa	APB	6.0			8.3			55		≥49			
Ulnar (m)	Wrist	ADM	2.9		≥6	3.2		≤3.3				34		≤32
Ulnar (m)	Below elbow	ADM	2.7			6.5			58		≥49			
Ulnar (m)	Above elbow	ADM	2.4			9.4			34		≥49			
Median (s)	Wrist	Index finger	27		≥20	3.2		≤3.5	58		≥50			
Ulnar (s)	Wrist	Little finger	7	22	≥17	3.1	3.0	≤3.1	49	53	≥50			
Radial (s)	Forearm	Snuffbox	28		≥15	2.5		≤2.9	55		≥50			
Median (mixed study)	Palm	Wrist	50		≥50	2.2		≤2.2	50		≥50			
Ulnar (mixed study)	Palm	Wrist	4		≥12	2.3		≤2.2	49		≥50			
Mixed difference						−0.1		≤0.3						

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis; ADM = abductor digiti minimi.

Note: All sensory and mixed latencies are peak latencies. All sensory and mixed-nerve conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 19–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right FDI	↑	+3	0	NL	↓↓	+2	+2	+2
Right APB	NL	0	0	NL	↓	+1	+1	NL
Right extensor indicis proprius	↑	0	0	NL	↓↓	+1	+1	+1
Right FCU	NL	0	0	NL	↓	+1	+1	NL
Right FDP 5	NL	0	0	NL	↓	+1	+1	NL
Right biceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right pronator teres	NL	0	0	NL	NL	NL	NL	NL
Right triceps brachii	NL	0	0	NL	↓	NL	NL	NL/+1
Right C7 paraspinal	↑	0	0	NL	NL	NL	NL	NL
Right C8 paraspinal	↑	+2	0	NL	NL	NL	+1	+1
Right T1 paraspinal	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓ = slightly reduced; ↓↓= moderately reduced; NL = normal; FDI = first dorsal interosseous; APB = abductor pollicis brevis; FCU = flexor carpi ulnaris; FDP = flexor digitorum profundus.

the median nerve. This study of the ulnar nerve clearly demonstrates a UNE: there is a demyelinating conduction velocity in the segment across the elbow. There is also clear differential slowing (24 m/s) when the forearm segment is compared with the across-elbow segment. Any slowing of more than 10 to 11 m/s in the flexed elbow position denotes focal slowing. The ulnar F response is prolonged; the reason is similar to why the median F response is prolonged in cases of CTS. The F response must travel antidromically through the ulnar lesion at the elbow, then to the anterior horn cells, and then back down the arm, again through the ulnar lesion,

and finally distally to the ADM muscle. Because the F response must travel twice through the area of demyelination, prolonged, dispersed, or absent F responses are not unusual in UNE.

Next, the routine median sensory study is performed, which is normal including the distal peak latency of 3.2 ms. Thus, there is not good evidence at this time that the prolonged median distal motor latency is due to a median neuropathy at the wrist. Finding a normal median sensory latency with slowed median motor fibers is extraordinarily unusual in CTS. The routine ulnar study shows a low SNAP on the involved right side, with a normal contralateral potential. There is already a good explanation for the abnormal ulnar SNAP: the motor studies have already clearly defined a UNE. The low ulnar sensory amplitude signifies that there has been secondary axonal loss in the ulnar sensory fibers, as was also found in the ulnar motor fibers. The normal radial sensory response reinforces the evidence that there is not a more widespread polyneuropathy or brachial plexopathy. Finally, the median and ulnar palm-to-wrist mixed nerve studies are performed, showing peak latencies of 2.2 and 2.3 ms, respectively, with a low ulnar amplitude. Although the ulnar latency is slightly prolonged compared to normal, there is no significant asymmetry between the two latencies, and there is no electrophysiologic evidence for a median neuropathy across the wrist. The prolonged median distal motor latency to the APB still has not been adequately explained. With normal median sensory and palm-to-wrist mixed nerve responses, a median neuropathy at the wrist is unlikely.

The EMG shows prominent denervation and reinnervation with decreased recruitment in the FDI, consistent with the previously defined UNE. Although the APB does not show any denervation, it does show reduced recruitment with some reinnervation of motor unit action potentials (MUAPs). This finding correlates well with the mild prolongation of the median distal motor latency, suggesting that there has been some loss of the fastest conducting axons. One might ask why the median motor CMAP amplitude is normal when the EMG study shows evidence of axonal loss. CMAP amplitudes can remain in the normal range for one of two reasons. First, if reinnervation has been sufficient, the CMAP amplitude may remain normal. Second, the CMAP amplitude is only in the "normal range." There is a wide range of normal values. In this particular case, the patient's CMAP amplitude may have been greater initially and then decreased, still remaining within the "normal range."

The reason for the reinnervation in the APB remains unclear. There must be a second problem beyond the UNE. Moving on, the extensor indicis proprius (also a C8-innervated muscle) not only shows increased insertional activity, but also dramatic changes in recruitment and MUAP size. At this point, the additional abnormalities in the APB and extensor indicis proprius suggest that there is either a lesion distally (because both are distal muscles), such as a polyneuropathy, or that there is a superimposed lower brachial plexus lesion or cervical radiculopathy at the C8 level. The normal median and radial sensory amplitudes from the nerve conduction studies effectively exclude a polyneuropathy. These EMG abnormalities possibly represent a superimposed lesion of the lower brachial plexus or C8 nerve root. Because the extensor indicis proprius (a radial, posterior cord-innervated muscle) is abnormal, a medial cord lesion is excluded. The additional lesion must be at the level of the lower trunk of the brachial plexus or located more proximally. Further EMG demonstrates that both the FCU and the FDP to digit 5 show decreased recruitment and mild reinnervation, consistent with both UNE (as demonstrated from the nerve conduction studies) and the superimposed lesion that is being investigated. Examination of the biceps and pronator teres shows normal results, suggesting that there is not a more widespread lesion affecting the C6–C7 nerve roots or the upper and middle trunks of the brachial plexus. The triceps brachii also is slightly abnormal, but the triceps, a C6–C7–C8-innervated muscle, also runs through the middle and lower trunks of the brachial plexus. Finally, the paraspinal muscles are extremely informative, showing frank fibrillation potentials at the C8 paraspinals. This finding unequivocally demonstrates that the additional lesion is at or proximal to the root level, although the myotomal level of the lesion is best determined by the limb muscles.

Therefore, at this time we can form an electrophysiologic impression.

IMPRESSION: *There is electrophysiologic evidence of an ulnar neuropathy at the elbow with a superimposed C8 radiculopathy.*

Several questions deserve consideration.

Does the Clinical–Electromyographic Correlation Make Sense?

The important findings in this case are the unequivocal nerve conduction abnormalities of the ulnar nerve around the elbow, demonstrating a lesion at that site, and the presence on EMG of clear neuropathic changes in several C8-innervated muscles beyond the ulnar-innervated muscles, including the paraspinal muscles. The finding of paraspinal denervation signifies that the lesion is at or proximal to the root level (root or motor neuron). Thinking back to the clinical history and examination, we now have a better explanation for the patient's pain not only in the shoulder and elbow, which may be seen with UNE, but also in the neck, which is a consequence of the radiculopathy. The radiculopathy also explains the slight weakness of all intrinsic hand muscles, some of which are median and some of which are ulnar innervated. Some would call this a *double crush syndrome*, in that ulnar fibers have been affected at two lesion sites. Whether or not these two lesions are causally related remains controversial. The important point is that detailed nerve conduction and EMG studies are required to sort out that

there are, in fact, two superimposed lesions. One can easily see that if the nerve conduction studies had been limited to ulnar nerve conductions and the EMG studies had been limited to ulnar-innervated muscles and the APB, the cervical radiculopathy could easily have been missed, as one might have diagnosed only a UNE and possibly (inaccurately) a superimposed median neuropathy at the wrist. As noted earlier, however, the normal median sensory response and normal median palmar mixed nerve response effectively exclude the diagnosis of median neuropathy at the wrist.

Why is the Median Distal Motor Latency Prolonged if there is no Carpal Tunnel Syndrome?

The mild prolongation of the distal median motor latency is consistent with dropout of the fastest conducting axons. Once the study is completed, there is an adequate explanation for this finding. Some of the fastest conducting axons to the APB muscle have been lost because of the C8 radiculopathy. The mild distal latency prolongation does not indicate unequivocal demyelination but is only in the range of axonal loss. The needle EMG shows clear evidence of reinnervation in the APB, indicating some prior axonal loss.

Case 19–2

History and Physical Examination

A 53-year-old right-handed man developed numbness over the fourth and fifth digits of the right hand. There was no history of elbow trauma. Subsequently, he developed weakness of grip and loss of dexterity.

Examination demonstrated a Tinel's sign over the right elbow and mild wasting of the ulnar intrinsic hand muscles, along with weakness of distal flexion of the little finger. Sensory loss was present in the fifth and splitting the fourth finger, and it extended just proximal to the distal wrist crease.

Summary

The history and examination in this case are similar to those in Case 19–1. There appear to be clear abnormalities in the distribution of the ulnar nerve. Again, the numbness of the fourth and fifth fingers is in the distribution of the ulnar nerve, along with weakness of grip and loss of dexterity, which can easily be explained by weakness of ulnar-innervated intrinsic hand muscles. The examination demonstrates a Tinel's sign over the right elbow, suggesting that the lesion may be at that site. One must always be cautious in interpreting Tinel's signs, however, because they occur in some normal subjects. The sensory loss appears to be quite consistent with ulnar neuropathy.

The first nerve conductions demonstrate normal median CMAP amplitudes, latencies, conduction velocities, and F responses. When the ulnar study is performed, however, a low CMAP amplitude is seen on the involved right side, with a normal amplitude on the contralateral side. The distal latency on the involved side is just at the upper limit of normal. Notably, there is slight slowing around the elbow compared to the forearm velocity, but the conduction velocity does not slow by 10 to 11 m/s compared to the forearm segment, nor is it slowed in an

CASE 19–2. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F Wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	5.8	8.2	≥4	3.3	3.3	≤4.4				25	26	≤31
Median (m)	Antecubital fossa	APB	5.4	7.1		7.2	7.0		51	53	≥49			
Ulnar (m)	Wrist	ADM	3.2	8.2	≥6	3.3	3.1	≤3.3				31	28	≤32
Ulnar (m)	Below elbow	ADM	2.9	8.1		6.4	6.0		65	68	≥49			
Ulnar (m)	Above elbow	ADM	2.8	8.1		8.0	7.5		61	66	≥49			
Median (s)	Wrist	Index finger	21	23	≥20	3.1	3.1	≤3.5	54	56	≥50			
Ulnar (s)	Wrist	Little finger	NR	20	≥17	NR	2.7	≤3.1	NR	55	≥50			
Dorsal ulnar (s)	Wrist	Dorsal medial hand	NR	10	≥8	NR	3.0	≤2.8	NR	57	≥50			
Median (mixed study)	Palm	Wrist	52		≥50	2.0		≤2.2	53		≥50			
Ulnar (mixed study)	Palm	Wrist	NR		≥12	NR		≤2.2	NR		≥50			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; APB = abductor pollicis brevis; ADM = abductor digiti minimi.
Note: All sensory and mixed latencies are peak latencies. All sensory and mixed-nerve conduction velocities are calculated using onset latencies.
The reported F wave latency represents the minimum F wave latency.

CASE 19–2. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Configuration			
					Recruitment	Duration	Amplitude	Polyphasia
Right FDI	↑	+2	0	NL	↓↓	1+	NL	NL
Right ADM	NL	+1	0	NL	↓	1+	+1	+1
Right APB	NL	0	0	NL	NL	NL	NL	NL
Right extensor indicis proprius	NL	0	0	NL	NL	NL	NL	NL
Right FCU	NL	0	0	NL	NL	NL	NL	NL
Right FDP 4,5	↑	+1	0	NL	NL	+1	+1	+1
Right biceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right flexor pollicis longus	NL	0	0	NL	NL	NL	NL	NL
Right triceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right medial deltoid	NL	0	0	NL	NL	NL	NL	NL
Right C7 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right C8 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right T1 paraspinal	NL	0	0	NL	NL	NL	NL	NL

↑= increased; ↓ = slightly reduced; ↓↓= moderately reduced; NL = normal; FDI = first dorsal interosseous; ADM = abductor digiti minimi; APB = abductor pollicis brevis; FCU = flexor carpi ulnaris; FDP = flexor digitorum profundus.

absolute sense in the demyelinating range (<35 m/s). In addition, there is no evidence of conduction block across the elbow. The ulnar F response, however, is prolonged in comparison to the median F response.

The sensory studies are performed next. The median sensory amplitudes are normal bilaterally, as are the latencies and conduction velocities. The ulnar sensory study demonstrates an absent response on the involved right side and a normal contralateral response. Therefore, at this point in the study, it is clear that there is involvement of ulnar motor and sensory fibers. *However, there is no localizing electrophysiology*. The only localizing information comes from the absence of the sensory response, which denotes a postganglionic lesion. This finding is not consistent with a cervical radiculopathy.

To look for evidence of ulnar neuropathy at the wrist, some additional studies are performed. The dorsal ulnar cutaneous study is performed, and the response is absent on the involved side, whereas a normal response is found on the contralateral side. Because the dorsal ulnar cutaneous sensory nerve originates several centimeters proximal to the wrist, an ulnar nerve lesion at the wrist has effectively been ruled out. The lesion affecting the ulnar nerve remains non-localizable, but it must be above the level of the wrist. The EMG study will be needed to localize the lesion further.

The EMG study shows clear denervation and reinnervation in the FDI, ADM, and FDP to digits 4 and 5, all ulnar-innervated muscles. The FCU is normal. Next, non-ulnar C8–T1-innervated muscles must be sampled. The APB, flexor pollicis longus, and extensor indicis proprius are sampled and are normal. The lack of abnormalities in these muscles makes a lesion of the C8–T1 nerve roots or lower trunk of the brachial plexus much less likely. Finally, the lower cervical paraspinal muscles are sampled and are normal.

At this time we are ready to form our electrophysiologic impression.

IMPRESSION: *There is electrophysiologic evidence consistent with an ulnar neuropathy at or above the takeoff to the FDP muscle.*

Several questions should be considered.

Can the Ulnar Neuropathy be More Precisely Localized?

One may ask whether the ulnar nerve lesion can be localized further using the information at hand. For instance, the FDP is abnormal whereas the FCU is normal. Does not that localize the lesion to between those two sites? Unfortunately, the answer is no. In nerve lesions of any kind, the distal muscles tend to be the most affected. In addition, especially in entrapment neuropathy, certain fascicles are often relatively spared while others are preferentially involved.

Demonstrating an ulnar neuropathy (which most likely is localized at the elbow) whose electrophysiology does

not clearly localize it at the elbow often is frustrating for the electromyographer. In this case, a lesion at the wrist has been excluded by the abnormal dorsal ulnar cutaneous sensory response. Unusual lesions in the distal forearm have also been excluded because the FDP is abnormal. The lesion must be at or above that site. Often, in UNE, the branch to the FCU is spared. This finding can be seen in ulnar neuropathy at both the groove and the cubital tunnel.

What Other Studies Might Localize the Lesion Further?

One might consider performing inching studies across the elbow. The procedure is technically demanding, but it clearly increases the diagnostic sensitivity of the electrophysiologic examination. Stimulating the ulnar nerve at the elbow in 1 cm increments from above to below the elbow (looking for either an abrupt decrease in amplitude or an abrupt increase in latency) may be very useful in localizing the lesion at the elbow.

Another possibility would be to repeat the ulnar motor study but recording from the FDI muscle. Sometimes, focal slowing or conduction block may be identified when recording the FDI, even in cases when recording the ADM muscle is normal. One also might consider performing either sensory or mixed-nerve conduction studies across the elbow. Although sensory and mixed-nerve conduction studies are more sensitive than motor conduction studies, when the sensory nerve action potential is low or absent with wrist stimulation, as in this case, usually one can expect absent potentials at the more proximal sites above and below the elbow. These studies are best reserved for the patient who clinically demonstrates a clear ulnar neuropathy and whose distal sensory potentials are relatively intact.

To localize a lesion by nerve conduction studies requires demonstrating demyelination, either focal slowing or conduction block. Unfortunately, the pathophysiology of UNE is often axonal loss alone. In that case, the routine as well as the additional nerve conduction studies often fail to localize the lesion.

The abnormal ulnar SNAP signifies that the lesion is at or distal to the dorsal root ganglion. The abnormal EMG findings in the flexor digitorum profundus signify that the lesion is at or proximal to that muscle. The lesion is somewhere between those two sites but unfortunately cannot be localized further based on the present study. The electrophysiologic study cannot completely exclude the possibility that the ulnar nerve lesion is in the higher arm in an unusual location or in the lower part of the brachial plexus, either the lower trunk or the medial cord. The medial antebrachial cutaneous sensory nerve could be studied if there is a clinical suspicion of a lower brachial plexopathy.

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Ulnar Neuropathy at the Wrist 20

Ulnar neuropathy at the wrist (UNW) is a rare condition that sometimes is confused with ulnar neuropathy at the elbow (UNE) or, more often, with early motor neuron disease. Knowledge of the detailed anatomy of the ulnar nerve at the wrist is necessary to understand the several unique clinical and electrophysiologic patterns that can occur with UNW (Figure 20–1).

ANATOMY

At the wrist, the ulnar nerve enters *Guyon's canal* at the level of the distal wrist crease. The canal is formed proximally by the pisiform bone and distally by the hook of the hamate. The floor is formed by a combination of the thick transverse carpal ligament and the adjacent hamate and triquetrum bones. The roof is loosely formed. In contrast, there is a thick band at the outlet that runs from the hook of the hamate to the pisiform bone, the pisohamate hiatus. In the canal, the nerve divides into *superficial* and *deep* branches. Before exiting through the pisohamate hiatus, motor fibers are given off the deep branch (also known as the *deep palmar motor* branch) to three of the four hypothenar muscles (abductor digiti minimi [ADM], flexor digiti minimi and opponens digiti minimi). After the hiatus, the superficial branch supplies sensation to the volar fifth and medial fourth digits, and also supplies motor innervation to the one remaining hypothenar muscle, the palmaris brevis. The deep palmar motor branch goes on to innervate the third and fourth lumbricals, the four dorsal and three palmar interossei, the adductor pollicis, and the deep head of the flexor pollicis brevis.

CLINICAL

Several subtypes of UNW occur, depending on the exact location of the lesion and which fibers are affected (Table 20–1 and Box 20–1). The following lesions have been described:

- *Distal deep palmar motor lesion*: Affects all muscles supplied by the deep palmar motor branch except the hypothenar muscles; the superficial branch containing the sensory fibers and motor innervation to the palmaris brevis is not affected.
- *Proximal deep palmar motor lesion*: Affects all ulnar-innervated hand muscles, including the hypothenar muscles, with the exception of the palmaris brevis; the superficial branch containing the sensory fibers and motor innervation to the palmaris brevis is not affected.
- *Proximal canal lesion*: Affects all branches of the ulnar nerve, including the proximal and distal deep palmar motor and the superficial branches which contain the sensory fibers and motor innervation to the palmaris brevis.
- *Superficial branch lesion*: Affects only the superficial branch, which is primarily sensory. Note that while the palmaris brevis muscle is affected, this is not clinically apparent.

The first two patterns are the most common, accounting for more than 75% of all cases of UNW. In both, the superficial branch is not affected; thus, there are no sensory symptoms or sensory loss. Patients present with painless weakness and atrophy of ulnar intrinsic hand muscles. Because the ulnar-innervated adductor pollicis and deep head of the flexor pollicis brevis are in the thenar eminence, both the hypothenar and thenar eminences may be wasted, if the lesion is in the proximal deep palmar motor branch. Similar to UNE, the Benediction hand posture, Froment's sign, and Wartenberg's sign may be present in advanced cases. In addition, another somewhat obscure sign, known as the "palmaris brevis sign," may be seen in severe lesions of the deep palmar motor branch. Remember that the palmar brevis is the only muscle supplied by the superficial branch, and is therefore spared in lesions of the deep branch. When the palmaris brevis contracts, it results in puckering of the skin along the proximal medial border of the hand. Because the other intrinsic hand muscles are wasted, prominent contraction (and possibly hypertrophy) of the palmaris brevis may be seen when the fifth digit is forcibly contracted in the more common lesions of the deep palmar motor branch of the ulnar nerve at the wrist (the "palmaris brevis sign," Figure 20–2).

In more proximal lesions, the superficial branch will also be affected, leading to sensory disturbance of the volar fifth and medial fourth digits. *The dorsal medial aspect of the*

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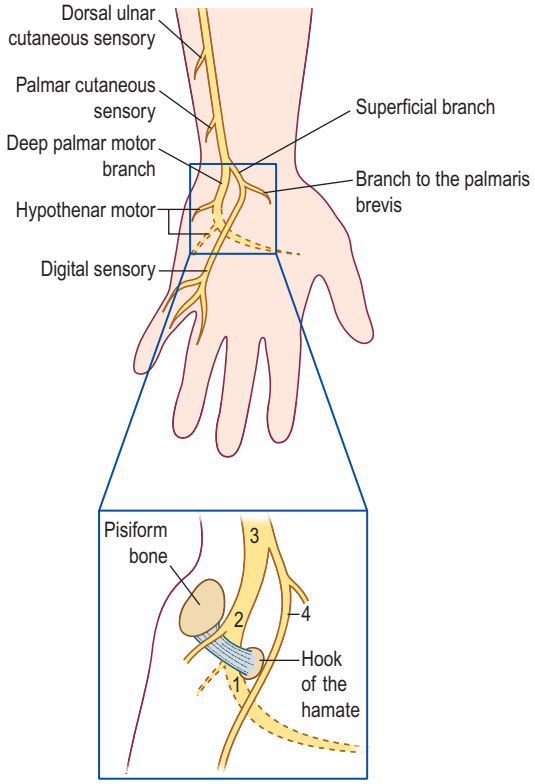

FIGURE 20–1 Detailed anatomy of the ulnar nerve at the wrist. Entrapment of the ulnar nerve at the wrist can take on several patterns: (1) pure motor affecting only the distal deep palmar motor branch, distal to the hypothenar muscles, (2) pure motor affecting the proximal deep palmar branch including the hypothenar motor branches, (3) motor and sensory (proximal canal lesion), and rarely (4) sensory affecting the superficial branch involving the sensory fibers to the volar fourth and fifth fingers. The superficial branch does supply one muscle, the palmaris brevis. This muscle, however, is difficult to assess clinically or by EMG, although there are reports of the "palmaris brevis sign" wherein this muscle is spared or prominent in lesions of the deep palmar motor branch (see Figure 20–2).
(Adapted with permission from Olney, R.K., Hanson, M., 1988. AAEE case report no. 15: ulnar neuropathy at or distal to the wrist. Muscle Nerve 11, 828.)

Box 20–1. Clinical and Electrophysiologic Abnormalities *not* Consistent with Ulnar Neuropathy at the Wrist

Clinical

- Weakness of thumb abduction (abductor pollicis brevis – median innervated)
- Weakness of the finger flexors of digits 4 and 5 (flexor digitorum profundus – ulnar innervated in the forearm)
- Weakness of index finger extension (extensor indicis proprius – radial innervated)
- Sensory symptoms/signs in the dorsal medial hand/dorsal fifth and fourth fingers (territory of the dorsal ulnar cutaneous sensory branch)
- Sensory symptoms/signs in the medial forearm (territory of the medial antebrachial cutaneous sensory nerve)

Nerve conduction studies

- Abnormal median motor study (unless there is a coexistent carpal tunnel syndrome)
- Abnormal dorsal ulnar cutaneous sensory study
- Focal slowing or conduction block of the ulnar nerve at the elbow

Needle electromyography

- Abnormalities in the proximal ulnar-innervated muscles (flexor carpi ulnaris and flexor digitorum profundus to digits 4 and 5)
- Abnormalities in non-ulnar C8-innervated muscles (abductor pollicis brevis, flexor pollicis brevis, extensor indicis proprius)

Table 20–1. Clinical and Electrophysiologic Differentiating Factors in Variants of Ulnar Neuropathy at the Wrist

	Deep Palmar Motor Branch Distal	Deep Palmar Motor Branch Proximal	Proximal Canal	Superficial Branch[†]
Weakness – interossei and 3rd/4th lumbricals	X	X	X	
Weakness – hypothenar muscles (ADM, ODM, FDM)		X	X	
Sensory loss – volar medial hand and little finger, medial half ring finger			X	X
Reduced CMAP at FDI	X	X	X	
Reduced CMAP at ADM		X	X	
Prolonged FDI latency	X	X	X	
Prolonged ADM latency		X	X	
Reduced SNAP to digit 5			X	X
Prolonged latency comparing INT to 2nd LUM	X	X	X	
Conduction block at the wrist	X	X	X	
CV slowing at the wrist	X	X	X	
EMG abnormalities in FDI	X	X	X	
EMG abnormalities in ADM		X	X	

X = abnormalities may be present; INT = interossei; LUM = lumbrical; ADM = abductor digiti minimi; ODM = opponens digit minimi; FDM = flexor digiti minimi; CV = conduction velocity; CMAP = compound muscle action potential.

[†]The superficial branch is often thought of as a "sensory branch." However, it does supply one muscle, the palmaris brevis.

hand and fingers will be spared because they are innervated by the dorsal ulnar cutaneous sensory branch, which arises several centimeters proximal to the wrist. This is an important clinical point to remember when trying to discern if the ulnar nerve lesion is at the wrist or more proximal. In addition, the proximal volar medial hand should be spared because the palmar cutaneous branch also arises just proximal to the wrist.

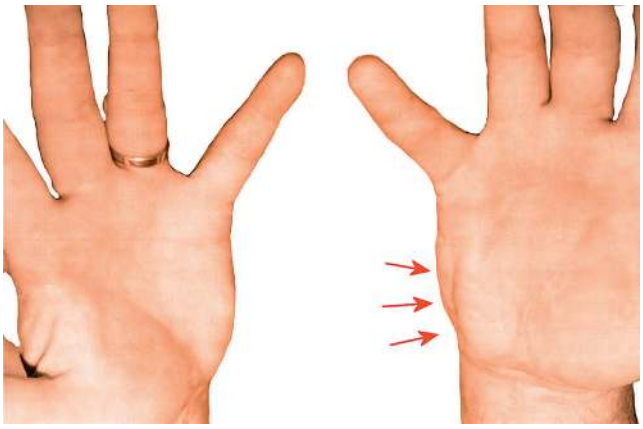

FIGURE 20–2 Palmaris brevis sign. When the palmaris brevis contracts, it results in puckering of the skin along the proximal medial border of the hand. As the palmar brevis is the only muscle supplied by the superficial branch of the ulnar nerve at the wrist, it will be spared in lesions of the deep branch. Thus, prominent contraction of the palmaris brevis may be seen when trying to abduct digit 5 in the more common lesions of the deep palmar motor branch of the ulnar nerve at the wrist. Note the prominent contraction of the palmaris brevis and wrinkling of the skin on the right hand (arrows) compared to the normal left hand.
(Adapted with permission from Iyer, V.G., 1998. Palmaris brevis sign in ulnar neuropathy. Muscle Nerve 21, 675–677.)

ETIOLOGY

Entrapment of the ulnar nerve at the wrist is far less common than at the more usual sites at the elbow. It has been described in association with trauma and wrist fracture. However, more common is a ganglion cyst within Guyon's canal that compresses the ulnar nerve (Figure 20–3). Rarely, an anomalous muscle or other mass lesions have been reported, including ulnar artery aneurysms, lipomas and other tumors. In addition, certain occupations or activities that involve repetitive movement or pressure against the ulnar wrist predispose to lesions at this location. This is especially true for bikers or laborers who use the same hand tools repetitively, which results in pressure on the hypothenar eminence (Figure 20–4). In such patients, the hypothenar area may be calloused at the compression site.

DIFFERENTIAL DIAGNOSIS

In lesions where the superficial branch containing the sensory fibers is not affected, UNW is most often confused with early motor neuron disease. Motor neuron disease is well known to present with painless atrophy and weakness of a distal limb, a pattern essentially identical to distal UNW lesions. *The key differentiating finding on physical examination in UNW is the intact strength and bulk of the abductor pollicis brevis muscle, supplied by the median nerve*. In motor neuron disease, one would expect all C8–T1-innervated muscles to be equally affected. In UNW, there is a marked difference between ulnar C8–T1-innervated muscles (which are weak and wasted) and median C8–T1-innervated muscles (which are spared). However, this difference in ulnar versus median innervated muscles

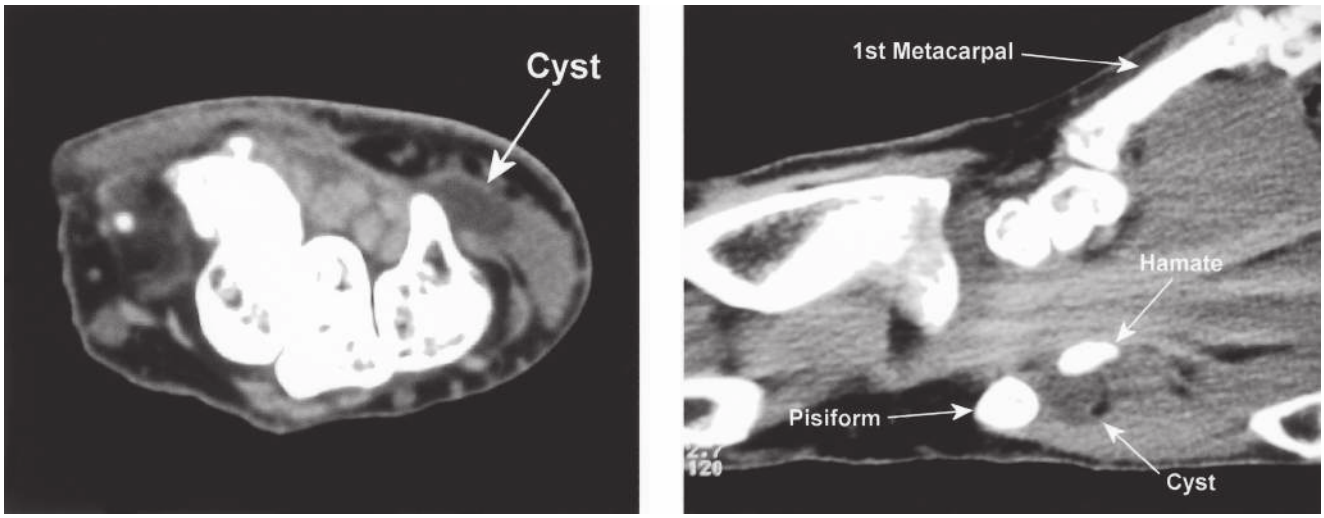

FIGURE 20–3 Ganglion cyst in Guyon's canal. One of the more common causes of ulnar neuropathy at the wrist is compression of the ulnar nerve by a ganglion cyst. Computed tomographic scan of the wrist. **Left:** Axial scan, volar side up. Note the cyst medial to the hook of the hamate. **Right:** Coronal scan, lateral hand up. Note the cyst between the pisiform and the hamate.
(From Preston, D.C., Shapiro, B.E., Schecht, H.M., 2001. Ganglion cyst at Guyon's canal: electrophysiology and pathology. J Clin Neuromusc Dis 3, 89–91.)

FIGURE 20–4 Occupational and activity risk factors for ulnar neuropathy at the wrist. Occupations that require repetitive use of hand tools can result in pressure on the hypothenar eminence (upper arrow). In addition, certain activities, especially prolonged cycling, can similarly result in ulnar neuropathy at the wrist (bottom arrow).

can also be seen in some atypical motor neuron disorders, such as multifocal motor neuropathy with conduction block, a rare autoimmune mediated motor neuropathy that preferentially affects distal muscles in a non-myotomal pattern of weakness (see Chapter 26).

In proximal lesions at the wrist where the superficial branch (and hence sensory fibers) is affected, the differential diagnosis is similar to that of UNE. Indeed, in UNW with sensory involvement, the most important diagnosis to exclude is UNE. Unequivocal sensory loss over the medial dorsal aspect of the hand and fingers and/or weakness of the distal flexors of the ring and little fingers are consistent with a lesion at the elbow, not at the wrist. However, in mild or early cases of UNE, these signs may not be present. In addition to UNE, one must keep in mind the possibilities of C8–T1 radiculopathy, lower trunk or medial cord brachial plexopathy, and rare cases of ulnar nerve entrapment in the arm or forearm, which can present with similar symptoms and signs.

ELECTROPHYSIOLOGIC EVALUATION

Nerve Conduction Studies

The findings on nerve conduction studies in UNW depend on (1) whether the superficial sensory branch is involved and (2) if the deep motor branch is involved, whether it is affected proximal or distal to the hypothenar muscles. If the lesion is distal, affecting only the deep palmar motor branch after the take-off to the hypothenar muscles, then the routine ulnar sensory study, recording the fifth digit, and the routine ulnar motor conduction study, recording the ADM, will be normal. In suspected UNW, additional nerve conduction studies must always be performed in order to detect abnormalities that may not be present on routine ulnar motor and sensory studies (Box 20–2).

In addition to routine ulnar motor studies recording ADM and sensory studies recording digit 5, the following studies often are helpful.

Ulnar Motor Studies Recording the First Dorsal Interosseous

In all cases of suspected UNW, it is imperative to perform ulnar motor studies recording the first dorsal interosseous (FDI). In lesions of the distal deep palmar motor branch, the latency to the FDI may be prolonged with a decreased compound muscle action potential (CMAP) amplitude. Comparison with the contralateral asymptomatic side often is helpful as well. In cases where the lesion is more proximal, affecting the hypothenar branches, the distal motor latency (DML) to the ADM also may be prolonged, with a decreased CMAP amplitude. *However, one of the patterns highly suggestive of UNW is preferential involvement of the distal deep palmar motor branch, whereby the ulnar motor study recording the FDI is affected out of proportion to the ulnar motor study recording the ADM.* Comparison of their relative distal motor latencies often can be helpful:

Normal Values:

DML to FDI:	≤4.5 ms
DML comparing FDI to ADM:	≤2.0 ms difference
DML comparing symptomatic FDI to contralateral FDI:	≤1.3 ms difference

Dorsal Ulnar Cutaneous Sensory Study

In cases of suspected UNW where the routine ulnar sensory conduction to digit 5 is abnormal, it is important to study the dorsal ulnar cutaneous sensory nerve. As the dorsal ulnar cutaneous sensory nerve arises 5 to 8 cm proximal to the wrist, it is expected to be normal in all cases of UNW. A normal antidromic response is greater than 8 μV, but, as in other uncommonly performed sensory nerve conduction studies, comparison with the contralateral asymptomatic side frequently is helpful. Any potential that is less than 50% of the amplitude of the contralateral asymptomatic

Box 20–2. Recommended Nerve Conduction Study Protocol for Ulnar Neuropathy at the Wrist

Routine studies:

1. Ulnar motor study recording abductor digiti minimi, stimulating wrist, below groove, and above groove in the flexed elbow position
2. Ulnar motor study recording first dorsal interosseous, stimulating wrist, below groove, and above groove in the flexed elbow position
3. Ulnar motor study recording first dorsal interosseous, stimulating the wrist (3 cm proximal to the distal wrist crease) and palm (4 cm distal to the distal wrist crease)
4. Median motor study recording abductor pollicis brevis, stimulating wrist and antecubital fossa
5. Median and ulnar F responses
6. Ulnar sensory response, recording digit 5, stimulating wrist (bilateral studies)
7. Median sensory response, recording digit 2 or 3, stimulating wrist
8. Dorsal ulnar cutaneous sensory response (bilateral studies)

Additional studies to consider:

9. Ulnar motor study recording the contralateral first dorsal interosseous, stimulating the wrist (in order to compare distal latencies and amplitudes side to side)
10. Lumbrical–interossei distal latency comparison study
11. Ulnar motor study recording the first dorsal interosseous, inching across the wrist in 1 cm increments

The following patterns are consistent with ulnar neuropathy at the wrist:

DML to FDI: >4.5 ms (provided CMAP amplitude is not markedly reduced)
DML comparing FDI to ADM: >2.0 ms difference
DML comparing symptomatic FDI to contralateral FDI: >1.3 ms difference
DML comparing ulnar INT to second lumbrical: >0.4 ms difference

The following patterns denote ulnar neuropathy at the wrist with certainty:

DML to FDI in the demyelinating range: >130% upper limit of normal (i.e., any DML to the FDI >6.0 ms)
Focal slowing across the wrist during inching studies: ≥0.5 ms over a 1 cm increment, recording FDI
Conduction block, comparing palm and wrist stimulations, recording FDI
Conduction velocity slowing across the wrist recording FDI

Special considerations:

- If the superficial sensory branch is affected, the SNAP amplitude will be low or absent, with a normal dorsal ulnar cutaneous SNAP. (Caution must be taken in interpreting this pattern, which also can occur in patients with UNE.)
- Occasional false-positive results occur when using the DML to FDI or ADM; comparing DML to FDI versus ADM; and the lumbrical–interossei study, especially in cases of moderate or severe UNE with axonal loss. Wrist versus palmar stimulation studies, or inching studies across the wrist should be done to demonstrate UNW with certainty.
- If the dorsal ulnar cutaneous sensory study is performed and is absent, it is prudent to stimulate the superficial radial sensory nerve along the lateral radius with the recording electrodes in place for the dorsal ulnar cutaneous sensory study to ensure that an anomalous innervation is not present (recall there is a very rare anomalous innervation wherein the superficial radial sensory nerve supplies the entire dorsum of the hand, including the usual territory of the dorsal ulnar cutaneous sensory nerve).

SNAP, sensory nerve action potential; CMAP, compound muscle action potential; DML, distal motor latency; UNE, ulnar neuropathy at the elbow; ADM, abductor digiti minimi; FDI, first dorsal interosseous; INT, interossei.

side likely is abnormal as well, even if the absolute amplitude is greater than 8 μV*.

Although the dorsal ulnar cutaneous sensory study often is helpful in establishing the level of the lesion, there are significant limitations of which every electromyographer must be aware. Although a *normal* dorsal ulnar cutaneous sensory study in the context of an *abnormal* digit 5 ulnar sensory study certainly suggests a diagnosis of UNW, this is not always the case. This pattern does not necessarily exclude the possibility of UNE (see Chapter 19). In some patients with definite UNE with axonal loss (although usually mild), the dorsal ulnar cutaneous sensory potential is spared. This is thought to be due to preferential fascicular sparing of the dorsal ulnar cutaneous sensory fibers. Therefore, care must be taken when interpreting the findings of a patient with a normal dorsal ulnar cutaneous SNAP and an abnormal digit 5 ulnar sensory response, especially if there is no conduction block or focal conduction velocity slowing across the elbow. These findings must be interpreted in light of findings on the ulnar motor studies and the needle electromyographic (EMG) study. Only when the dorsal ulnar cutaneous sensory study is abnormal is one assured that the lesion is above the level of the wrist; the converse is not always true.

*Very rarely there is an anomalous innervation wherein the superficial radial sensory nerve supplies the entire dorsum of the hand, including the usual territory of the dorsal ulnar cutaneous sensory nerve. Thus, in cases where the dorsal ulnar cutaneous sensory response is absent, it is prudent to stimulate the superficial radial sensory nerve along the lateral radius, with the recording electrodes in place for the dorsal ulnar cutaneous sensory study, to ensure that this very rare anomalous innervation is not present (see Figure 7–12 from Chapter 7).

Median Second Lumbrical versus Ulnar Interossei Distal Motor Latencies

The lumbrical–interossei distal latency comparison often is performed as a sensitive, internal comparison study to demonstrate median nerve slowing across the carpal tunnel (see Chapter 17, Figure 17–9). However, this study can

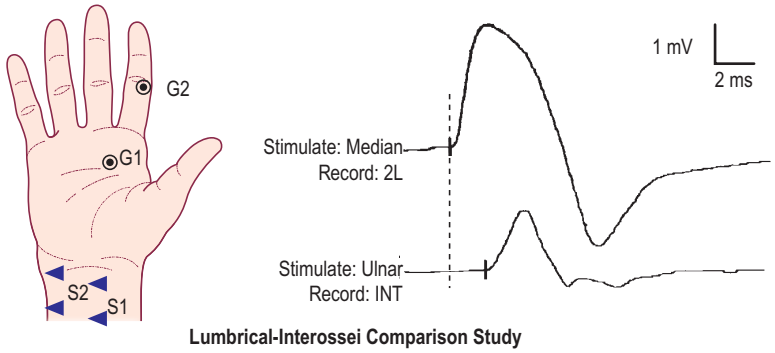

FIGURE 20–5 Lumbrical-interossei comparison study. This study is used most often in the diagnosis of carpal tunnel syndrome but can be equally helpful in the diagnosis of ulnar neuropathy at the wrist. The median nerve is stimulated at the wrist while the second lumbrical muscle is recorded **(right top trace)**; the ulnar nerve is stimulated at the wrist, using the same distance, while the interossei muscles are recorded **(right bottom trace)**. In normal controls, latencies are similar. In a patient with ulnar neuropathy at the wrist, the interossei latency is prolonged compared with the second lumbrical.

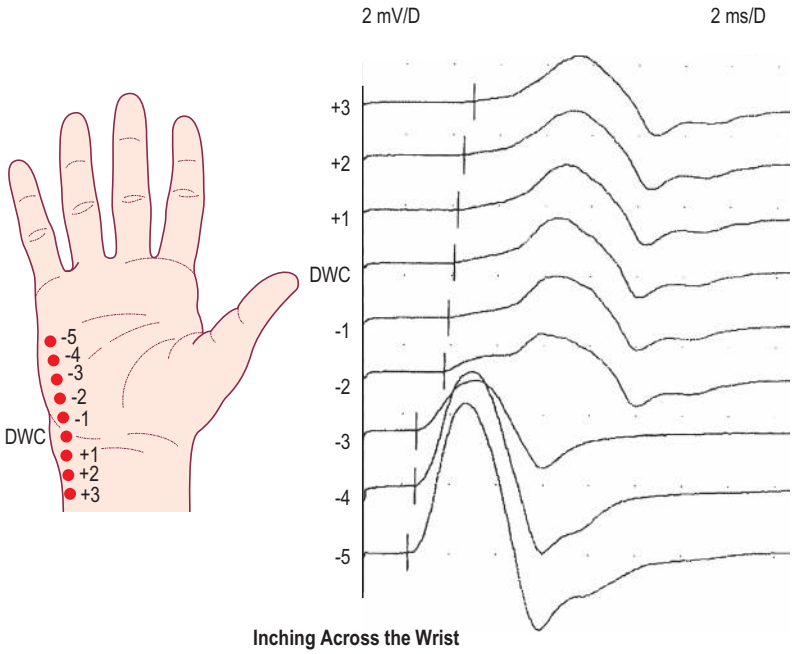

FIGURE 20–6 Short segment incremental study of the ulnar nerve across the wrist. **Left:** Recording the first dorsal interosseous, the ulnar nerve is stimulated in successive 1 cm increments across the wrist. **Right:** Note the abrupt increase in amplitude, shift in latency, and change in morphology of the compound muscle action potential between 2 and 3 cm distal to the distal wrist crease (DWC). Inching studies allow for exact localization of the lesion.
(From Preston, D.C., Shapiro, B.E., Schecht, H.M., 2001. Ganglion cyst at Guyon's canal: electrophysiology and pathology. J Clin Neuromusc Dis 3, 89–91.)

be used just as effectively to demonstrate UNW (Figure 20–5), looking for significant slowing of ulnar compared with median fibers across the wrist. Because the interossei are innervated by the distal deep palmar motor branch of the ulnar nerve and the second lumbrical is innervated by the median nerve, this comparison test can be very useful in identifying ulnar slowing at the wrist. A DML difference of greater than 0.4 ms comparing the ulnar interossei with the median second lumbrical, stimulating the nerves at the same distance, suggests focal slowing of the ulnar nerve across the wrist.

This study is reliable and easy to perform. However, two limitations must be kept in mind. First, if an ulnar neuropathy has a moderate or severe amount of axonal loss, be it at the wrist or higher, one should expect some mild slowing across the wrist simply on the basis of loss of some of the fastest conducting axons. Second, the lumbrical–interossei study will fail in cases of UNW if there is a coexistent median neuropathy at the wrist. This is generally not an issue when using this comparison study for median neuropathy at the wrist, as UNW is so rare. However, when looking for a UNW, an incidental median neuropathy at the wrist may not be that uncommon.

Short Segment Incremental Studies

Using a technique identical to that used for ulnar nerve lesions at the elbow, short segment incremental studies (SSIS) or "inching" can be effectively performed at the wrist, recording the FDI, looking for an abrupt change in either latency or amplitude (Figure 20–6). One centimeter increments are carefully marked off from 2 to 4 cm above the distal wrist crease to 4 to 5 cm below. The ulnar nerve is then stimulated supramaximally at each location at successive 1 cm intervals, from below to above the wrist. Any abrupt increase in latency or drop in amplitude between successive stimulation sites implies focal demyelination. In

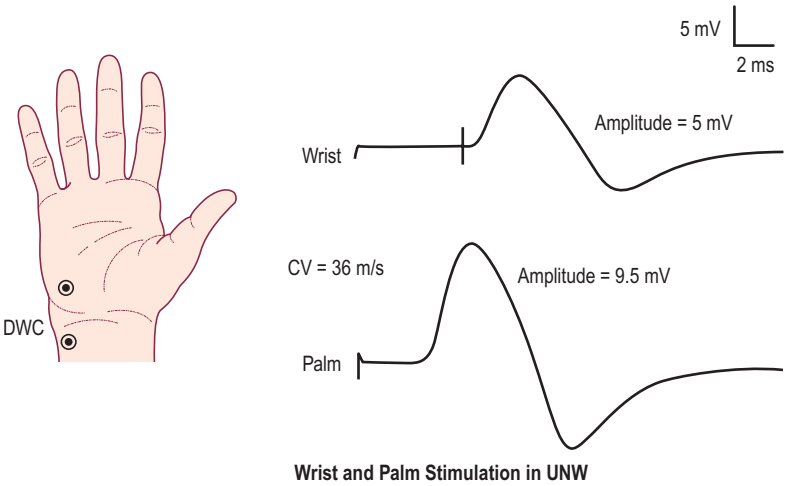

FIGURE 20–7 Wrist and palm stimulation in ulnar neuropathy at the wrist. As an alternative to inching studies, a compound muscle action potential can be recorded at the first dorsal interosseous with stimulation at the wrist and palm, looking for conduction block and/or conduction velocity slowing across the ulnar wrist. Note that in this case of ulnar neuropathy at the wrist, there is a large decrease in amplitude with stimulation at the wrist compared to the palm, signifying conduction block, and a slowed conduction velocity. Both findings localize the ulnar neuropathy to the wrist.

normal individuals, the latency between two successive 1 cm stimulation sites usually is 0.1 to 0.3 ms and rarely 0.4 ms. Any latency shift ≥0.5 ms suggests focal slowing.

Wrist and Palmar Stimulation

Comparing the CMAP amplitudes stimulating at the wrist and palm can be technically easier than inching across the wrist, and yield similar information (Figure 20–7). To perform this study, the ulnar nerve is stimulated 3 cm above the wrist and 4 cm distal to the distal wrist crease in the palm, recording the FDI. Whereas inching requires multiple stimulations at 1 cm increments, this study only requires single palm and wrist stimulations. UNW can be localized either by finding a conduction block between the wrist and palm stimulation sites or by finding conduction velocity slowing across the wrist. Similar to all routine motor studies, if a nerve is stimulated at two sites, a conduction velocity can be calculated. *In UNW, any conduction velocity less than 37 m/s is considered abnormal and is of localizing value.* In UNW, the demonstration of conduction block or conduction velocity slowing is most helpful in definitively localizing the lesion. However, additional information is gained about prognosis, as demyelinating lesions have a far better prognosis than those associated with axonal loss.

Comparison of the Various Electrophysiologic Tests in Ulnar Neuropathy at the Wrist

There has been little data comparing the relative usefulness of the various studies outlined earlier, because UNW is relatively uncommon. Most reports of UNW have been single case reports or reports of a small number of patients. One large study of 20 consecutive patients with clinically defined UNW was performed prospectively, comparing the following studies: (1) wrist and palmar stimulation studies, recording FDI, looking for conduction block across the wrist; (2) wrist and palmar stimulation studies, recording FDI, looking for conduction velocity slowing across the wrist; (3) lumbrical–interossei study, comparing ulnar versus median distal latencies; and (4) routine ulnar motor studies, recording FDI and ADM, comparing their respective DMLs. In five patients, inching studies across the wrist also were performed. Importantly, these studies were also compared in 30 asymptomatic normal control subjects and in 20 consecutive disease control patients with definite UNE.

The most sensitive and specific studies for localizing the lesion to the wrist were conduction block across the wrist and a slowed wrist-to-palm conduction velocity recording the FDI. Conduction block was found in 70% and a slowed wrist-to-palm conduction velocity in 80% of patients with UNW, using wrist and palmar stimulation (Figure 20–8). Overall, 95% of the patients with UNW had either conduction block or a slowed conduction velocity. These findings were 100% specific. Neither conduction block nor conduction velocity slowing across the wrist was found in any of the control patients with UNE. Of the five patients in whom inching was performed, all showed focal slowing and conduction block.

The lumbrical–interossei comparison study had a sensitivity of 60% (Figure 20–9). However, one patient with a severe UNE had an abnormal study (latency difference of 0.6 ms). One reason for the lower than expected sensitivity for this study was the presence of coexistent median neuropathy at the wrist in 25% of patients.

A prolonged DML to the FDI or ADM also had a lower sensitivity, in the range of 55 to 60% (Figure 20–9). More importantly, prolonged distal latencies to these muscles were also less specific than the previously described studies. A prolonged DML to the FDI was found in one patient with mild UNE and in 40% of patients with severe UNE. Similarly, a prolonged DML to the ADM was found in 40% of patients with severe UNE. The prolonged DMLs in patients with UNE presumably were the result of axonal loss and dropout of some of the faster conducting fibers.

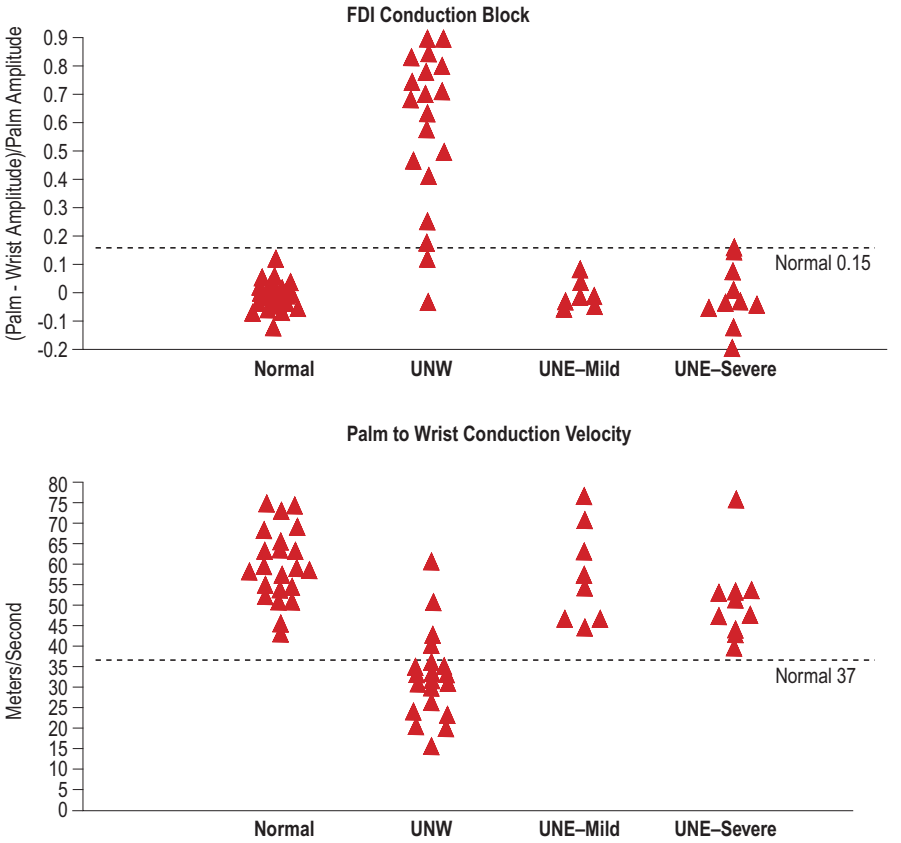

FIGURE 20–8 Conduction block and focal slowing across the wrist. **Top:** Change in first dorsal interosseous (FDI) compound muscle action potential (CMAP) amplitude with the ulnar nerve stimulated above and below the wrist is plotted for normals, patients with ulnar neuropathy at the wrist (UNW), and patients with ulnar neuropathy at the elbow (UNE) (mild and severe). Conduction block is calculated as (Palmar–Wrist CMAP Amplitude)/(Palmar CMAP Amplitude). **Bottom:** Conduction velocity across the ulnar wrist, recording the FDI, is plotted for normals, patients with UNW, and patients with UNE (mild and severe). Normal limits are shown as dotted lines.
(From Cowdery, S.R., Preston, D.C., Herrmann, D.N., et al., 2002. Electrodiagnosis of ulnar neuropathy at the wrist: conduction block versus traditional tests. Neurology 59, 420–427.)

The least sensitive study for UNW was the comparison of DMLs to the FDI versus ADM, being abnormal in only 15% of patients with UNW. However, one patient with a mild UNE also had a relatively prolonged DML to FDI compared with ADM.

The important points to take away from this study are as follows:

1. By performing an additional stimulation at the palm, while recording the FDI, conduction block or focal slowing across the wrist can be demonstrated in 95% of patients with clinically definite UNW. This finding was 100% specific; it was not seen in any control patient with UNE.
2. Inching studies across the wrist also are very sensitive and specific. However, these studies are more time consuming and technically demanding than simply stimulating at one additional site in the palm.
3. The lumbrical–interossei study is a sensitive and helpful test, with one important exception. Its usefulness is greatly diminished if there is a coexistent median neuropathy at the wrist. Rarely, a false-positive result can occur if a patient has a severe UNE. Increasing the cutoff value to 0.7 ms or above may eliminate this problem.
4. Prolongation of the DML to FDI or ADM is much less sensitive than conduction block or slowing across the wrist, recording the FDI. In addition, it is also much less specific, being present in some cases of UNE.
5. Comparing the DML to FDI versus ADM is only infrequently helpful, being fairly insensitive to ulnar neuropathy at the wrist.

Electromyographic Approach

The needle EMG examination in suspected UNW is straightforward (Box 20–3). The FDI and ADM must be sampled, with the electromyographer looking for involvement of the distal and proximal deep palmar motor branches, respectively. The flexor digitorum profundus (FDP) 5 and flexor carpi ulnaris (FCU) must be sampled to exclude an ulnar neuropathy proximal to the wrist. Finally, median- and radial-innervated C8 muscles (e.g., abductor pollicis brevis, flexor pollicis longus, extensor indicis proprius) and the lower cervical paraspinal muscles must be sampled to exclude a cervical root or motor neuron lesion.

As in UNE, the lesion in UNW can be purely axonal, indicated by low CMAP amplitudes at ADM and FDI with normal or only mild slowing of distal latency. In these cases, it can be difficult to differentiate a lesion of the deep palmar motor branch from a lesion proximal to the dorsal root ganglion (cervical root or motor neuron). The EMG is helpful in this regard. The electromyographer can confirm

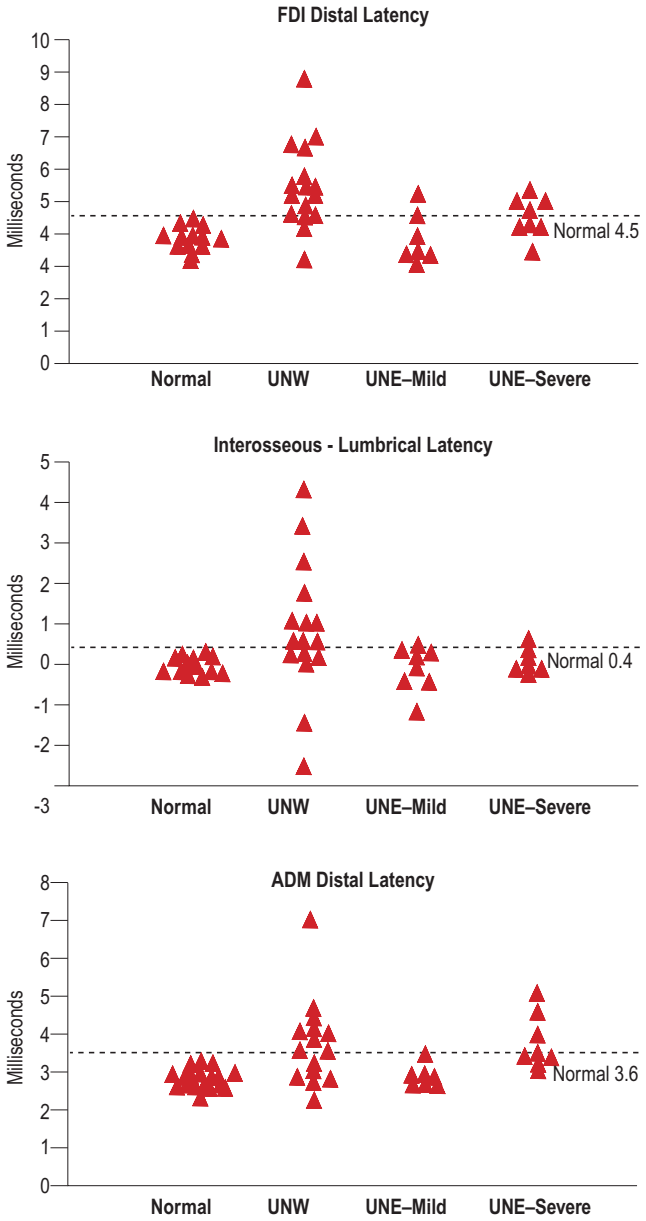

FIGURE 20–9 Distal motor latency studies in ulnar neuropathy at the wrist (UNW). Distal motor latencies to the first dorsal interosseous **(top)**, difference in distal motor latencies between the interosseous and lumbrical **(middle)**, and distal motor latencies to the abductor digiti minimi **(bottom)** are plotted for normals, patients with UNW, and patients with ulnar neuropathy at the elbow (UNE) (mild and severe). Normal limits are shown as dotted lines. Note the false-positive results that occur in some cases of UNE.
(From Cowdery, S.R., Preston, D.C., Herrmann, D.N., et al., 2002. Electrodiagnosis of ulnar neuropathy at the wrist: conduction block versus traditional tests. Neurology 59, 420–427.)

that the abnormalities are limited to ulnar-innervated muscles distal to the wrist by also sampling proximal ulnar-innervated and non-ulnar C8–T1-innervated muscles. Again, however, early motor neuron disease may be difficult to exclude. In these cases, the clinical presentation and serial follow-up remain important.

Box 20–3. Recommended Electromyographic Protocol for Ulnar Neuropathy at the Wrist

Routine studies:

1. Distal deep palmar motor ulnar-innervated muscle (first dorsal interosseous)
2. Proximal deep palmar motor ulnar-innervated branches to hypothenar muscles (abductor digiti minimi)
3. Forearm ulnar-innervated muscles (flexor carpi ulnaris and flexor digitorum profundus 5)

If any of the ulnar-innervated muscles are abnormal, test the following additional muscles:

4. At least two non-ulnar lower trunk/C8 innervated muscles (e.g., abductor pollicis brevis, flexor pollicis longus, extensor indicis proprius) to exclude a lower trunk brachial plexopathy, polyneuropathy, C8–T1 radiculopathy, or motor neuron disease
5. C8 and T1 paraspinal muscles

Special consideration: If the pathology at the wrist is purely axonal and spares sensory fibers, it is difficult to completely exclude a lesion proximal to the dorsal root ganglion (i.e., root or motor neuron).

EXAMPLE CASE

Case 20–1

History and Physical Examination

A 36-year-old right-handed man complained of numbness and paresthesias over digits 4 and 5, as well as right arm pain for 6 months. The sensory disturbance had become worse over the past few weeks. He worked in a library stacking books and denied any history of trauma. He had vague complaints of right elbow pain.

On examination, there was mild atrophy of the intrinsic hand muscles. There was mild weakness of the ADM and interossei muscles on the right. The long flexors of digits 4 and 5 were strong. There was no Tinel's sign at the elbow. Sensation to pin and light touch was normal.

Summary

The history and physical examination both are suggestive of ulnar neuropathy. Despite the normal sensory examination, the patient noted paresthesias and numbness in the ulnar-innervated fourth and fifth digits. In addition, the motor examination showed atrophy and weakness of the right ADM and the interossei. Thus, the patient has clear symptoms of ulnar sensory and motor dysfunction. The suggestion of pain at the right elbow leads one to seriously consider the possibility of ulnar neuropathy in the region of the elbow. However, at this point there are no other signs to help localize the lesion. The fact that the long flexors to digits 4 and 5 (ulnar portion of the FDP) are normal suggests that the ulnar neuropathy either is mild and has not affected these more proximal muscles or is more distal.

The clinical approach to this case is similar to that used in other cases of ulnar nerve dysfunction. The differential diagnosis includes UNW, UNE, lower trunk/

CASE 20–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = μV			Latency (ms)			Conduction Velocity (m/s)			F-wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	12.5		≥4	4.2		≤4.4				28		≤31
Median (m)	Antecubital fossa	APB	12.2			8.3			50		≥49			
Ulnar (m)	Wrist	ADM	4.2		≥6	4.1		≤3.3				31		≤32
Ulnar (m)	Below elbow	ADM	4.1			7.4			60		≥49			
Ulnar (m)	Above elbow	ADM	4.1			9.2			57		≥49			
Median (s)	Wrist	Index finger	48		≥20	3.2		≤3.5	58		≥50			
Ulnar (s)	Wrist	Little finger	10	23	≥17	3.4	3.2	≤3.1	42	52	≥50			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis; ADM = abductor digiti minimi; FDI = first dorsal interosseous.

Note: All sensory and mixed latencies are peak latencies. All sensory and mixed-nerve conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 20–1. Additional Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = μV			Latency (ms)			Conduction Velocity (m/s)			F-wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Dorsal ulnar (s)	Lateral wrist	Dorsal medial hand	24	26	≥8	2.1	2.2	≤2.8	50	51	≥50			
Median (m)	Wrist	Second lumbrical	4.1	3.8	≥1.0	4.4	4.4							
Ulnar (m)	Wrist	Interosseous	5.5	6.2	≥2.5	5.5	4.4							
Lum–int diff.						1.1	0.0	≤0.4						
Ulnar (m)	Wrist	FDI	3.6	11	≥7	5.2	4.4	≤4.5						
Ulnar (m)	Below elbow	FDI	3.4			7.6			55		≥50			
Ulnar (m)	Above elbow	FDI	3.4			8.9			57		≥50			
Ulnar (m)	Palm	FDI	8.0			3.2			35		≥50			

CASE 20–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right FDI	↑	+1	0	NL	↓	+1	+1	+1
Right ADM	↑	+1	0	NL	↓	+1	+1	+1
Right APB	NL	0	0	NL	NL	NL	NL	NL
Right EIP	NL	0	0	NL	NL	NL	NL	NL
Right FCU	NL	0	0	NL	NL	NL	NL	NL
Right FDP 5	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓ = slightly reduced; NL = normal; FDI = first dorsal interosseous; ADM = abductor digiti minimi; APB = abductor pollicis brevis; EIP = extensor indicis proprius; FCU = flexor carpi ulnaris; FDP = flexor digitorum profundus.

medial cord lesions of the brachial plexus, or a C8–T1 radiculopathy.

The nerve conduction studies include, first, a normal median motor conduction study recording the abductor pollicis brevis muscle. However, the ulnar motor conduction study shows a mildly low CMAP amplitude recording the ADM with a moderately prolonged distal latency but a normal conduction velocity in the forearm and across-elbow segments. There is no conduction block or significant differential slowing of the ulnar nerve across the elbow (>10–11 m/s) to substantiate the possibility of UNE. Median and ulnar routine sensory studies are then performed. The median study is completely normal, but the ulnar study shows a decreased amplitude on the right with a normal amplitude on the left. Therefore, at this point in the study, one can be fairly certain that the patient has an ulnar neuropathy because both the ulnar motor and sensory studies are abnormal. The normal median motor and sensory studies exclude a more generalized process such as a polyneuropathy to explain the abnormal ulnar motor and sensory findings. Although a lower trunk brachial plexopathy is still a consideration, one would expect to also see a low median CMAP amplitude in this case. At this point in the study, we are confronted with a common problem, that of a non-localizable ulnar neuropathy. There is no focal slowing or conduction block to suggest an ulnar neuropathy at the elbow.

Several questions should be addressed.

What is the Significance of the Prolonged Ulnar Distal Motor Latency?

The only unusual abnormality is the moderately prolonged distal latency to the ADM muscle (4.1 ms). This value is more than 125% of the upper limit of normal and suggests the possibility of a demyelinating lesion at the wrist. Recall from the history that the patient uses his hands to stack books repetitively, which may be a risk factor for entrapment of the ulnar nerve at the wrist. Further studies of the ulnar nerve at the wrist are indicated.

What Other Tests can be Used to Help Localize the Lesion?

Because the routine ulnar conduction studies typically are normal or equivocal in UNW, additional nerve conduction studies are required to localize the lesion to the wrist (Box 20.2). In UNW, the dorsal ulnar cutaneous sensory response is expected to be normal, whereas the sensory potential to the fifth digit may be abnormal. When the dorsal ulnar cutaneous sensory response is checked and compared with the contralateral side, it is normal and symmetric bilaterally. The presence of a normal dorsal ulnar cutaneous response with an abnormal digit 5 ulnar response is consistent with UNW, although, as already noted, this pattern occasionally can be seen in mild cases of UNE.

Next, the lumbrical–interossei comparison study is performed using identical distances. On the left (asymptomatic) side, an identical distal latency of 4.4 ms to both the lumbrical and interossei is found. On the involved right side, however, there is a clear asymmetry: the ulnar latency is 1.1 ms longer than the median latency. Any difference of more than 0.4 ms suggests focal slowing across the wrist.

Lastly, the ulnar motor study is repeated but recording the FDI. There is no focal slowing or conduction block across the elbow. However, the FDI distal latency on the involved right side is moderately prolonged at 5.2 ms, with a normal value of 4.4 ms on the contralateral side. In addition, the CMAP amplitude is reduced on the right compared with the left. Comparing the distal latency to the FDI to that of the ADM, there is a difference of 1.1 ms, which is in the range of normal (≤2.0 ms). When an additional stimulation is given in the palm while recording the FDI, the amplitude markedly increases to 8.0 mV, signifying a conduction block between the palm and wrist. In addition, the calculated velocity across the wrist is in the demyelinating range, being less than 37 m/s.

Proceeding to the needle EMG study, particular attention must be paid to the ulnar-innervated muscles above the level of the wrist, which would be expected to be normal in cases of UNW. The EMG study shows active denervation and reinnervation in the FDI (innervated by the distal deep palmar motor branch of the ulnar nerve). The right ADM yields similar findings, indicating that the branch to the hypothenar muscles is also affected. The right abductor pollicis brevis is normal, as is the right extensor indicis proprius. The normal findings in these two non-ulnar C8-innervated muscles again signify that the problem likely is limited to the ulnar nerve. Finally, both proximal ulnar muscles, the FCU and FDP 5, are sampled and are normal.

Therefore, with EMG and nerve conduction studies completed, we are ready to form an electrophysiologic impression.

IMPRESSION: *There is electrophysiologic evidence of an ulnar neuropathy at the wrist.*

From the pattern of the nerve conduction and EMG data, we can conclude that the patient has an ulnar nerve lesion at the wrist affecting the superficial sensory branch and the proximal deep palmar branch. This pattern is one variant of UNW. In this case, the patient's history, examination, and electrophysiologic results all correlate well. The atrophy and weakness of the intrinsic hand muscles correlate with the reduced ulnar CMAP amplitudes seen on nerve conduction studies and with the denervation and reinnervation with reduced recruitment of MUAPs revealed by the needle EMG findings. The findings that, taken together, tend to localize the lesion at the wrist include not only the EMG abnormalities that are limited to ulnar muscles distal to the wrist but also the intact dorsal ulnar cutaneous sensory response and the

prolonged ulnar latency on the lumbrical–interossei study. *However, the study that unequivocally localizes the ulnar neuropathy to the wrist is the palmar stimulation compared to the wrist stimulation, while recording the FDI*. The finding of focal demyelination across the wrist (conduction block and/or conduction velocity slowing) is the key finding.

One can easily see that if additional studies had not been performed (i.e., the dorsal ulnar cutaneous sensory study, motor conduction study to the FDI including palmar stimulation, and lumbrical–interossei distal latency comparison study), the erroneous diagnosis of a non-localizable ulnar neuropathy might have been made. The initial clue to this diagnosis on the nerve conduction studies was the relatively prolonged distal latency to the ADM muscle in conjunction with only a mildly reduced CMAP amplitude.

In this case, sensory symptoms and abnormalities on nerve conduction studies indicated an ulnar nerve lesion. However, one should remember that in other cases of UNW, in which the lesion affects the deep palmar motor branch in isolation, only the motor fibers are affected; the sensory fibers are spared. In such cases, excluding a lesion proximal to the dorsal root ganglion (either nerve root or anterior horn cell) may be very difficult. If the pathology is axonal loss alone and there is no focal slowing or conduction block of ulnar motor fibers across the wrist, making that differentiation is impossible. In those unusual cases, the EMG report must be considered indeterminate. Although EMG abnormalities may be limited to ulnar-innervated muscles, the possibility that those muscles are the first to be affected in a lesion of the nerve root or anterior horn cells cannot be completely excluded. Indeed, there are cases of focal motor neuron disease that mimic UNW on initial presentation, preferentially affecting the deep palmar motor branch. Clinical history and often follow-up electrophysiologic studies are required to make the differentiation.

Suggested Readings

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21 Radial Neuropathy

In the electromyography (EMG) laboratory, the radial nerve is studied less frequently than the median and ulnar nerves and their respective well-known lesions. Nevertheless, entrapment of the radial nerve does occur, often affecting the main radial nerve either in the upper arm or axilla. Isolated lesions of its terminal divisions in the forearm, the posterior interosseous and superficial radial sensory nerves, also occur. Although radial motor nerve conduction studies are technically demanding, the electrophysiologic evaluation of radial neuropathy usually is able to localize the lesion, assess the underlying pathophysiology, and provide useful information regarding severity and subsequent prognosis.

ANATOMY

The radial nerve receives innervation from all three trunks of the brachial plexus and, correspondingly, a contribution from each of the C5–T1 nerve roots (Figures 21–1 and 21–2). After each trunk divides into an anterior and posterior division, the posterior divisions from all three trunks unite to form the posterior cord. The *posterior cord* gives off the *axillary, thoracodorsal,* and *subscapular nerves* before becoming the radial nerve. In the high arm, the radial nerve first gives off the *posterior cutaneous nerve of the arm*, the *lower lateral cutaneous nerve of the arm*, and the *posterior cutaneous nerve of the forearm* (Figure 21–3), followed by muscular branches to the three heads of the triceps brachii (medial, long, and lateral) and the anconeus. The anconeus is a small muscle in the proximal forearm that effectively is an extension of the medial head of the triceps brachii. After giving off these muscular branches, the radial nerve wraps around the posterior humerus in the *spiral groove*. Descending into the region of the elbow, muscular branches are then given off to the brachioradialis and the long head of the extensor carpi radialis. Next, three to four cm distal to the lateral epicondyle, the radial nerve bifurcates into two separate nerves: one superficial and the other deep. The superficial branch, known as the *superficial radial sensory nerve*, descends distally into the forearm over the radial bone to supply sensation over the lateral dorsum of the hand as well as part of the thumb and the dorsal proximal phalanges of the index, middle, and ring fingers (Figure 21–4). Distally, the nerve is quite superficial, running over the extensor tendons to the thumb, where it can easily be palpated (Figure 21–5).

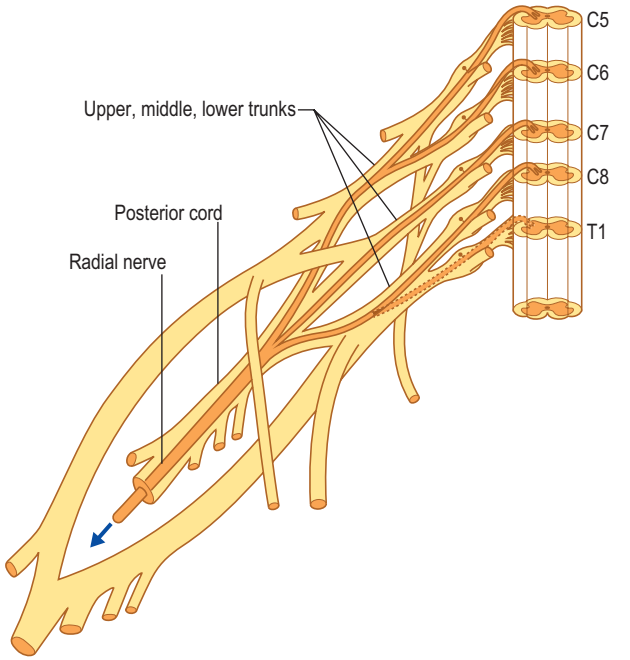

FIGURE 21–1 Anatomy of the radial nerve. The radial nerve receives innervation from all three trunks of the brachial plexus and, correspondingly, a contribution from each of the C5–T1 nerve roots. (Adapted with permission from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia.)

The deep branch, known as the *deep radial motor branch*, first supplies the extensor carpi radialis brevis and the supinator muscles before it enters the supinator muscle under the Arcade of Frohse (Figure 21–6). The Arcade of Frohse is the proximal border of the supinator and in some individuals is quite tendinous. After the nerve enters the supinator, it is known as the *posterior interosseous nerve*, which then supplies the remaining extensors of the wrist, thumb, and fingers (extensor digitorum communis, extensor carpi ulnaris, abductor pollicis longus, extensor indicis proprius [EIP], extensor pollicis longus, and extensor pollicis brevis). Although the posterior interosseous nerve is thought of as a pure motor nerve (supplying no cutaneous sensation), it does contain sensory fibers that supply deep sensation to the interosseous membrane and joints between the radial and ulna bones.

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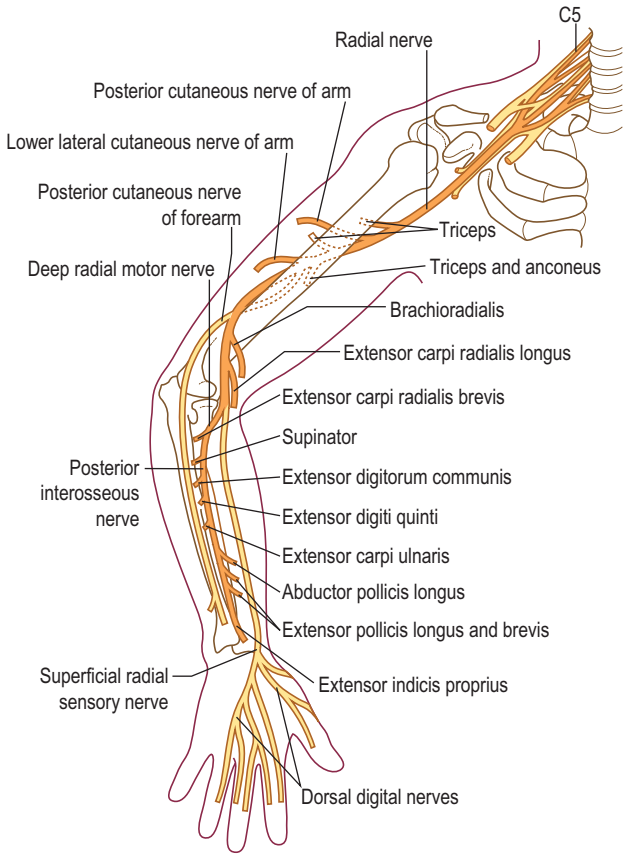

FIGURE 21–2 Anatomy of the radial nerve. The radial nerve is derived from the posterior cord of the brachial plexus. In the high arm, the radial nerve first gives off the posterior cutaneous nerve of the arm, the lower lateral cutaneous nerve of the arm, and the posterior cutaneous nerve of the forearm, followed by muscular branches to the triceps brachii and anconeus. The radial nerve then wraps around the humerus, descending into the region of the elbow, where muscular branches are given to the brachioradialis and long head of the extensor carpi radialis. The nerve then bifurcates into the superficial radial sensory and deep motor branch of the radial nerve. The deep motor branch supplies the extensor carpi radialis brevis (in most cases) and the supinator muscle before continuing on as the posterior interosseous nerve. The posterior interosseous nerve supplies the remainder of the wrist and finger extensors, as well as the abductor pollicis longus.
(Adapted with permission from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia.)

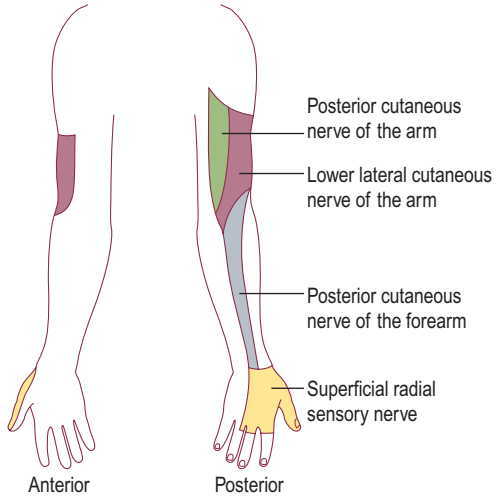

FIGURE 21–3 Sensory territories supplied by the radial nerve.
(Adapted with permission from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia.)

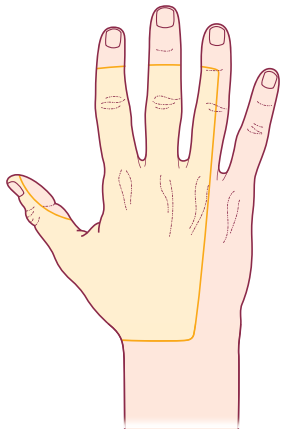

FIGURE 21–4 Sensory territory of the superficial radial sensory nerve. The superficial radial sensory nerve supplies sensation over the lateral dorsum of the hand, as well as part of the thumb and dorsal proximal phalanges of the index, middle, and ring fingers.

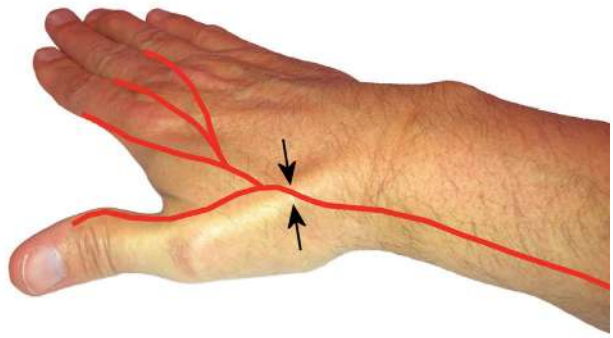

FIGURE 21–5 Superficial radial sensory nerve. The superficial radial nerve runs distally in the forearm over the radial bone to supply sensation over the lateral dorsum of the hand as well as part of the thumb and the dorsal proximal phalanges of the index, middle, and ring fingers. It runs over the extensor tendons to the thumb (arrows), where it can easily be palpated.

Nomenclature of the Branches of the Radial Nerve near the Elbow

One of the more confusing aspects of radial nerve anatomy is the inconsistency regarding the nomenclature of the branches of the radial nerve near the elbow used in various anatomic texts and clinical reports (Figure 21–7). The following points should help the electromyographer when dealing with potential lesions of the radial nerve in this area:

Radial Nerve between the Spiral Groove and the Bifurcation near the Elbow

- Distal to the spiral groove but before the elbow, the main radial nerve always supplies two muscles: the

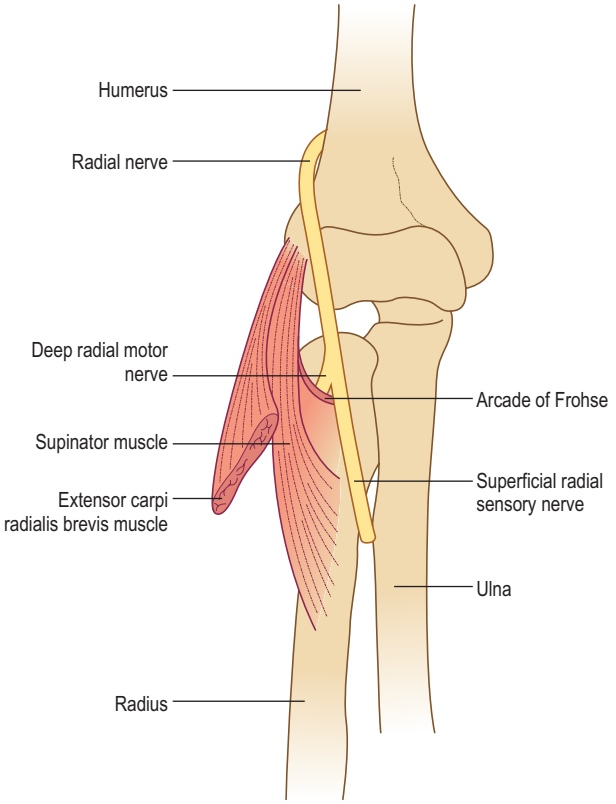

FIGURE 21–6 Anatomy of the radial nerve at the elbow. Distal to the elbow, the radial nerve bifurcates into the superficial radial sensory and deep radial motor branch. The deep radial motor branch enters the supinator muscle under the Arcade of Frohse where it is then known as the posterior interosseous nerve which supplies the remaining extensors of the wrist, thumb, and fingers.
(Adapted with permission from Wilbourn, A.J., 1992. Electrodiagnosis with entrapment neuropathies. AAEM plenary session I: entrapment neuropathies. Charleston, South Carolina.)

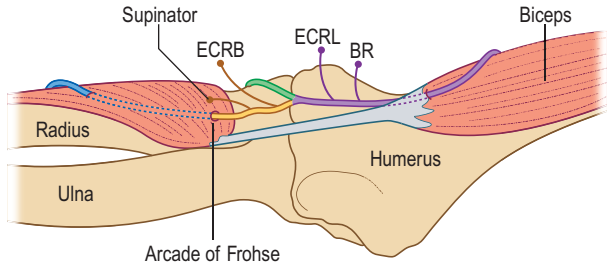

FIGURE 21–7 Anatomy and nomenclature of the radial nerve around the elbow. As the main radial nerve enters the region of the elbow (purple), it supplies the brachioradialis (BR) and extensor carpi radialis longus (ECRL) muscles. It then divides into a *superificial radial sensory branch* (green) and a *deep radial motor branch* (yellow). The deep radial motor branch typically innervates the extensor carpi radialis brevis (ECRB) and supinator muscles before entering into the substance of the supinator muscle at the Arcade of Frohse. Past the Arcade of Frohse, the continuation of the deep radial motor branch is known as the *posterior interosseous nerve* (blue). However, please note that some anatomic texts define the posterior interosseous nerve as originating at the bifurcation of the main radial nerve, and thus use the terms *deep radial motor branch* and *posterior interosseous nerve* interchangeably. If this definition is used, then both the ECRB and the supinator muscle would both be supplied by the posterior interosseous nerve.
(Adapted with permission from Thomas, S.J., Yakin, D.E., Parry, B.R., et al., 2000. The anatomical relationship between the posterior interosseous nerve and the supinator muscle. J Hand Surg Am 25 (5), 936–941.)

brachioradialis and the extensor carpi radialis longus (also known as the long head of the extensor carpi radialis).

- In some individuals, the main radial nerve will also supply a third muscle, the extensor carpi radialis brevis muscle*.

The Bifurcation near the Elbow

- The main radial nerve always bifurcates into superficial and deep branches just distal to the elbow.

Superficial Branch

- The superficial branch continues as a pure cutaneous sensory branch (the *superficial radial sensory branch*).
- However, in a small number of individuals, there is an anatomic variation wherein the superficial branch near its origin will supply one muscle, the extensor carpi radialis brevis*.

*Thus, the innervation to the extensor carpi radialis brevis has several normal variations: from the main radial nerve, the superficial radial nerve, and the deep radial motor branch of the radial nerve.

Deep Branch

- The *deep radial motor branch* first supplies the extensor carpi radialis brevis muscle in some individuals*.
- It then supplies one or more branches to the supinator muscle before entering the supinator muscle proper.
- The *deep radial motor branch* then runs under the Arcade of Frohse (the proximal border of the supinator) and through the supinator muscle.
- After leaving the supinator muscle, branches are given off that supply the extensor muscles to the thumb and fingers as well as the abductor pollicis longus and extensor carpi ulnaris. The inconsistency in the nomenclature regarding these nerve branches involves where the posterior interosseous nerve begins, and whether the posterior interosseous nerve and the deep radial motor branch are one and the same nerve:
  - In some textbooks and many clinical reports, the entire *deep radial motor branch* is known as the *posterior interosseous nerve*, with the two names used interchangeably. Thus, using this anatomic definition, a complete posterior interosseous neuropathy would include the supinator and the extensor carpi radialis brevis muscles, as well as the extensors to the thumb and fingers, and the abductor pollicis longus and extensor carpi ulnaris.
  - In most anatomic texts, however, only the segment of the deep branch between the bifurcation of the main radial nerve at the elbow to

where the nerve enters the supinator muscle at the Arcade of Frohse is known as the *deep radial motor branch*. The *posterior interosseous nerve* is then the continuation of the deep radial motor branch *after it enters the supinator*. In the remainder of this text, we will use this latter anatomic definition. Thus, with this anatomic definition, a complete posterior interosseous neuropathy would spare the supinator and the extensor carpi radialis brevis muscles. As the most common entrapment site of the posterior interosseous nerve is at the Arcade of Frohse, the use of this anatomic convention fits the common clinical syndromes most appropriately as well.

CLINICAL

Radial neuropathies can be divided into those caused by lesions at the spiral groove, lesions in the axilla, and isolated lesions of the posterior interosseous and superficial radial sensory nerves. These lesions usually can be differentiated by clinical findings.

Radial Neuropathy at the Spiral Groove

The most common radial neuropathy occurs at the spiral groove. Here, the nerve lies juxtaposed to the humerus and is quite susceptible to compression, especially following prolonged immobilization (Figure 21–8). One of the times this characteristically occurs is when a person has draped an arm over a chair or bench during a deep sleep or while intoxicated ('Saturday night palsy'). The subsequent prolonged immobility results in compression and demyelination of the radial nerve. Other cases may occur after strenuous muscular effort, fracture of the humerus, or infarction from vasculitis. Clinically, marked wrist drop and finger drop develop (due to weakness of the EIP, extensor digitorum communis, extensor carpi ulnaris, and long head of the extensor carpi radialis), along with mild weakness of supination (due to weakness of the supinator muscle) and elbow flexion (due to weakness of the brachioradialis). Notably, elbow extension (triceps brachii) is spared. Sensory disturbance is present in the distribution of the superficial radial sensory nerve, consisting of altered sensation over the lateral dorsum of the hand, part of the thumb, and the dorsal proximal phalanges of the index, middle, and ring fingers.

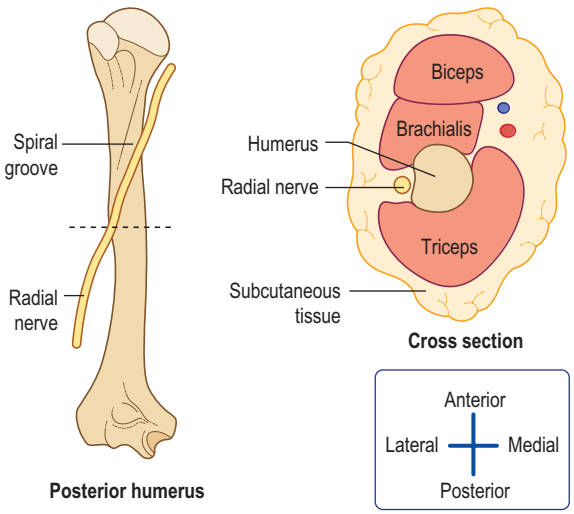

FIGURE 21–8 Radial nerve and the spiral groove. The most common radial neuropathy occurs at the spiral groove on the posterior side of the humerus. Here, the nerve lies juxtaposed to bone and is susceptible to external compression.

In isolated radial neuropathy at the spiral groove, median- and ulnar-innervated muscles are normal. However, tested in a wrist drop and finger drop posture, finger abduction may appear weak, giving the mistaken impression of ulnar nerve dysfunction. To prevent this error, one should test the patient's finger abduction (ulnar-innervated function) with the fingers and wrist passively extended to a neutral wrist position. This often can be accomplished by placing the hand on a flat surface.

Radial Neuropathy in the Axilla

Radial neuropathy may occur in the axilla from prolonged compression. For instance, this is often seen in patients on crutches who use them inappropriately, applying prolonged pressure to the axilla. The clinical deficit is similar to that seen in radial neuropathy at the spiral groove, with the notable exception of additional weakness of arm extension (triceps brachii) and sensory disturbance extending into the posterior forearm and arm (posterior cutaneous nerves of the forearm and arm). Radial neuropathy in the axilla is differentiated from even more proximal posterior cord lesions by normal strength of the deltoid (axillary nerve) and latissimus dorsi (thoracodorsal nerve).

Posterior Interosseous Neuropathy

Posterior interosseous neuropathy (PIN) clinically resembles entrapment of the radial nerve at the spiral groove at first glance. In both conditions, patients present with wrist drop and finger drop with sparing of elbow extension. However, with closer inspection, several important differences easily separate the two. In PIN, there is sparing of radial-innervated muscles above the takeoff of the posterior interosseous nerve (i.e., brachioradialis, long and short heads of the extensor carpi radialis, triceps). Thus, a patient with PIN still may be able to extend the wrist, but weakly, with a radial deviation. This is due to the relative preservation of the extensor carpi radialis longus and brevis that arise proximal to the posterior interosseous nerve, with a weak extensor carpi ulnaris. In addition, of course, are the sensory findings. In PIN, there is no cutaneous sensory loss. However, there may be pain in the forearm from involvement of the deep sensory fibers of the posterior interosseous nerve that supply the interosseous membrane and joint capsules.

PIN usually occurs as an entrapment neuropathy under the tendinous Arcade of Frohse. Rarely, other mass lesions (e.g., ganglion cysts, tumors) result in PIN.

Radial Tunnel Syndrome

In radial tunnel syndrome, patients are reported to have isolated pain and tenderness in the extensor forearm, not unlike persistent tennis elbow, thought to result from compression of the posterior interosseous nerve near its origin. However, this is one of the more controversial and disputed nerve entrapment syndromes. As opposed to patients with a true posterior interosseous neuropathy (see above), these patients typically have no objective neurologic signs on examination, and accordingly have normal EDX studies. They are said to have increased pain with maneuvers that contract the extensor carpi radialis or the supinator (e.g., resisted extension of the middle finger or resisted supination, respectively). However, there is no compelling evidence that this chronic pain syndrome is caused by any nerve entrapment. Nevertheless, this syndrome is important to know of, as it is not unusual for a patient to be referred to the EMG laboratory for evaluation of "radial tunnel syndrome." In such cases, the focus of the EDX is to look for any objective evidence of a posterior interosseous neuropathy, although in the absence of any weakness or other neurological signs, the EDX study is almost always normal.

Superficial Radial Sensory Neuropathy

The superficial radial sensory nerve is derived from the main radial nerve in the region of the elbow. In the distal third of the forearm, it runs subcutaneously next to the radius. Its superficial location next to bone makes it extremely susceptible to compression, a syndrome coined "Cheiralgia Paresthetica" which translates from the Greek as *cheir* + *algos*, meaning pain in the hand. Tight-fitting bands, watches, or bracelets may result in compression of the superficial radial nerve. Handcuffs, especially when excessively tight, also characteristically result in a superficial radial neuropathy. Because the superficial radial sensory nerve is purely sensory, no weakness develops. A characteristic patch of altered sensation develops over the lateral dorsum of the hand, part of the thumb, and the dorsal proximal phalanges of the index, middle, and ring fingers.

DIFFERENTIAL DIAGNOSIS

The differential diagnosis of wrist drop, aside from a radial neuropathy at the spiral groove, axilla, and PIN, includes unusual presentations of C7–C8 radiculopathy, brachial plexus lesions, and central causes (Box 21–1). Because most muscles that extend the wrist and fingers are innervated by the C7 nerve root, C7 radiculopathy may rarely present solely with a wrist drop and finger drop, with relative sparing of non-radial C7-innervated muscles. However, several key clinical features help differentiate a C7 radiculopathy from a radial neuropathy, PIN, brachial plexopathy, or central lesion (Table 21–1). Radial neuropathy at the

Box 21–1. Wrist Drop: Possible Anatomic Localizations

- Posterior interosseous nerve
- Radial nerve at the spiral groove
- Radial nerve in the axilla
- Posterior cord of the brachial plexus
- C7 root
- Central nervous system

Table 21–1. Clinical Differentiating Factors in Wrist Drop

	Posterior Interosseous Neuropathy	Radial Nerve: Spiral Groove	Radial nerve: Axilla	Posterior Cord	C7
Wrist drop or finger drop	X	X	X	X	X
Radial deviation on wrist extension	X				
Weakness of supination (mild)		X	X	X	
Weakness of elbow flexion (mild)		X	X	X	
Diminished brachioradialis tendon reflex		X	X	X	
Weakness of elbow extension			X	X	X
Diminished triceps tendon reflex			X	X	X
Weakness of shoulder abduction				X	
Sensory loss in lateral dorsal hand		X	X	X	X (equivocal)
Sensory loss in posterior arm or forearm			X	X	X (equivocal)
Weakness of wrist flexion					X

X, may be present.

Table 21–2. Electromyographic and Nerve Conduction Abnormalities Localizing the Lesion Site in Wrist Drop

	Posterior Interosseous Neuropathy	Radial Nerve: Spiral Groove	Radial Nerve: Axilla	Posterior Cord	C7
EMG Findings					
Extensor indicis proprius	X	X	X	X	X
Extensor digitorum communis	X	X	X	X	X
Extensor carpi ulnaris	X	X	X	X	X
Extensor carpi radialis-long head		X	X	X	X
Brachioradialis		X	X	X	
Supinator		X	X	X	
Anconeus			X	X	X
Triceps			X	X	X
Deltoid				X	
Latissimus dorsi				X	X
Flexor carpi radialis, pronator teres					X
Cervical paraspinal muscles					X
Nerve Conduction Study Findings					
Abnormal radial SNAP (if axonal)		X	X	X	
Low radial CMAP (if axonal)	X	X	X	X	X
Conduction block at spiral groove (if demyelinating)		X			
Conduction block between forearm and elbow (if demyelinating)	X				

X, may be abnormal; CMAP, compound muscle action potential; SNAP, sensory nerve action potential.

spiral groove or axilla should result in weakness of the brachioradialis, a C5–C6-innervated muscle, which should not be weak in a lesion of the C7 nerve root. On the other hand, radial neuropathy at the spiral groove and PIN should spare the triceps, which would be expected to be weak in a C7 radiculopathy. If a C7 radiculopathy is severe enough to cause muscle weakness, other non-radial C7-innervated muscles also should be weak (e.g., pronator teres, flexor carpi radialis), leading to weakness of arm pronation and wrist flexion. However, in rare situations, non-radial C7-innervated muscles may be relatively spared, making the clinical differentiation quite difficult.

Although lesions of the posterior cord of the brachial plexus result in weakness of radial-innervated muscles, the deltoid (axillary nerve) and latissimus dorsi (thoracodorsal nerve) should also be weak. Central lesions may result in a wrist drop and finger drop. The typical upper motor neuron posture results in flexion of the wrist and fingers, which in the acute phase or when the lesion is mild may superficially resemble a radial neuropathy. Central lesions are identified by increased muscle tone and deep tendon reflexes (unless acute), slowness of movement, associated findings in the lower face and leg, and altered sensation beyond the radial distribution.

ELECTROPHYSIOLOGIC EVALUATION

In the evaluation of a patient with a wrist drop, the role of nerve conduction studies and EMG is to identify a potential radial neuropathy, assess its location and severity, and, by defining the underlying pathophysiology, establish a prognosis (Table 21–2).

Nerve Conduction Studies

The most important nerve conduction study in assessing a wrist drop is the radial motor study (Box 21–2). A radial compound muscle action potential (CMAP) can be recorded over the EIP muscle, placing the active electrode two fingerbreadths proximal to the ulnar styloid with a reference electrode placed over the ulnar styloid (Figure 21–9). The radial nerve can be stimulated in the forearm, at the elbow (in the groove between the biceps and brachioradialis muscles), and below and above the spiral groove. The normal CMAP recorded from the EIP typically is 2 to 5 mV. Comparing the CMAP amplitude to that on the contralateral asymptomatic side is always important. Any axonal loss will result in a decreased distal CMAP amplitude after 3 to 5 days, when wallerian degeneration for motor fibers has occurred. In fact, the best way to assess the degree of axonal loss is to compare the CMAP amplitudes between the involved side and the contralateral side.

Several significant technical considerations must be taken into account when performing radial motor studies. First, placement of the active recording electrode over the EIP almost always results in a CMAP with an initial positive deflection. This occurs because volume-conducted potentials from other nearby radial-innervated muscles (e.g., extensor pollicis brevis and longus) contaminate the CMAP response, resulting in an initial positive deflection.

Box 21–2. Recommended Nerve Conduction Study Protocol for Radial Neuropathy

Routine studies:

1. Radial motor study recording extensor indicis proprius, stimulating forearm, elbow, below spiral groove, and above spiral groove; bilateral studies
2. Ulnar motor study recording abductor digiti minimi, stimulating wrist, below groove, and above groove in the flexed elbow position
3. Median motor study recording abductor pollicis brevis, stimulating wrist and antecubital fossa
4. Median and ulnar F responses
5. Superficial radial sensory study recording over the extensor tendons to thumb, stimulating forearm; bilateral studies
6. Ulnar sensory study recording digit 5, stimulating wrist
7. Median sensory study recording digit 2 or 3, stimulating wrist

The following patterns may result:

- *Posterior interosseous neuropathy (axonal loss lesion)*: Normal superficial radial SNAP, low amplitude distal radial CMAP.
- *Posterior interosseous neuropathy (demyelinating lesion)*: Normal superficial radial SNAP, normal amplitude distal radial CMAP with motor conduction block between forearm and elbow.
- *Posterior interosseous neuropathy (mixed axonal loss and demyelinating lesion)*: Normal superficial radial SNAP, low amplitude distal radial CMAP with motor conduction block between forearm and elbow.
- *Radial neuropathy at the spiral groove (axonal loss lesion)*: Reduced superficial radial SNAP, low-amplitude distal radial CMAP. No conduction block across spiral groove.
- *Radial neuropathy at the spiral groove (demyelinating lesion)*: Normal superficial radial SNAP, normal amplitude distal radial CMAP with conduction block across spiral groove.
- *Radial neuropathy at the spiral groove (mixed axonal loss and demyelinating lesion)*: Reduced superficial radial SNAP, low amplitude distal radial CMAP with conduction block across spiral groove.
- *Radial neuropathy at the axilla (axonal loss lesion)*: Reduced superficial radial SNAP, low amplitude distal radial CMAP.
- *Radial neuropathy at the axilla (demyelinating lesion)*: Normal superficial radial SNAP, normal amplitude distal radial CMAP with normal motor study to above spiral groove.
- *Superficial radial sensory neuropathy*: Reduced superficial radial SNAP, normal radial motor study.

CMAP, compound muscle action potential; SNAP, sensory nerve action potential.

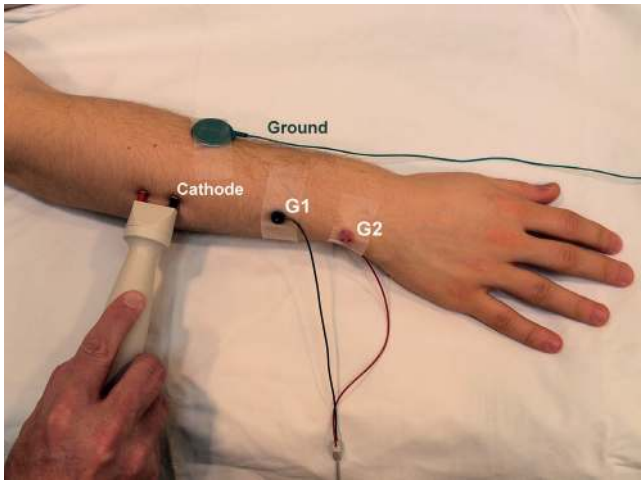

FIGURE 21–9 Radial motor study. The active electrode is placed over the extensor indicis proprius, 2 cm proximal to the ulnar styloid, with the reference electrode over the ulnar styloid. The radial nerve can be stimulated in the forearm, at the elbow, and below and above the spiral groove.

Second, it may be difficult to make accurate surface distance measurements. Because the radial nerve winds around the humerus and takes a somewhat circuitous course through the forearm, surface distance measurements often are inaccurate. Measuring distance with obstetric calipers, especially between the elbow and arm, reduces some of this error. However, the combination of difficulty measuring the true nerve length and the initial positive deflection CMAP can lead to considerable potential inaccuracies in measuring true conduction velocities. Radial conduction velocities sometimes are calculated as factitiously fast (>75 m/s). The value of performing radial motor studies usually lies not in the measurement of conduction velocities but in looking for a focal conduction block between the proximal and distal sites and determining the relative CMAP amplitude to assess axonal loss (Figure 21–10).

In cases of radial neuropathy at the spiral groove, CMAPs recorded with stimulation at the forearm, elbow, and below the spiral groove can be completely normal if the lesion is purely demyelinating. However, stimulation above the spiral groove will result in electrophysiologic evidence of a conduction block, i.e., a marked decrease of amplitude and area. The relative drop in distal to proximal CMAP amplitude will give some indication of the proportion of fibers blocked.

Rarely, in cases of PIN, there may be conduction block between the forearm and elbow sites. However, most cases of PIN are pure axonal loss lesions (akin to ulnar neuropathy at the elbow), and no conduction block is demonstrable. In these cases, the distal radial CMAP amplitude will be decreased in proportion to the amount of axonal loss.

In contrast to radial motor studies, the superficial radial sensory nerve is easy to stimulate and record (Figures 21–11 and 21–12). The active electrode is placed over the extensor tendons to the thumb, with the reference electrode placed 3 to 4 cm distally. The nerve is easily stimulated 10 cm proximally, over the radius. If there has been secondary axonal loss, the response will be diminished in amplitude. Similar to motor studies, it is often useful to compare the response with the contralateral asymptomatic

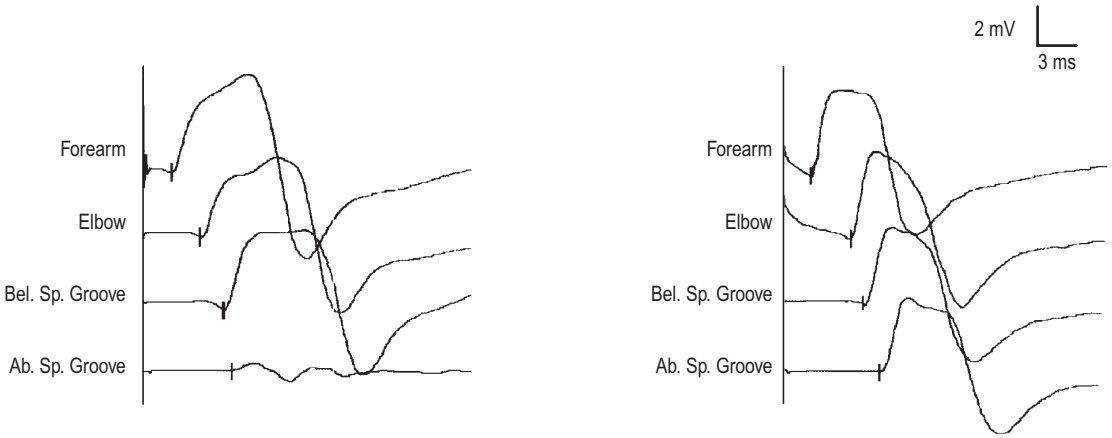

FIGURE 21–10 Radial motor studies for radial neuropathy at the spiral groove. **Left:** Symptomatic arm. **Right:** Contralateral asymptomatic arm. Recording extensor indicis proprius and stimulating the forearm, elbow, below spiral groove, and above spiral groove. Note the marked drop in amplitude and area across the spiral groove on the left (conduction block) and the symmetric distal compound motor action potential amplitudes from side to side. Taken together, these findings imply a predominantly demyelinating lesion at the spiral groove.

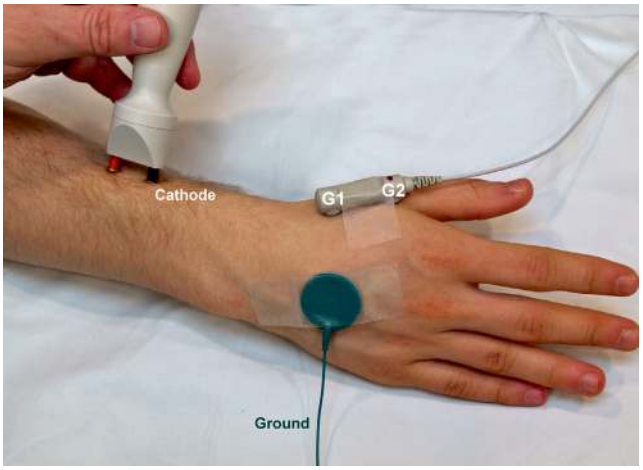

FIGURE 21–11 Radial sensory study. The superficial radial sensory nerve is easy to palpate over the extensor tendons. The active electrode is placed over the nerve with the reference electrode placed 3 to 4 cm distally. The superficial radial nerve is stimulated 10 cm proximal to GI over the radial bone.

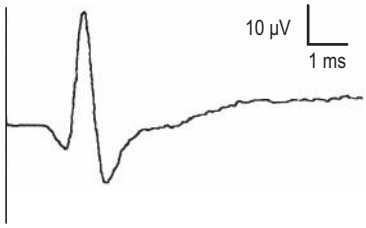

FIGURE 21–12 Radial sensory nerve action potential. The radial sensory nerve action potential is easy to record and typically has a triphasic morphology. It is expected to be normal in all posterior interosseous neuropathy lesions, as well as in other higher radial neuropathies that are purely demyelinating.

Box 21–3. Causes of Wrist Drop and a Normal Superficial Radial Sensory Nerve Action Potential

Posterior interosseous neuropathy
Demyelinating radial neuropathy at the spiral groove or axilla
C7 radiculopathy
Central nervous system lesion
Hyperacute axonal loss injury of the main radial nerve (<4 days old)

side. If the pathology is one of pure or predominant proximal demyelination, a very interesting phenomenon occurs. Although the patient reports marked numbness in the distribution of the superficial radial sensory nerve, the superficial radial sensory nerve action potential (SNAP) will be normal, even comparing side to side. This unusual finding (a normal sensory response in the distribution of cutaneous numbness) can occur in only one of three situations: (1) a hyperacute axonal loss lesion (before wallerian degeneration has occurred), (2) a lesion proximal to the dorsal root ganglion, or (3) a lesion caused by proximal demyelination. Thus, in cases of radial neuropathy at the spiral groove or axilla, a pure proximal demyelinating lesion will result in a normal superficial radial sensory potential, despite sensory loss on clinical exam. A normal superficial radial sensory response is also seen in PIN, as expected, as the nerve carries no cutaneous sensory fibers. One can see that if a patient presents with a wrist drop and the superficial radial SNAP is normal, the differential diagnosis is quite limited (Box 21–3).

Note that if the clinical examination suggests weakness beyond the radial distribution, investigation for a more widespread neuropathy is indicated, especially a search for conduction blocks along other motor nerves, which may

Box 21–4. Recommended Electromyographic Protocol for Radial Neuropathy

Routine muscles:

1. At least two posterior interosseous-innervated muscles (e.g., extensor indicis proprius, extensor carpi ulnaris, extensor digitorum communis)
2. At least one radial-innervated muscle proximal to the bifurcation of the main radial nerve near the elbow but distal to the spiral groove (e.g., brachioradialis, long head of extensor carpi radialis)
3. At least one radial-innervated muscle proximal to the spiral groove (e.g., triceps brachii, anconeus)
4. At least one non-radial posterior cord-innervated muscle (e.g., deltoid, latissimus dorsi)
5. At least two non-radial C7-innervated muscles (e.g., flexor carpi radialis, pronator teres, flexor digitorum sublimis, cervical paraspinal muscles)

Special considerations:

- The only electromyographic abnormality in purely demyelinating lesions with conduction block will be decreased recruitment of MUAPs in weak muscles.
- The supinator muscle is best avoided. It is deep and difficult to localize and often is spared in posterior interosseous neuropathy.

MUAP, motor unit action potential.

indicate multifocal motor neuropathy with conduction block (see Chapter 26).

Electromyographic Approach

The EMG approach is straightforward in suspected radial neuropathy (Box 21–4). In a patient with wrist drop and finger drop, the EMG must differentiate among PIN, radial neuropathy at the spiral groove, radial neuropathy in the axilla, a posterior cord lesion, a C7 radiculopathy, and a central lesion. In PIN, abnormalities will be limited to those muscles innervated by the posterior interosseous nerve (among them, the EIP, extensor digitorum communis, and extensor carpi ulnaris), notably sparing the brachioradialis, long head of the extensor carpi radialis, and triceps. In radial neuropathy at the spiral groove, the brachioradialis, long head of the extensor carpi radialis, and supinator will be abnormal, in addition to PIN-innervated muscles, with notable sparing of the triceps. If the lesion is at the axilla, the above muscles, as well as the triceps and anconeus, will be involved. A proximal lesion of the posterior cord will show additional abnormalities, including the deltoid (axillary nerve) and latissimus dorsi (thoracodorsal nerve). A C7 radiculopathy will show abnormalities of the cervical paraspinal muscles and radial-innervated C7 muscles (e.g., triceps, extensor digitorum communis) as well as non-radial-innervated C7 muscles (e.g., pronator teres, flexor carpi radialis). Finally, in central lesions, motor unit action potential (MUAP) configuration and recruitment will be normal in weak muscles, but decreased *activation* of normal configuration MUAPs will be seen.

Anatomic Considerations of Some Radial-Innervated Muscles on Needle EMG

The EMG evaluation of radial neuropathy is very orderly, as there are many muscles innervated by the radial nerve, including several below and above each potential entrapment site. However, there are unique characteristics and limitations of certain muscles, including:

- Anconeus. The anconeus is a unique muscle because it is the only muscle in the forearm proper that is supplied by the radial nerve *above the spiral groove*. The anconeus can essentially be thought of as an extension of the medial head of the triceps. Thus, in severe or complete radial neuropathies at the spiral groove, every radial-innervated muscle in the forearm (which includes every wrist and finger extensor), as well as the supinator and brachioradialis, may be completely denervated, and only the anconeus will be normal.
- Supinator. There are four muscles that come off between the radial nerve at the spiral groove and the origin of the posterior interosseous nerve at the Arcade of Frohse: the brachioradialis, the long and short heads of the extensor carpi radialis, and the supinator. Thus, these muscles are very helpful in determining if the lesion is at the level of the posterior interosseous nerve, or above it, in the region of the elbow. However, the supinator has several significant limitations. First, it is very deep (essentially in the center of the forearm) and, hence, placing the EMG needle correctly is quite problematic. Second, much of supination is subserved by the biceps muscle (the primary function of the biceps is elbow flexion; its secondary function is forearm supination). Thus, weakness of supination may be difficult to elicit in radial neuropathy. Third, the supinator and its relationship to the radial nerve are somewhat akin to that of the pronator teres and the median nerve: the deep branch of the radial nerve runs through the supinator muscle at which point it is known as the posterior interosseous nerve. However, the branch or branches supplying the supinator originate from the deep radial motor branch *before* it enters under the Arcade of Frohse. Lesions at that location may or may not affect the innervation to the supinator (again, akin to the pronator teres being spared in some case of pronator syndrome). Because of these limitations, the supinator is best avoided, especially since there are other muscles (especially the brachioradialis and long head of the extensor carpi radialis) that can be more easily sampled that are below the spiral groove but proximal to the posterior interosseous nerve.
- Extensor carpi radialis – long head. As noted above, several muscles come off between the main radial nerve at the spiral groove and the origin of the posterior interosseous nerve at the Arcade of Frohse, including the long head of the extensor carpi radialis and the brachioradialis. Thus, these muscles are very

helpful in determining if the lesion is at the level of the posterior interosseous nerve, or proximal to it, in the main radial nerve in the region of the elbow. However, in the case of the long head of the extensor carpi radialis, it is located anatomically just proximal to the short head of the extensor carpi radialis. Thus, in order to place the EMG needle correctly in the long head of the extensor carpi radialis, one has to be quite exact. This is especially important because if the needle is mistakenly placed in the short head of the extensor carpi radialis (also known as the extensor carpi radialis brevis), and found to be abnormal, the mistaken impression may arise of a lesion in the main radial nerve at or proximal to the elbow, whereas the lesion may actually be more distal, in the deep radial motor branch. This is because the short head of the extensor carpi radialis has several common anatomic variants: it can arise from the main radial nerve in the elbow as well as from the deep radial motor branch, and rarely from the proximal superficial radial nerve. One can see that if the short head of the extensor carpi radialis in this case is supplied by the deep radial motor branch rather than the main radial nerve, the mistaken impression of a lesion of the main radial nerve could be made. Because of the anatomic variations of the nerve supply to the extensor carpi radialis brevis, abnormalities in this muscle cannot differentiate between lesions of the main radial nerve in the elbow and the deep radial motor branch.

Thus, although the long head of the extensor carpi radialis can be routinely sampled, of the available muscles that can be sampled which are below the spiral groove but proximal to the bifurcation of the radial nerve just distal to the elbow, *the brachioradialis is the easiest and has the fewest potential problems*.

EXAMPLE CASES

Case 21–1

History and Physical Examination

A 42-year-old man was referred for persistent left wrist drop. The patient reported that he was well until approximately 3 weeks ago, when he awoke with a nearly complete left wrist drop and finger drop. Although there was no pain, he did notice an area of abnormal sensation on the back side of his hand between the thumb and index finger. The patient, initially concerned about a stroke, presented to his local emergency room, where no specific diagnosis was made. During the subsequent 3 weeks, no improvement occurred.

On physical examination, the patient was a well-appearing man with a prominent left wrist drop and finger drop. There was near paralysis of wrist and finger extension (MRC grade 1/5). Finger abduction initially appeared weak, but strength was much better when the hand was passively extended to the neutral position. Wrist and finger flexion were intact. Elbow flexion and extension were normal. Shoulder abduction was normal. On sensory examination, there was a well-demarcated area of numbness over the lateral dorsum of the left hand between the thumb and index fingers extending into the proximal phalanges of the index, middle, and ring fingers. Otherwise, sensation was intact. Reflexes were normal and symmetric at the biceps and triceps. The left brachioradialis reflex was absent, whereas the right was normal. In the lower extremities, the knee reflexes were normal, but both ankle reflexes were difficult to elicit.

Summary

In this case, the patient presented with the acute onset of marked wrist drop and finger drop. The differential diagnosis includes PIN, radial neuropathy at the spiral groove or in the axilla, a posterior cord lesion of the brachial plexus, an unusual C7 radiculopathy, or a central lesion. The pattern of weakness on the physical examination suggests radial neuropathy at the spiral groove as the most likely localization. Clinically, a PIN is excluded because of (1) the presence of abnormal sensation in the superficial radial distribution (superficial radial sensory nerve) and (2) the abnormal brachioradialis reflex (radial nerve above the elbow). A radial neuropathy in the axilla remains possible but is less likely in the absence of any sensory abnormality in the distribution of the posterior cutaneous nerve of the forearm and arm and especially in the presence of the intact triceps muscle strength and reflex. A lesion of the posterior cord of the brachial plexus is unlikely for the same reasons and also because of the normal strength of the deltoid and latissimus dorsi, which would be expected to be abnormal if the lesion affected the posterior cord. The clinical presentation of a C7 radiculopathy occasionally can mimic a radial neuropathy. However, in such a case the triceps strength and reflex would be expected to be abnormal, as well as the median-innervated C7 muscles (e.g., pronator teres, flexor carpi radialis). Finally, a central lesion appears very unlikely, both because the motor and sensory deficits fit the distribution of a peripheral nerve (i.e., radial nerve) and because no increased reflexes, spasticity, or other signs that accompany an upper motor neuron lesion are present.

Nerve conduction studies begin with the radial motor studies. On the involved left side, a normal radial CMAP is recorded over the EIP muscle, with the forearm, elbow, and below the spiral groove stimulated. When stimulating above the spiral groove, there is a marked drop in amplitude (4.6 mV below the spiral groove, 0.7 mV above). This finding (conduction block) is a clear indication of demyelination across the spiral groove. When the contralateral radial motor nerve is studied, no drop in amplitude with proximal stimulation is noted. Significantly, the distal CMAPs on the involved and uninvolved sides are nearly identical (the involved side actually is slightly higher than the uninvolved side). Because the lesion is 3 weeks old, sufficient time has passed that any wallerian degeneration that will occur has already occurred in the motor nerves (i.e., 3–5 days). *Comparing*

CASE 21–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F Wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Radial (m)	Forearm	EIP	5.0	5.7	≥2	3.1	3.1	≤3.3						
	Elbow	EIP	5.0	4.6		6.6	6.7		57	55	≥49			
	Below spiral groove	EIP	4.5	4.6		9.4	9.3		60	63	≥49			
	Above spiral groove	EIP	4.3	0.7		11.0	11.7		65	45	≥49			
Median (m)	Wrist	APB		8.0	≥4		4.3	≤4.4					31	≤31
	Antecubital fossa	APB		6.9			8.2			51	≥49			
Ulnar (m)	Wrist	ADM		7.1	≥6		2.9	≤3.3					31	≤32
	Below elbow	ADM		6.7			6.5			55	≥49			
	Above elbow	ADM		5.7			8.5			50	≥49			
Radial (s)	Forearm	Snuffbox	21	10	≥15	2.2	2.6	≤2.9	63	55	≥50			
Median (s)	Wrist	Index finger	12	11	≥20	3.6	3.7	≤3.5	48	46	≥50			
Ulnar (s)	Wrist	Little finger	11	12	≥17	2.9	3.2	≤3.1	44	46	≥50			
Sural (s)	Calf	Posterior ankle		2	≥6		4.3	≤4.4		45	≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis; ADM = abductor digiti minimi; EIP = extensor indicis proprius.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 21–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Left extensor indicis proprius	↑	+2	0	NL	↓↓↓	NL	NL	NL/+1
Left extensor digitorum communis	↑	+2	0	NL	↓↓↓	NL	NL	NL
Left extensor carpi ulnaris	↑	+1	0	NL	↓↓↓	NL	NL	NL
Left extensor carpi radialis-long head	↑	+2	0	NL	↓↓↓	NL	NL	NL
Left brachioradialis	↑	+1	0	NL	↓↓↓	NL	NL	NL
Left triceps brachii	NL	0	0	NL	NL	NL	NL	NL
Left medial deltoid	NL	0	0	NL	NL	NL	NL	NL
Left abductor pollicis brevis	NL	0	0	NL	NL	NL/+1	NL/+1	NL/+1
Left first dorsal interosseous	NL	0	0	NL	NL	NL/+1	NL/+1	NL/+1
Left pronator teres	NL	0	0	NL	NL	NL	NL	NL
Left biceps brachii	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓↓↓ = markedly reduced; NL = normal.

the CMAP amplitude on the involved side with that on the asymptomatic side is the best way to assess the amount of axonal loss. Thus, there are two pieces of evidence pointing to demyelination as the predominant pathophysiology in this radial neuropathy: conduction block at the spiral groove and intact distal CMAP amplitude. The median and ulnar motor conduction studies are then performed to exclude a more widespread lesion of the brachial plexus. The results of both motor studies are normal.

Next, the sensory studies are performed. The median sensory amplitudes are reduced, with mild prolongation of peak latency bilaterally. However, these potentials are relatively symmetric between the involved and uninvolved sides. Similar findings are discovered in the ulnar sensory studies. When the radial sensory potentials are obtained, however, there is a clear asymmetry: the involved left side is significantly lower in amplitude than the asymptomatic right side.

At this point in the study, there is definite evidence of a left radial neuropathy across the spiral groove that is predominantly demyelinating. The low superficial radial sensory amplitude implies an axonal loss component as well. In addition, there are reduced median and ulnar sensory potentials bilaterally. An ipsilateral brachial plexopathy cannot account for these reduced sensory potentials because the contralateral side shows similar changes in the median and ulnar sensory nerves. This suggests the possibility of a superimposed polyneuropathy. To investigate this idea further, the sural sensory potential is obtained, and it is found to be low in amplitude as well. Thus, the nerve conduction studies have provided additional evidence of an underlying mild polyneuropathy.

Moving onto EMG, three muscles innervated by the posterior interosseous nerve (EIP, extensor digitorum communis, extensor carpi ulnaris) are checked first. Each of them shows fibrillation potentials and markedly reduced recruitment of MUAPs with normal morphology. This is the classic pattern of a subacute lesion. Enough time has occurred so that fibrillation potentials are present (2–3 weeks), but there has not been sufficient time for reinnervation to occur (months). This is the typical pattern that occurs following acute trauma, compression, or nerve infarction. Note that this pattern always indicates that something acute has occurred within the last several weeks, and is not seen with the typical polyneuropathy, which is usually slowly progressive.

Moving onto muscles innervated above the posterior interosseous nerve, both the brachioradialis and extensor carpi radialis-long head show similar findings to the distal radial (PIN) muscles. When checking the extensor carpi radialis, sampling the long head is important. The long head is always innervated by the radial nerve above the bifurcation near the elbow, whereas the short head may be innervated by either the deep motor branch of the radial nerve or the main radial nerve in the elbow. Next, the triceps brachii and medial deltoid are sampled and are found to be normal. Since these two muscles are normal, this makes a radial lesion above the spiral groove, in the axilla, or a lesion in the posterior cord of the brachial plexus much less likely. Next, two non-radial-innervated distal muscles (i.e., abductor pollicis brevis and first dorsal interosseous) are sampled. They show only borderline enlarged polyphasic MUAPs without fibrillation potentials. These findings are much less dramatic than those seen in the radial-innervated muscles, and, because the muscles are distal, the findings may be consistent with a polyneuropathy, as suggested by the nerve conduction studies. Finally, proximal, non-radial-innervated C6 and C7 muscles (pronator teres, biceps brachii) are sampled and found to be normal.

At this point, we are ready to form an electrophysiologic impression.

IMPRESSION: *There is electrophysiologic evidence of a subacute, predominantly demyelinating radial neuropathy across the spiral groove with a superimposed mild axonal sensorimotor polyneuropathy.*

Several questions can be considered.

Could the Radial Neuropathy and Sensorimotor Polyneuropathy have a Common Etiology?

After the EMG, the patient was questioned regarding possible alcohol use. He described moderately heavy use of alcohol for the past 10 years and excessive drinking the night before he awakened with the wrist drop. Thus, there may be a good explanation for the underlying polyneuropathy (alcohol-induced), along with a reasonable answer to why the patient awoke with an acute compressive radial neuropathy at the spiral groove. Prolonged immobilization from a deep sleep or after intoxication is the most common cause of this type of radial neuropathy.

Do the Nerve Conduction Studies and EMG Correlate Well?

The nerve conduction studies and EMG findings correlate quite closely. Nerve conduction abnormalities point to a definite demyelinating lesion across the spiral groove, and the EMG findings show subacute changes only in radial-innervated muscles below the spiral groove. Both nerve conduction studies and EMG studies localize the lesion to the same location. In addition, the results can help to assess the severity and underlying pathophysiology. Clearly, the severity is fairly pronounced. There is markedly reduced recruitment of MUAPs in the weak muscles, signifying that most of the motor axons have been blocked. However, despite the severity of the lesion, given that the distal radial CMAP amplitude is normal, and the lesion is predominantly demyelinating, the prognosis is quite good.

If the Lesion is Predominantly Demyelinating, Why are so Many Fibrillation Potentials Seen?

One can be fairly certain that the primary pathophysiology is demyelination. Demyelination is demonstrated by

preservation of the distal radial CMAP amplitude and the clear finding of conduction block across the spiral groove. One then may ask why are there so many fibrillation potentials if the primary pathophysiology is demyelination? Almost all demyelinating lesions are associated with some secondary axonal loss and, accordingly, with fibrillation potentials. Many studies have shown that the number of fibrillation potentials correlates quite poorly with the amount of axonal loss. Indeed, prominent fibrillation potentials are common even with a small amount of axonal loss. Loss of CMAP amplitude much more accurately approximates the amount of axonal loss, especially with acute lesions, but after enough time has elapsed that wallerian degeneration has occurred. Therefore, although this study shows both a demyelinating and an axonal loss component to the radial neuropathy, the primary problem here is demyelination. This fact has direct implications for prognosis because the prognosis for demyelination usually is very good. It is likely that this patient will recover completely, probably over the next several weeks to months. If, on the other hand, the distal CMAP amplitude had been very low or unobtainable, implying axonal loss, the prognosis would be much more guarded. In that case, nerve regrowth would have to occur from the distal stump, at a rate of 1 mm/day. Axonal regrowth down the length of the arm could easily take months to years and likely would be incomplete.

Case 21–2

History and Physical Examination

An 18-year-old man was referred for right-hand weakness of 2 months' duration. There were no sensory symptoms. Examination showed marked weakness of finger extension. Wrist extension also was weak, and a radial deviation was noted. Finger and wrist flexion were normal, as was intrinsic hand function. Reflexes and sensation were normal.

Summary

The history and physical examination in this case are primarily indicative of wrist drop and finger drop. The differential diagnosis again includes a lesion of the posterior interosseous nerve, a radial neuropathy at the spiral groove or at the axilla, a posterior cord lesion, a C7 radiculopathy, and a central lesion. The physical examination provides several clues that help limit the differential diagnosis. Normal sensation favors a lesion of the posterior interosseous nerve as opposed to the main radial nerve. Of course, sensory loss may be vague or ill-defined in a radiculopathy, and sensation could also be normal in a central lesion. With voluntary wrist extension, there is a radial deviation, suggesting that the long head of the extensor carpi radialis is relatively preserved compared to the extensor carpi ulnaris. Such a pattern is commonly seen in an isolated lesion of the posterior interosseous nerve.

When the radial motor study is performed on the involved side, there is a very low CMAP amplitude with forearm stimulation when recording the EIP. No potential can be elicited when stimulating at the elbow or above. In contrast, the contralateral side shows a normal distal CMAP amplitude, and no drop is seen with proximal stimulation. Therefore, we can be certain that there has been severe axonal loss of the right radial motor fibers. One might question the possibility of a conduction block

CASE 21–2. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = μV			Latency (ms)			Conduction Velocity (m/s)			F Wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Radial (m)	Forearm	EIP	0.2	7.8	≥2	2.4	1.7	≤2.9						
	Elbow	EIP	NR	7.7	≥2	NR	4.7			67	≥49			
	Above spiral groove	EIP	NR	7.7	≥2	NR	8.9			64	≥49			
Median (m)	Wrist	APB	5.4		≥4	3.6		≤4.4				27		≤31
	Antecubital fossa	APB	5.3		≥4	7.0			59		≥49			
Ulnar (m)	Wrist	ADM	9.8		≥6	2.7		≤3.3				25		≤32
	Below elbow	ADM	9.6		≥6	6.0			61		≥49			
	Above elbow	ADM	9.0		≥6	7.6			63		≥49			
Radial (s)	Forearm	Snuffbox	31	30	≥15	1.9	1.7	≤2.9	66	68	≥50			
Median (s)	Wrist	Index finger	50		≥20	2.6		≤3.5	69		≥50			
Ulnar (s)	Wrist	Little finger	33		≥17	2.2		≤3.1	65		≥50			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis; ADM = abductor digiti minimi; EIP = extensor indicis proprius.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 21–2. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right extensor indicis proprius	↑	+3	0	NL	↓↓↓	NL/–1	NL/–1	+2
Right extensor digitorum communis	↑	+2	0	NL	↓↓↓	NL	NL	NL
Right extensor carpi ulnaris	MK	+1	0	NL	↓	+1	+1	+2
Right extensor carpi radialis-long head	NL	0	0	NL	NL	NL	NL	NL
Right brachioradialis	NL	0	0	NL	NL	NL	NL	NL
Right triceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right anconeus	NL	0	0	NL	NL	NL	NL	NL
Right first dorsal interosseous	NL	0	0	NL	NL	NL	NL	NL
Right pronator teres	NL	0	0	NL	NL	NL	NL	NL
Right biceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right medial deltoid	NL	0	0	NL	NL	NL	NL	NL

↑= increased; ↓= slightly reduced; ↓↓↓ = markedly reduced; NL = normal; MK = myokymic discharges.

between the forearm and elbow sites on the involved site, but with such a low distal potential, the drop in proximal amplitude would be of dubious significance. The median and ulnar motor and sensory studies are subsequently performed to ensure that there is not a more widespread lesion. These studies are normal. The superficial radial sensory potential on the involved side is normal and, when compared with the contralateral side, is symmetric. Thus, a normal superficial radial sensory potential accompanies the extremely abnormal radial motor amplitude. This pattern is consistent with either a pure motor lesion or a lesion proximal to the dorsal root ganglion (i.e., nerve root or anterior horn cell). A lesion of the main radial nerve severely affecting motor fibers but sparing sensory fibers would be very unlikely. This pattern is also consistent with a lesion of the posterior interosseous nerve, which is primarily a motor nerve that supplies no cutaneous sensation.

The EMG study shows florid fibrillation potentials in the EIP with markedly reduced recruitment of small, short, very polyphasic MUAPs. Fibrillation potentials and decreased recruitment are also seen in the extensor digitorum communis and extensor carpi ulnaris. All three of these muscles are innervated by the posterior interosseous nerve. In addition, myokymic discharges are present in the extensor carpi ulnaris, along with the fibrillation potentials. When radial muscles innervated proximal to the posterior interosseous nerve are sampled (long head of the extensor carpi radialis, brachioradialis, triceps brachii, anconeus), they are all normal, as are non-radial C5 through T1-innervated muscles in the upper extremity.

At this point, we can form an electrophysiologic impression.

IMPRESSION: *There is electrophysiologic evidence of a severe predominantly axonal lesion of the posterior interosseous nerve.*

The history, physical examination, and subsequent electrophysiologic evaluation are all consistent with a PIN. In PIN, the radial sensory potential is not involved because the superficial radial sensory nerve separates from the main radial nerve in the proximal forearm, before the take-off to the PIN. This explains why the patient has no sensory complaints and why the radial sensory potential is normal and symmetric in comparison with the asymptomatic side. Rarely, conduction block may be seen on radial motor studies in PIN between the forearm and elbow, but usually the lesion is one of axonal loss.

The EMG probably is the most important test in localizing a lesion to the posterior interosseous nerve, showing abnormalities in muscles innervated by that nerve alone. Once abnormalities are found in muscles innervated by the posterior interosseous nerve, the key muscles to check are those innervated by the radial nerve proximal to the posterior interosseous nerve (i.e., long head of extensor carpi radialis, brachioradialis, anconeus, triceps).

Several questions can be addressed.

What is the Significance of the Myokymic Discharges?

There are several interesting findings in this case. First is the presence of myokymic discharges in the extensor carpi ulnaris. Myokymia is spontaneous activity consisting of grouped repetitive discharges of MUAPs. The generator in myokymia is an abnormal motor nerve, and the pathophysiology is thought to be demyelinating. Myokymia is classically seen in radiation injury, Guillain–Barré syndrome, multiple sclerosis, and brainstem tumors, but it may also be seen in some entrapment neuropathies. Indeed, myokymia rarely is seen in the abductor pollicis brevis muscle in patients with carpal tunnel syndrome. In the case discussed here, myokymic discharges are seen in one of the posterior interosseous-innervated muscles, likely caused by entrapment of the posterior interosseous nerve, with some element of demyelination.

What is the Significance of the Small, Short, Polyphasic Motor Unit Action Potentials?

Small, short, polyphasic MUAPs in the EIP denote that individual motor units have a lower than normal number of muscle fibers. Such loss typically is associated with myopathy or severe disorders of the neuromuscular junction in which individual muscle fibers have been blocked. Therefore, one may ask if there is a coexistent myopathy or neuromuscular junction disorder here as well. The answer is unequivocally no. The other situation in which small, short, polyphasic MUAPs can be seen is in the setting of nascent motor units. In that situation, following severe denervation, the only way muscle fibers can be reinnervated is by regrowth of the axon from the terminal stump, because there are no nearby motor units to reinnervate the denervated muscle fibers by way of collateral sprouting. As such regrowth occurs, there will be a time early in reinnervation when the axon is connected to only a few muscle fibers (i.e., a "nascent motor unit"). Accordingly, the nascent motor unit potentials seen on EMG will be small, short, and polyphasic. How, then, can one distinguish a nascent from a myopathic MUAP? In myopathy, the number of MUAPs firing is normal for the level of activation; therefore, the recruitment is normal or sometimes even early. The converse is true with nascent motor units, which occur following severe denervation. In this situation, recruitment is always moderately to markedly reduced, often in association with prominent fibrillation potentials. Reviewing again the EMG findings in the EIP, we find more than sufficient evidence to suggest the presence of nascent motor unit potentials. Along with the small, short, polyphasic MUAPs, there are marked fibrillation potentials, and, more importantly, recruitment is markedly reduced.

After the electrophysiologic study, the patient underwent surgical exploration of the posterior interosseous nerve. Compression was identified and relieved at the Arcade of Frohse. Subsequently, the patient had complete recovery of his wrist drop and finger drop, although recovery required 12 months, signifying again that the predominant underlying pathology was axonal loss.

Suggested Readings

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22 Peroneal Neuropathy

Peroneal neuropathy is one of the most common mononeuropathies in the lower extremity. Most often, peroneal neuropathy occurs at the fibular neck, where the nerve is quite superficial and vulnerable to injury. Patients usually present with a foot drop and sensory disturbance over the lateral calf and dorsum of the foot. However, patients with sciatic neuropathy, lumbosacral plexopathy, or L5 radiculopathy may present with a similar pattern of numbness and weakness, due to the preferential susceptibility of the peroneal fibers. It often falls to the electromyographer to differentiate among these lesions. In addition, the electrophysiologic evaluation usually can localize the level of the peroneal neuropathy, identify the underlying pathophysiology, and establish the prognosis.

ANATOMY

The peroneal nerve is derived predominantly from the L4–S1 nerve roots, which travel through the lumbosacral plexus and eventually the sciatic nerve. Within the *sciatic nerve*, the fibers that eventually form the *common peroneal nerve* run separately from those that distally become the *tibial nerve* (Figure 22–1). In the posterior thigh, the peroneal fibers within the sciatic nerve innervate the *short head of the biceps femoris, the only peroneal-derived muscle above the level of the fibular neck* (Figure 22–2). More distally, the sciatic nerve bifurcates above the popliteal fossa into the common peroneal and tibial nerves. The common peroneal nerve first gives rise to the *lateral cutaneous nerve of the knee*, which supplies sensation to the lateral knee before winding around the fibular neck and passing through the fibular tunnel between the peroneus longus muscle and the fibula. At the fibular neck, the internal fascicular anatomy is such that the fibers destined for the deep peroneal nerve lie more medial (adjacent to the fibula) whereas the fibers destined for the superficial peroneal nerve are more lateral (Figure 22–3). The common peroneal nerve then divides into superficial and deep branches. The *deep peroneal nerve* (Figure 22–4) innervates the peroneus tertius and the dorsiflexors of the ankle and toes, including the tibialis anterior (TA), extensor digitorum longus, extensor hallucis longus (EHL), and extensor digitorum brevis (EDB). It continues on to supply sensation to the web space between the first and second toes. The *superficial peroneal nerve* (Figure 22–5) innervates the ankle everters (peroneus longus and peroneus brevis) and then supplies sensation to the mid and lower lateral calf. As it passes over the dorsum of the foot, it divides into the *medial and intermediate dorsal cutaneous nerves of the foot*, supplying sensation to the dorsum of the foot and to the dorsal medial three or four toes up to the level of the interphalangeal joints. In 15 to 20% of patients, an *accessory peroneal nerve* leaves the main superficial peroneal nerve and runs posterior to the lateral malleolus to ultimately supply the lateral EDB muscle. This is an important normal variant often encountered during routine nerve conduction studies.

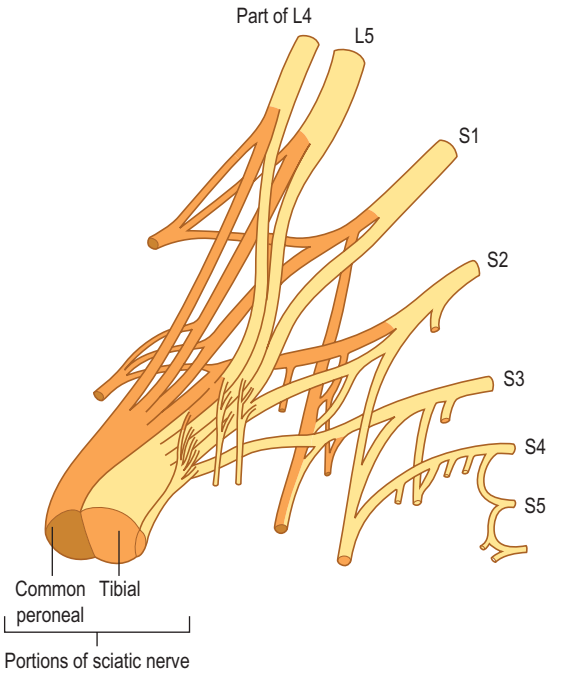

FIGURE 22–1 Common peroneal and tibial fibers within the sciatic nerve. Within the sciatic nerve, the fibers that go on to form the common peroneal nerve run separately from those that eventually form the tibial nerve.
(Adapted with permission from Hollinshead, W.H., 1969. Anatomy for surgeons, volume 2: the back and limbs. Harper & Row, New York.)

DOI: 10.1016/B978-1-4557-2672-1.00022-2

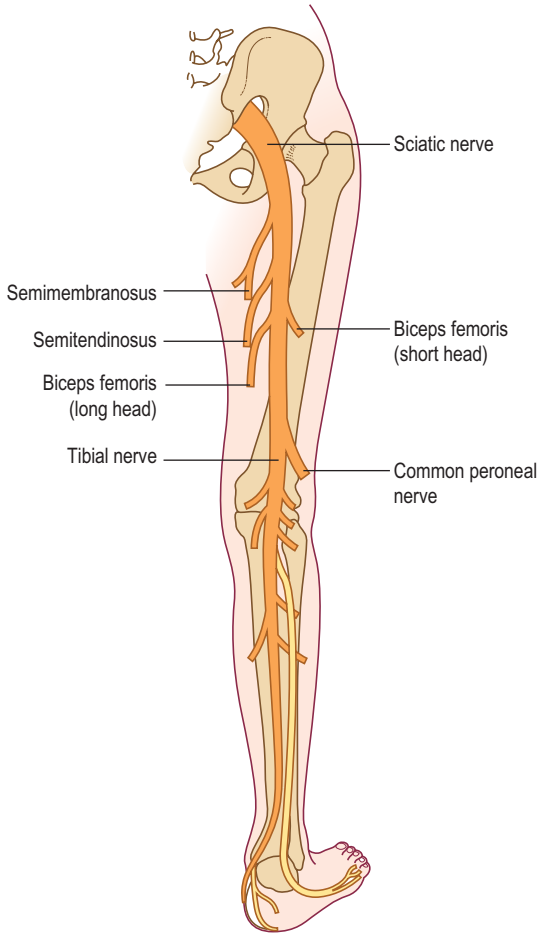

FIGURE 22–2 Sciatic-innervated muscles in the thigh. The short head of the biceps femoris is the only muscle innervated by the peroneal division of the sciatic nerve that arises above the fibular neck. All other sciatic-innervated muscles in the posterior thigh are derived from the tibial division of the sciatic nerve (semimembranosus, semitendinosus, long head of the biceps femoris).
(Adapted with permission from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia.)

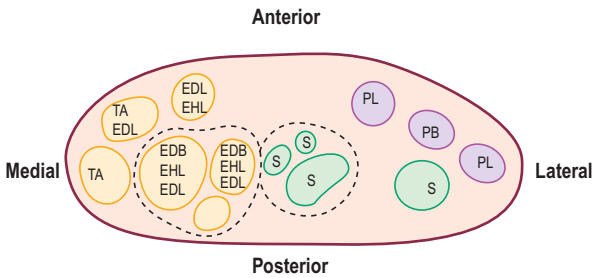

FIGURE 22–3 Internal fascicular anatomy of the common peroneal nerve at the fibular neck. **Yellow:** Ankle and toe dorsiflexors; **Green:** Cutaneous sensory fibers; **Purple:** Ankle evertors. (TA=tibialis anterior; EDL=extensor digitorum longus; EDB=extensor digitorum brevis; S=sensory fibers; PL=peroneus longus; PB=peroneus brevis.)
(Adapted with permission from Sunderland, S., 1973. Nerves and nerve injuries, second ed. Churchill-Livingstone, London.)

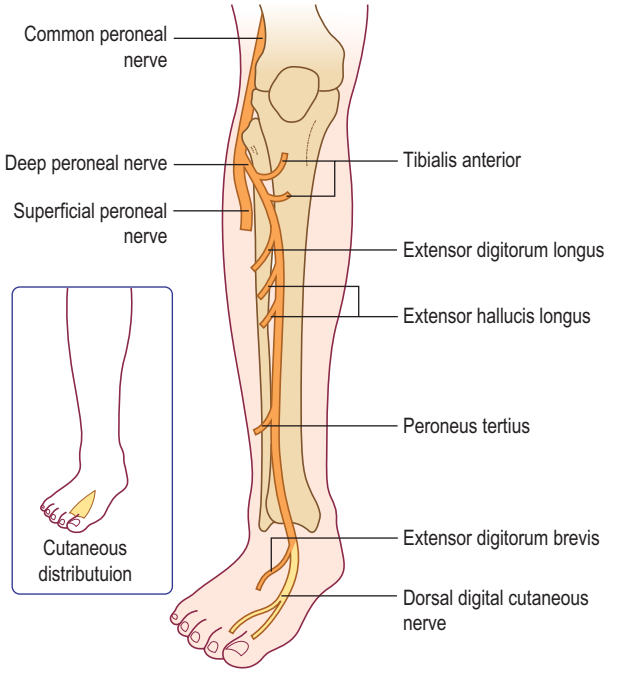

FIGURE 22–4 Deep peroneal nerve anatomy.
(Reprinted with permission from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia.)

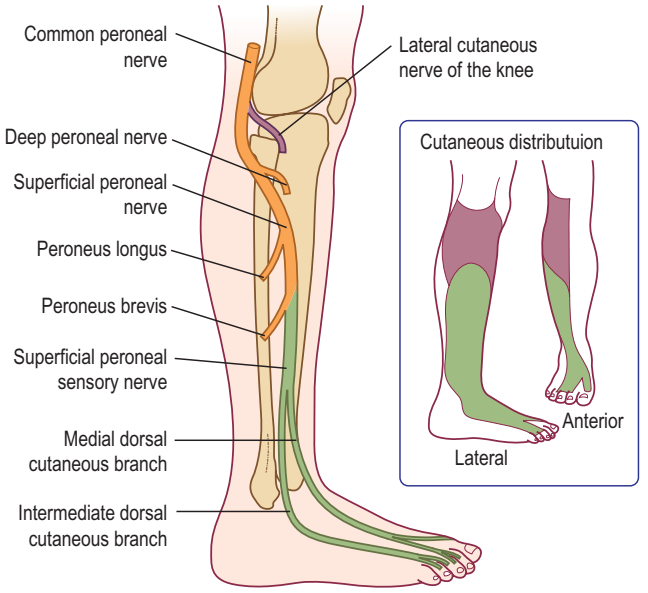

FIGURE 22–5 Common and superficial peroneal nerve anatomy.
(Reprinted with permission from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia.)

CLINICAL

Peroneal Neuropathy at the Fibular Neck

Patients with peroneal neuropathy at the fibular neck present with a characteristic neurologic picture. Most often, both the deep and superficial peroneal nerves are affected. Involvement of the deep peroneal nerve leads to weakness of toe and ankle dorsiflexion, resulting in a foot and toe drop. Dysfunction of the superficial peroneal nerve results in weakness of foot eversion. Clinically, weakness of these muscles results in a stereotyped set of symptoms. Patients note a slapping quality of their foot as it hits the ground while they are walking. Weakness of eversion leads to a tendency to trip, especially on uneven sidewalks or curbs, and an increased risk of sprained ankles. When observed while walking, patients have a so-called *steppage gait* whereby they bring their knee up higher than usual so that the dropped foot clears the floor. Sensory disturbance develops over the mid and lower lateral calf and the dorsum of the foot. Local pain and a Tinel's sign may be present over the lateral fibular neck.

In isolated peroneal neuropathy at the fibular neck, function of the sciatic, tibial, and sural nerves remains normal. Most important, ankle inversion is spared, mediated by the tibialis posterior (L5, sciatic–tibial innervated nerve). If the ankle is tested in a dropped position, however, ankle inversion may appear weak (similar to testing finger abduction in a dropped wrist position). Accordingly, to test ankle inversion in a patient with a foot drop, the ankle should be passively dorsiflexed to avoid the mistaken impression that the tibialis posterior is weak. The remainder of the muscles innervated by the tibial and sciatic nerves are normal (ankle and toe plantar flexion, knee flexion). Hip abduction, internal rotation, and extension also are normal, innervated by the superior and inferior gluteal nerves, which come directly off the lumbosacral plexus. Sensation is normal over the lateral foot (sural territory), sole of the foot (medial and lateral plantar territory), and medial calf and foot (saphenous territory). Sensation over the lateral knee is preserved because that area is innervated by the lateral cutaneous nerve of the knee, which arises from the common peroneal nerve above the fibular neck. Finally, all reflexes, including the ankle reflex, remain normal in an isolated peroneal neuropathy.

As already noted, lesions of the sciatic nerve, lesions of the lumbosacral plexus, and L5 radiculopathy may present with a foot drop and numbness over the lateral calf and dorsum of the foot. Indeed, these lesions, especially early on, occasionally mimic a peroneal palsy almost exactly, including abnormalities of sensation (Table 22–1). It is in these cases that electrodiagnostic studies are especially

Table 22–1. Clinical Differentiating Factors in Foot Drop

	Deep Peroneal Nerve	Common Peroneal Nerve	Sciatic Nerve	Lumbosacral Plexus	L5
Weakness of foot dorsiflexion	X	X	X	X	X
Weakness of foot eversion		X	X	X	X
Weakness of foot inversion			X	X	X
Weakness of knee flexion			X	X	X
Weakness of glutei				X	X
Reduced ankle tendon reflex			X*	X*	X*
Sensory loss in web space great toe	X	X	X	X	X
Sensory loss in dorsum of foot		X	X	X	X
Sensory loss in lateral calf		X	X	X	X
Sensory loss in lateral knee			X	X	X
Sensory loss in sole foot			X*	X*	X*
Sensory loss in posterior thigh				X*	X*
Tinel's sign at fibular neck	X	X			
Hip and thigh pain			X	X	X
Back pain					X
Positive straight-leg raise test					X

X, may be present.
*May be abnormal if lesion involves S1 fibers as well.

helpful. On the clinical examination, any of the following abnormalities in a patient with a foot drop should suggest a lesion more proximal to the peroneal nerve at the fibular neck:

- Weakness of ankle inversion (tibialis posterior – innervated by the tibial nerve)
- Preferential weakness of the EHL (**L5**–S1) out of proportion to the TA (**L4–L5**) when the two are compared. In a peroneal neuropathy, these two muscles usually are equally affected; in an L5 radiculopathy, the EHL usually is weaker than the TA because of its predominant L5 innervation
- Sensory loss over the lateral knee (distribution of the lateral cutaneous nerve of the knee)
- Sensory loss over the sole of the foot, lateral foot, or medial calf (distribution of the plantar, sural, or saphenous nerves, respectively)
- Any weakness of hip abduction, extension, or internal rotation (gluteus medius, tensor fascia latae, gluteus maximus – innervated by the superior and inferior gluteal nerves). Because these muscles are quite strong, they must be tested at mechanical disadvantage to demonstrate subtle weakness
- Any asymmetry of the ankle reflex

Deep Peroneal Neuropathy at the Ankle

Compression of the deep peroneal nerve at the ankle is known as "Anterior Tarsal Tunnel Syndrome." This is a rare entrapment neuropathy that occurs from compression of the deep peroneal nerve under the inferior extensor retinaculum at the ankle. Patients present with foot pain and paresthesias of the dorsum of the foot between the great and second toes. Atrophy and weakness of the extensor digitorum brevis muscle may be present. Sensation may be decreased in the web space between the great and second toes. Plantar flexion may result in increased symptoms, which may be relieved by dorsiflexion. A Tinel's sign may be elicited by percussing over the anterior ankle.

ETIOLOGY

Peroneal neuropathy at the fibular neck can be seen as a result of a variety of conditions (Box 22–1). Acute peroneal neuropathy often follows trauma, forcible stretch injury, or compression from prolonged immobilization. In the hospital, peroneal neuropathy at the fibular neck occurs most often postoperatively in patients who have received anesthesia or heavy sedation. Slowly progressive lesions often suggest a mass lesion, such as a ganglion or nerve sheath tumor. Entrapment of the peroneal nerve at the fibular tunnel, although quite uncommon, also may present in a progressive manner.

Several other circumstances predispose one to peroneal neuropathy at the fibular neck. Habitual leg crossing may repetitively injure the peroneal nerve at the fibular neck, where it is quite superficial. Similarly, repetitive stretch from squatting, for example, by gardeners has been associated with peroneal neuropathy at the fibular neck. In addition, patients who are thin or who have recently lost a substantial amount of weight may be prone to peroneal palsy, probably because of the lack of protective supporting adipose tissue at the fibular neck.

Isolated neuropathy of the superficial peroneal sensory nerve is rarely reported. However, this nerve can be compressed externally, especially by tight-fitting boots. Most often, this is seen from ski boots (Figure 22–6).

Compression of the deep peroneal nerve at the anterior tarsal tunnel has been reported with trauma, tight shoes (especially in dancers), bony abnormalities of the ankle, ganglion cysts, and pes cavus.

Box 22–1. Etiology of Peroneal Neuropathy at the Fibular Neck

- Trauma (including fracture)
- Stretch (forcible ankle inversion)
- Compression
  - Casts
  - Stockings
  - Immobilization after anesthesia, sedation, or intoxication
- Occupational
  - Gardening
  - Farm work (squatting, kneeling)
- Entrapment (fibular tunnel)
- Mass lesions (ganglia, tumors, Baker's cyst)
- Miscellaneous (weight loss, habitual leg crossing)

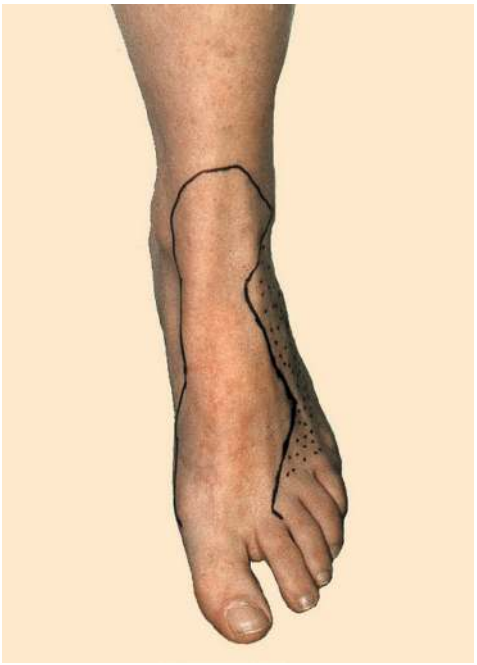

FIGURE 22–6 Ski boot neuropathy. Left foot numbness in a patient after skiing. The outlined area was completely anesthetic, and the dotted area had decreased sensation. This territory corresponds to the medial and intermediate dorsal cutaneous branches of the superficial peroneal nerve, respectively. Rarely, tightly fitting shoes or boots can compress the distal sensory branches of the superficial peroneal nerve.

ELECTROPHYSIOLOGIC EVALUATION

Nerve Conduction Studies

In a patient with a foot drop and suspected peroneal neuropathy, peroneal motor, F response, and superficial peroneal sensory studies should be performed first (Box 22–2). The findings will depend on the location and severity of the lesion and on whether the underlying pathophysiology is demyelination, axonal loss, or a combination of both (Figure 22–7). In demyelinating lesions, if focal slowing or conduction block is seen across the fibular neck in the peroneal motor study, this can be used to localize the lesion. Usually, any slowing of more than 10 m/s is considered significant. Any drop in amplitude or area of more than 20%, especially over a very short segment, suggests focal conduction block (Figure 22–8). The amount of conduction block can be approximated by comparing the compound muscle action potential (CMAP) amplitude at the lateral popliteal fossa with that below the fibular head. In purely demyelinating lesions at the fibular neck, the distal superficial peroneal sensory response remains normal.

If axonal loss predominates, peroneal CMAP amplitudes will be reduced at all stimulation sites (ankle, below the fibular head, lateral popliteal fossa). As in other axonal loss lesions, conduction velocities and the distal motor latency may be normal or slightly slowed if the fastest-conducting axons have been lost. Likewise, the superficial peroneal sensory nerve action potential (SNAP) amplitude will be reduced or absent. If the pathophysiology is entirely axonal loss, the nerve conduction studies, although they

Box 22–2. Recommended Nerve Conduction Study Protocol for Peroneal Neuropathy

Routine studies:

1. Peroneal motor study, recording extensor digitorum brevis, stimulating ankle, below fibular head and lateral popliteal fossa. If there is no focal slowing or conduction block at the fibular neck, perform a peroneal motor study, recording tibialis anterior and stimulating below the fibular head and lateral popliteal fossa.
2. Tibial motor study, recording abductor hallucis brevis, stimulating medial ankle and popliteal fossa
3. Superficial peroneal sensory study, stimulating lateral calf, recording lateral ankle
4. Sural sensory study, stimulating calf, recording posterior ankle
5. Tibial and peroneal F responses

Special consideration: If any study is abnormal or borderline, especially the motor or sensory amplitudes, comparison to the contralateral asymptomatic side is often useful.

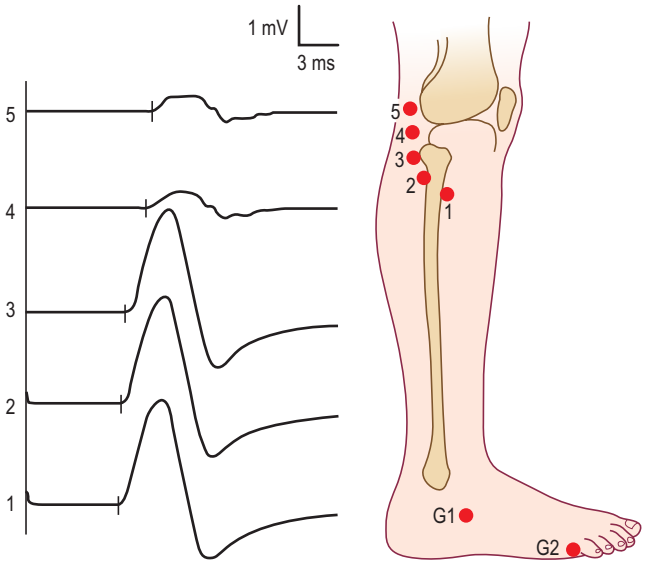

FIGURE 22–8 Conduction block across the fibular neck. The common peroneal nerve is stimulated, and the extensor digitorum brevis is recorded. From bottom to top: Stimulating below the fibular neck and proceeding proximally in 1 cm increments.

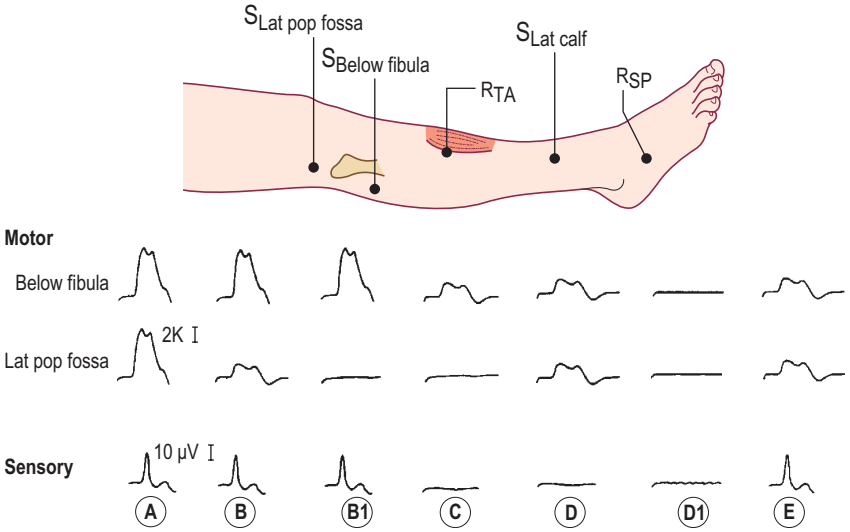

FIGURE 22–7 Nerve conduction patterns in peroneal neuropathy. In each panel, the waveforms at the top are peroneal motor waveforms, stimulating below fibular head and recording the tibialis anterior; the waveforms in the middle are peroneal motor waveforms, stimulating the lateral popliteal fossa and recording tibialis anterior (TA); the waveforms at the bottom are superficial peroneal (SP) sensory waveforms, stimulating the lateral calf and recording the lateral ankle. **A:** Normal. **B:** Partial conduction block. **B1:** Complete conduction block. **C:** Complete conduction block with axonal loss. **D:** Partial axonal loss. **D1:** Complete axonal loss. **E:** Partial axonal loss lesion of deep peroneal nerve. (Note: This last pattern can also be seen in L5 radiculopathy or anterior horn cell disorders.) (Adapted from Katirji, M.B., Wilbourn, A.J., 1988. Common peroneal mononeuropathy: a clinical and electrophysiologic study of 116 lesions. Neurology 38, 1723. Reprinted with permission from Little, Brown.)

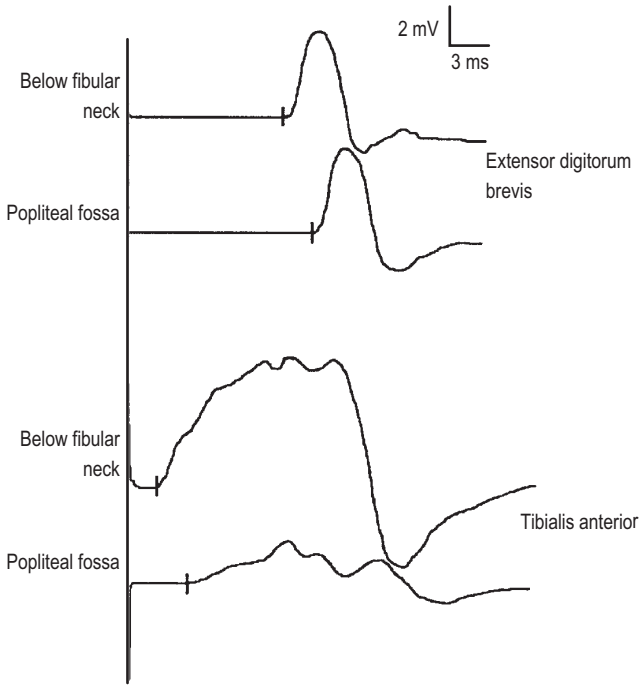

FIGURE 22–9 Usefulness of recording the tibialis anterior in peroneal neuropathy. When performing peroneal motor studies, recording the tibialis anterior often is more informative than routine studies recording the extensor digitorum brevis. In some cases of peroneal neuropathy at the fibular neck, conduction block may be seen recording the tibialis anterior but not the extensor digitorum brevis. In the traces shown here, the tibialis anterior and extensor digitorum brevis are co-recorded while the peroneal nerve is stimulated below the fibular head and at the lateral popliteal fossa. Note the conduction block pattern recording the tibialis anterior but not the extensor digitorum brevis. The studies are from a patient with an occupational peroneal palsy across the fibular neck due to repetitive squatting.

demonstrate a peroneal neuropathy, cannot localize the level of the lesion. The amount of axonal loss can be approximated by comparing the distal CMAP amplitude on the involved side with that on the contralateral asymptomatic side. Often, there may be evidence of both axonal loss and demyelination in the same patient.

The EDB muscle usually is chosen as the recording site for peroneal motor studies. However, in patients with a foot drop, it is weakness of the TA that accounts for the clinical deficit. *Hence, recording the TA when performing the peroneal motor study often is more useful than the routine motor study recording the EDB*. Indeed, in some cases of peroneal neuropathy at the fibular neck, conduction block may be seen when recording the TA but not the EDB (Figure 22–9). If recording the EDB does not localize the lesion by demonstrating focal slowing or conduction block, the peroneal motor study should be repeated recording the TA, stimulating below the fibular head and at the lateral popliteal fossa.

In addition to the peroneal motor and sensory studies, tibial motor, F response, and sural sensory studies must be performed. Because lesions of the sciatic nerve and lumbosacral plexus can present in a similar manner to peroneal neuropathy, excluding a more widespread lesion is imperative. Of course, if any motor or sensory study is borderline, comparing it with the contralateral asymptomatic side often is useful.

Most peroneal lesions affect both the superficial and deep branches. However, it is common that the deep branch is more affected than the superficial. Occasionally, only the deep peroneal branch is involved. This presumably happens due to selective fascicular vulnerability of the deep fibers which lie the closest to the fibula, and are more prone to compression (Figure 22–3). In such cases, interpretation of the nerve conduction studies can be more difficult. The sensory response, which is mediated by the superficial branch of the peroneal nerve, will be normal. If peroneal motor studies show evidence of axonal loss only, without focal slowing or conduction block across the fibular neck, the nerve conduction studies in an isolated deep peroneal neuropathy may appear identical to those seen in a severe L5 radiculopathy associated with axonal loss.

Electromyographic Approach

After the nerve conduction studies are completed, electromyography (EMG) (Box 22–3) is used to confirm the localization and assess the severity of the lesion and, most importantly, to exclude a sciatic neuropathy, lumbosacral

Box 22–3. Recommended Electromyographic Protocol for Peroneal Neuropathy

Routine muscles:

1. At least two muscles innervated by the deep peroneal nerve (e.g., tibialis anterior, extensor hallucis longus)
2. At least one muscle innervated by the superficial peroneal nerve (e.g., peroneus longus, peroneus brevis)
3. Tibialis posterior and at least one other tibial muscle (e.g., medial gastrocnemius, soleus, flexor digitorum longus)
4. Short head of the biceps femoris

Special considerations:

- If any muscle is borderline, compare with the contralateral side.
- If the short head of the biceps femoris or any tibial-innervated muscle is abnormal or if nerve conduction studies demonstrate a non-localizing peroneal neuropathy or abnormal tibial motor or sural responses, a more extensive needle examination of other sciatic, gluteal, and paraspinal muscles should be performed to identify the level of the lesion.
- If the diagnosis of Anterior Tarsal Tunnel Syndrome (ATTS) is considered, then one should sample the EDB muscle. Comparison of the contralateral side may be helpful. The diagnosis of ATTS is made clinically; EMG abnormalities of the EDB muscle are supportive but not diagnostic of the syndrome. Many normal individuals without any symptoms will display reinnervation in the EDB (presumably from the repetitive compression by shoes at the anterior ankle). This is so common that routine sampling of the EDB on needle EMG is not recommended as it is so difficult to determine what is truly "abnormal."

plexopathy, or radiculopathy, any of which can mimic a peroneal neuropathy (Table 22–2). The first muscles that should be sampled are those innervated by the deep and superficial peroneal nerves (TA, EHL, peroneus longus). Acute to subacute lesions associated with axonal loss will result in fibrillation potentials and decreased recruitment of normal-configuration motor unit action potentials (MUAPs). In chronic axonal lesions, decreased recruitment of long-duration, high-amplitude, polyphasic MUAPs will be seen. If the lesion is predominantly demyelinating with conduction block, only decreased MUAP recruitment will occur, and the MUAP morphology will remain normal.

If any of the peroneal-innervated muscles are abnormal, non-peroneal-innervated muscles supplied by the L5 root must be sampled to exclude a sciatic neuropathy, lumbosacral plexopathy, or radiculopathy. Note that even if the conduction studies localize the lesion to the peroneal nerve at the fibular neck (focal slowing or conduction block), a few critical non-peroneal L5-innervated muscles still should be sampled to confirm that the lesion is restricted to the peroneal nerve and to exclude a superimposed lesion. Tibial-innervated muscles are sampled next, especially the tibialis posterior, which is an L5-innervated muscle that mediates ankle inversion. The flexor digitorum longus also can be sampled. If any abnormalities are found in these muscles, an isolated lesion of the common peroneal nerve has been excluded.

Next, the hamstring muscles should be sampled. *The short head of the biceps femoris has an important role in suspected peroneal neuropathy at the fibular neck. It is the only muscle supplied by the peroneal division of the sciatic nerve that originates above the fibular neck.* Abnormalities in this muscle or in any of the hamstring muscles imply a lesion proximal to the peroneal nerve, in the sciatic nerve or higher. In some cases, sciatic neuropathy may mimic the EMG pattern of peroneal neuropathy, with the exception of abnormalities found in the short head of the biceps femoris. The short head of the biceps femoris can easily be sampled four fingerbreadths above the lateral knee, just medial to the tendon to the long head of the biceps femoris. If the nerve conduction studies demonstrate clear evidence of peroneal neuropathy at the fibular neck and if EMG abnormalities are found only in peroneal-innervated muscles, with sparing of the tibialis posterior and short head of the biceps femoris, then no further needle EMG is required.

If any abnormalities are found in the hamstring or distal tibial-innervated muscles, a more extensive needle EMG must be performed, including sampling the gluteal and paraspinal muscles. Similarly, if the nerve conduction

Table 22–2. Electromyographic and Nerve Conduction Abnormalities Localizing the Lesion Site in Foot Drop

	Deep Peroneal Nerve	Common Peroneal Nerve	Sciatic Nerve	Lumbosacral Plexus	L5
Electromyographic Findings					
Tibialis anterior	X	X	X	X	X
Extensor hallucis longus	X	X	X	X	X
Peroneus longus		X	X	X	X
Tibialis posterior			X	X	X
Flexor digitorum longus			X	X	X
Short head of the biceps femoris			X	X	X
Gluteus medius				X	X
Tensor fascia latae				X	X
Paraspinal muscles					X
Nerve Conduction Study Findings					
Abnormal peroneal SNAP (if axonal)		X	X	X	
Abnormal sural SNAP (if axonal)			X	X	
Low peroneal CMAP (if axonal)	X	X	X	X	X
Low tibial CMAP (if axonal)			X*	X*	X*
Abnormal H reflex			X*	X*	X*
Conduction slowing/block at fibular neck (if demyelinating)	X	X			

X, abnormalities may be present; CMAP, compound muscle action potential; SNAP, sensory nerve action potential.
*May be abnormal if lesion involves S1 fibers as well.

studies demonstrate a non-localizing axonal loss lesion of the peroneal nerve (low peroneal CMAP and SNAP amplitudes without focal slowing or conduction block) or abnormal tibial motor or sural responses, a more extensive needle EMG study should be performed, at least to the level of the gluteal muscles. If abnormalities are found, the EMG can localize the lesion only at or proximal to the take-off to the most proximal abnormal muscle sampled.

The classic electrophysiologic picture of peroneal neuropathy at the fibular neck is a reduced peroneal motor amplitude compared with the contralateral side, typically conduction block across the fibular neck (focal slowing is less common), and a reduced peroneal SNAP amplitude. The peroneal F responses are generally prolonged or absent on the symptomatic side, with normal peroneal F responses contralaterally and in the tibial nerve. The tibial motor and sural sensory studies are normal. Needle EMG shows active denervation and/or reinnervation in muscles supplied by the deep and superficial peroneal nerves. Tibial- and sciatic-innervated muscles are spared, especially the tibialis posterior and the short head of the biceps femoris. If the lesion is purely demyelinating, the superficial peroneal SNAP and distal peroneal motor latencies and amplitudes will be normal, with conduction block and/or focal slowing across the fibular neck, on motor studies. Needle EMG will show only decreased recruitment without active denervation or changes in MUAP morphology. The presence of a predominantly demyelinating lesion has important prognostic implications. Because the underlying axons remain intact, the prognosis for full recovery over a relatively short period is excellent, provided the cause of the entrapment is no longer present.

In the unusual situation of suspected Anterior Tarsal Tunnel Syndrome, the only abnormality will be denervation and/or reinnervation limited to the extensor digitorum brevis (EDB). However, caution must always be used in assessing the EDB. It is not uncommon that "normal" individuals without any symptoms will have reinnervation in the EDB. This is so common that it is generally recommended to not even sample the EDB during routine needle EMG studies. In patients with symptoms limited to one side, comparison to the contralateral EDB is recommended. However, keep in mind that abnormalities in the EDB on needle EMG are much more commonly due to either peripheral neuropathy, peroneal neuropathy at the fibular neck or L5 radiculopathy, rather than Anterior Tarsal Tunnel Syndrome.

EXAMPLE CASE

Case 22–1

History and Physical Examination

A 56-year-old man was referred for a persistent foot drop 3 weeks after coronary artery bypass surgery. Shortly after awakening from anesthesia, the patient noted difficulty dorsiflexing his right foot and toes. In addition, there was a pins-and-needles sensation over the dorsum of the right foot. He noted that when he was walking, his right foot would slap with each step. There was no pain, and the left leg was unaffected.

On examination, the patient was tall and quite thin. Muscle bulk and tone were normal and symmetric in both legs. There was marked weakness of right ankle and toe dorsiflexion (1/5) as well as ankle eversion (2/5). There was a suggestion of mild weakness of foot inversion. Ankle and toe plantar flexion, knee flexion, and all movements around the hip were normal. Deep tendon reflexes were intact and symmetric, including both ankle reflexes. Sensory examination showed a well-demarcated loss of sensation to pinprick and temperature over the dorsum of the right foot extending into the lateral calf. Sensation over the right lateral knee was normal, as was sensation over the lateral foot, sole of the foot, and medial calf. No pain or Tinel's sign was produced by palpating the peroneal nerve across the fibular neck on the right.

CASE 22–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = μV			Latency (ms)			Conduction Velocity (m/s)			F wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Peroneal (m)	Ankle	EDB	6.3	7.1	≥2	5.8	5.6	≤6.5				NR	47	≤56
	Below fibula	EDB	6.2	6.9		12.6	12.1		44	46	≥44			
	Lateral popliteal fossa	EDB	1.7	6.6		16.0	14.2		20	47	≥44			
Tibial (m)	Ankle	AHB	12.2		≥4	4.8		≤5.8				48		≤56
	Popliteal fossa	AHB	10.8		≥4	13.4			45		≥41			
Peroneal (s)	Lateral calf	Ankle	7	16	≥6	3.5	3.2	≤4.4	47	50	≥40			
Sural (s)	Calf	Posterior ankle	14	12	≥6	3.5	3.4	≤4.4	47	48	≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; EDB = extensor digitorum brevis; AHB = abductor hallucis brevis.
Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 22–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right tibialis anterior	↑	+2	0	NL	↓↓↓	NL	NL	NL
Right extensor hallucis longus	↑	+1	0	NL	↓↓↓	NL	NL	NL
Right peroneus longus	↑	+1	0	NL	↓↓↓	NL	NL	NL
Right tibialis posterior	NL	0	0	NL	NL	NL	NL	NL
Right medial gastrocnemius	NL	0	0	NL	NL	NL	NL	NL
Right biceps femoris – short head	NL	0	0	NL	NL	NL	NL	NL
Right biceps femoris – long head	NL	0	0	NL	NL	NL	NL	NL
Right gluteus medius	NL	0	0	NL	NL	NL	NL	NL
Right L5 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right S1 paraspinal	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓↓↓ = markedly reduced; NL = normal.

Summary

In this case, there is a 3-week history of a foot drop, which was noted by the patient upon awakening from a surgical procedure. The history initially suggests a peripheral nerve lesion, given the paresthesias and weakness in the distribution of the peroneal nerve. Examination subsequently shows marked weakness in the distribution of both the deep and superficial peroneal nerves (ankle dorsiflexion and eversion, respectively). However, there is a suggestion of weakness of right foot inversion. This is potentially a very important sign because it suggests weakness of the tibialis posterior, a non-peroneal-innervated muscle. If foot inversion truly is weak, an isolated lesion of the peroneal nerve is excluded. Other tibial-innervated muscles are normal, however, including ankle and toe plantar flexors. In addition, the ankle reflex, mediated by the tibial and sciatic nerves, is normal and symmetric.

The sensory examination is normal over the lateral foot, sole of the foot, and medial calf, representing the territories of the sural, plantar, and saphenous nerves, respectively. In addition, sensation over the right lateral knee, the distribution of the lateral cutaneous nerve of the knee, is normal. Abnormalities found in any of these territories would suggest a lesion more proximal to the peroneal nerve. However, sensation is normal in all of them. There is a well-demarcated loss of sensation to pinprick and temperature over the dorsum of the foot and the lateral calf. Well-demarcated areas of sensory loss suggest a peripheral nerve lesion; they are uncommon in radiculopathy because dermatomes usually overlap widely with adjacent dermatomes.

Therefore, before approaching the nerve conduction and EMG study, the clinical suspicion is that of a peroneal neuropathy, most likely at the fibular neck, but a more proximal lesion must also be considered because of the question of weakness of foot inversion.

On nerve conduction studies, the right peroneal motor study shows a normal CMAP amplitude at the ankle and below fibular neck sites. The distal motor latency and conduction velocity in the leg also are normal. However, stimulating above the fibular neck in the lateral popliteal fossa demonstrates a marked decrease in amplitude with slowing of conduction velocity into the demyelinating range (20 m/s). On the contralateral asymptomatic side, the peroneal CMAP amplitude is slightly larger, and there is no conduction block or focal slowing around the fibular neck. The F responses are absent on the right but are present and normal on the contralateral side. The tibial motor study is then performed on the involved side; it shows a normal CMAP amplitude, distal latency, and conduction velocity. The tibial F waves also are normal.

The superficial peroneal sensory response is obtained next on the right and shows a normal amplitude. The amplitude is just slightly above the upper limit of normal. However, compared with the contralateral side, the responses are clearly asymmetric. The superficial peroneal SNAP amplitude on the left side is much larger than on the right side. Thus, while the superficial peroneal sensory response on the right side might be considered normal in an absolute sense, it is clearly shown to be abnormal when compared with the contralateral side. On the involved right side, the sural response is normal and much larger than the peroneal sensory response. When the involved and contralateral sides are compared, there is no significant asymmetry in the sural responses. The sural response actually is slightly larger on the right side

compared with the left, but the difference is not significant. Therefore, after completing the nerve conduction studies, assuming there are no technical problems, one is certain that there is a peroneal neuropathy across the fibular neck on the right side. That is, there is clear evidence of demyelination with both conduction block and focal slowing across the fibular neck. Because the distally recorded superficial peroneal sensory response is significantly lower in amplitude than that recorded on the contralateral side, there must also be some axonal degeneration. However, comparison of the peroneal motor studies from side to side reveals little asymmetry, which suggests that the amount of axonal loss probably is quite mild.

Moving on to the EMG study, muscles innervated by the deep peroneal nerve (TA, EHL) are sampled first. Both muscles show fibrillation potentials with markedly reduced recruitment of normal-appearing MUAPs. The peroneus longus, innervated by the superficial peroneal nerve, shows similar findings. We now move to the tibialis posterior. That muscle requires particular attention because its primary function is foot inversion, which may have been slightly weak on examination. Any abnormality in the tibialis posterior implies a more widespread lesion beyond the peroneal nerve. The tibialis posterior is sampled and found to be entirely normal. An additional tibial-innervated muscle, the medial gastrocnemius, is sampled and found to be normal. Next, both the short and long heads of the biceps femoris are sampled and found to be normal. Finally, a more proximal nonsciatic L5-innervated muscle, the gluteus medius, is sampled. It is normal, as are the lower lumbar paraspinal muscles.

At this point we are ready to formulate our impression.

IMPRESSION: *There is electrophysiologic evidence of a subacute common peroneal neuropathy at the fibular neck on the right side, which is predominantly demyelinating and shows some evidence of axonal loss.*

Several important questions should be considered.

What is the Most Likely Etiology of the Peroneal Neuropathy?

In this case, the patient most likely developed a peroneal neuropathy from prolonged immobilization at the time of his surgery. It also is possible that his being thin may have predisposed him to this complication. Patients who are thin or, more importantly, who have recently lost a substantial amount of weight are at greater risk for peroneal neuropathy at the fibular neck, possibly because of a lack of supporting protective adipose tissue.

How does the Electrophysiology Determine that the Lesion is Subacute?

The nerve conduction and EMG changes are in keeping with a subacute 3-week history. First, abnormal distal amplitudes on peroneal nerve conduction studies (i.e., low amplitude on the superficial peroneal sensory study) imply that some wallerian degeneration has occurred, which usually requires 3 to 5 days for motor fibers and 6 to 10 days for sensory fibers. Second, on EMG, recruitment of MUAPs decreases immediately after a nerve lesion, reflecting loss of motor units. This decrease can occur either from demyelination and conduction block or from disruption of axonal continuity. However, fibrillation potentials do not develop immediately. The time course depends on the length of the nerve between the muscle being studied and the site of injury. In peroneal neuropathy at the fibular neck associated with axonal loss, fibrillation potentials will occur in the peroneal-innervated muscles in the calf only after 2 to 3 weeks. Reinnervation following denervation commonly takes many weeks and usually months to occur. Thus, the pattern of an abnormal distal sensory amplitude on nerve conduction studies, along with fibrillation potentials and decreased recruitment of normal-configuration MUAPs (i.e., no reinnervation yet) on EMG, implies a subacute lesion.

How does One Explain the Mild Weakness of Foot Inversion if the Lesion is Purely Peroneal?

Although the diagnosis of a peroneal neuropathy at the fibular neck initially appeared likely from the history and examination, the possibility of weakness of foot inversion puts that clinical diagnosis in question. Foot inversion should be spared in peroneal neuropathy at the fibular neck because of the normal strength of the intact tibialis posterior muscle. However, patients with a foot drop from peroneal neuropathy may appear to have slight weakness of foot inversion for two reasons. First, when the foot is in a dropped position, foot inversion may appear weak, despite intact tibialis posterior function, because it is difficult to invert the foot in this position, due to purely mechanical reasons. This is similar to testing finger abduction with the hand in a dropped wrist position. In a patient with a foot drop, it is always best to passively dorsiflex the ankle to a neutral position before testing foot inversion. *Second, and not as well appreciated, is the fact that the TA, although predominantly serving ankle dorsiflexion, is also a mild secondary foot inverter.* If one looks closely at the ankle, notice that the tibialis anterior inserts on the medial side of the ankle, on the medial cuneiform and first metatarsal bones (Figure 22–10). It is this slightly medial insertion site that results in some foot inversion with contraction of the TA. This function can also easily be demonstrated in the EMG laboratory by asking a patient to invert the ankle with an EMG needle placed in the TA. One will see MUAPs firing in the TA with this movement. Therefore, it is not unusual to see a small amount of weakness of ankle inversion in peroneal neuropathy at the fibular neck. However, any significant weakness should always suggest dysfunction of the tibialis posterior and thus imply a higher lesion.

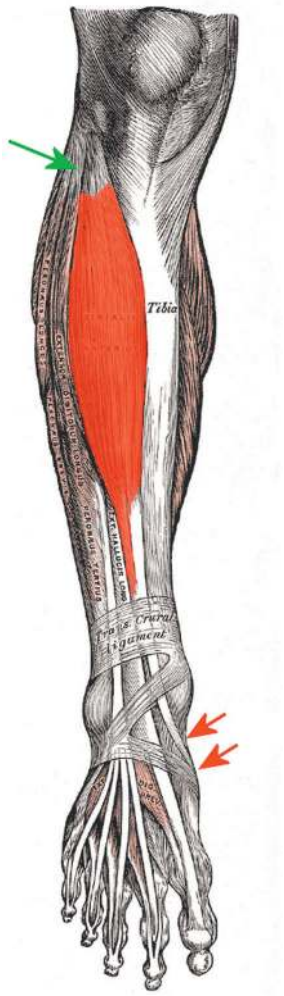

FIGURE 22–10 Anatomy of the tibialis anterior muscle. Note that the tibialis anterior originates in the upper two-thirds of the lateral surface of the tibia (green arrow) and inserts into the medial cuneiform and first metatarsal bones of the foot (red arrows). Its primary action is to dorsiflex the foot but it also acts as a secondary foot inverter.
(From Gray's anatomy of the human body, 1918.)

What is the Underlying Pathophysiology?

The electrophysiologic study has localized the lesion and accurately assessed its time course. Last and probably most important is the assessment of the underlying pathophysiology, either axonal loss or demyelination. In this case, the major pathophysiology is one of demyelination. First, there is evidence of conduction block and slowing across the fibular neck. The number of blocked fibers can be approximated by comparing the CMAP amplitude above and below the lesion. In this case, the CMAP amplitude is 1.7 mV above the fibular neck and 6.3 mV below. Thus, approximately 75% of the peroneal CMAP is blocked by demyelination, which is a substantial proportion.

To approximate the number of fibers that have undergone axonal degeneration, the distal CMAP amplitude on the involved side is compared with that on the contralateral side. This presumes that the contralateral side is normal and not affected. Comparing the involved side with the contralateral side (6.3 vs. 7.1 mV) approximates the amount of axonal loss from wallerian degeneration at about 10%. In addition to the slight decrease in CMAP amplitude, evidence of secondary axonal loss is provided by the decrease in the superficial peroneal SNAP amplitude and the EMG findings of fibrillation potentials in the peroneal-innervated muscles. It is well known that the number of fibrillation potentials correlates poorly with the degree of axonal loss. Indeed, a small amount of axonal loss can result in many fibrillation potentials. The best way to quantify axonal loss is to compare the distal CMAP amplitude on the symptomatic side with one of the following: the patient's own baseline (if known), the contralateral normal side, or normal control values.

Determining the underlying pathophysiology is of special importance in assessing the prognosis. In general, the prognosis for a demyelinating lesion is much more favorable than that for an axonal loss lesion. In demyelination, the underlying axon remains intact, and the repair process consists only of remyelination. Remyelination often occurs over several weeks. In contrast, recovery from axonal loss lesions requires regrowth of the terminal axon or collateral sprouting from adjacent unaffected axons. Each of these processes usually is quite slow (axonal regrowth occurs at approximately 1 mm/day) and can be incomplete. A patient with severe axonal loss in the peroneal nerve at the fibular neck likely would require many months and possibly well over 1 year to recover function. In contrast, a patient with a demyelinating peroneal neuropathy may recover completely over 1 to 2 months. Such quick recovery, of course, presumes that the cause of the peroneal neuropathy is no longer present, as is true in the case discussed here, in which the peroneal neuropathy likely was due to prolonged compression at the fibular neck during the anesthesia and surgery. This patient's prognosis likely is excellent.

Suggested Readings

Dawson, D.M., Hallett, M., Millender, L.H., 1990. Entrapment neuropathies, second ed. Little, Brown, Boston, p. 291.

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Femoral Neuropathy 23

Isolated lesions of the femoral nerve are uncommon in the electromyography (EMG) laboratory. More common are lesions of the lumbar plexus or L2–L4 nerve roots, which may present with symptoms and signs similar to femoral neuropathy. Especially in milder cases, differentiating among these three types of lesions may be quite difficult. The EMG serves two major roles in suspected lesions of the femoral nerve: first, to localize the lesion, which often suggests the correct diagnosis, and second, to assess the severity and degree of axonal loss, which has direct implications for the prognosis and duration of disability.

ANATOMY

The femoral nerve is derived from the *lumbar plexus* and receives innervation from the L2, L3, and L4 nerve roots (Figure 23–1). In the pelvis, the nerve emerges from behind the psoas muscle to run laterally, deep to the iliac fascia above the iliacus muscle. Muscular branches are first given off to the psoas and then to the iliacus muscles (sometimes known together as the iliopsoas muscle) before the nerve runs beneath the inguinal ligament. It enters the thigh lateral to the femoral artery, behind the inguinal ligament, dividing approximately 4 cm below the inguinal ligament into anterior and posterior divisions. The anterior division gives rise to the *medial and intermediate cutaneous nerves of the thigh* and muscular branches to the sartorius and pectineus muscles. The posterior division supplies the quadriceps femoris muscles and then continues along the medial border of the calf as the saphenous nerve (Figure 23–2). The lateral thigh is not supplied by the femoral nerve but is innervated by the *lateral femoral cutaneous nerve*, which is derived directly from the lumbar plexus, receiving innervation from the L2–L3 nerve roots.

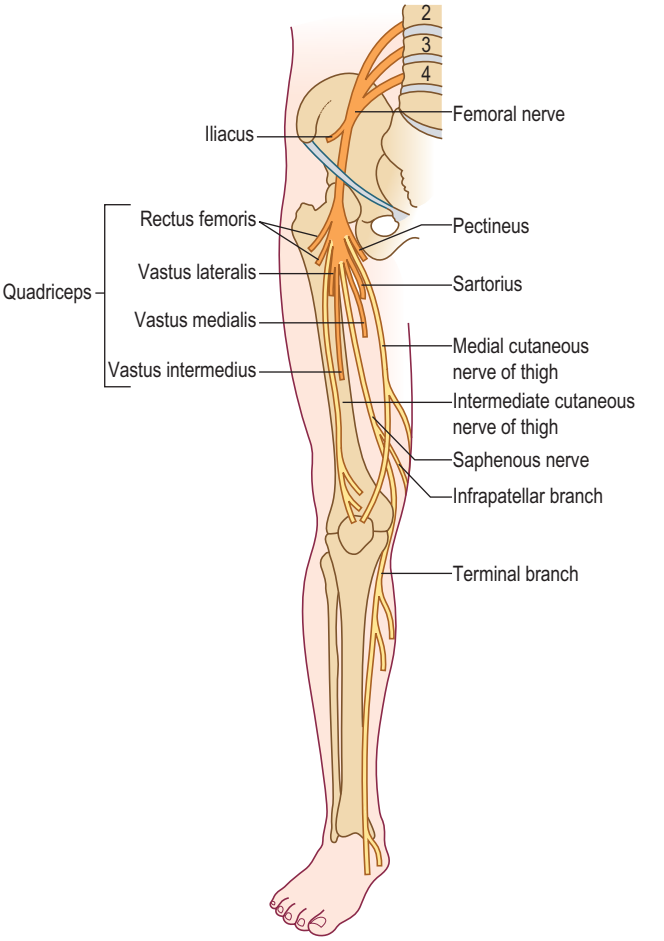

FIGURE 23–1 Anatomy of the femoral nerve.
(Reprinted with permission from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia.)

CLINICAL

Patients with femoral neuropathy develop buckling of the knee (from quadriceps weakness), difficulty lifting up the thigh, and dragging of the leg (from iliopsoas weakness). Sensory disturbance may be seen over the medial and anterior thigh and the medial calf. On examination, patients display weakness of knee extension due to quadriceps weakness. Because the four heads of the quadriceps are strong muscles, patients often have to be put at a mechanical disadvantage to demonstrate subtle weakness. This can be done by having the patient arise from the floor from the kneeling position. In more severe cases, the quadriceps may be atrophied. Weakness of hip flexion is an important sign because it indicates involvement of the iliopsoas muscle, localizing the lesion proximal to the inguinal ligament.

Examination of the deep tendon reflexes is important. In femoral neuropathy, the quadriceps reflex is depressed or absent. The other reflexes should be normal. Sensory

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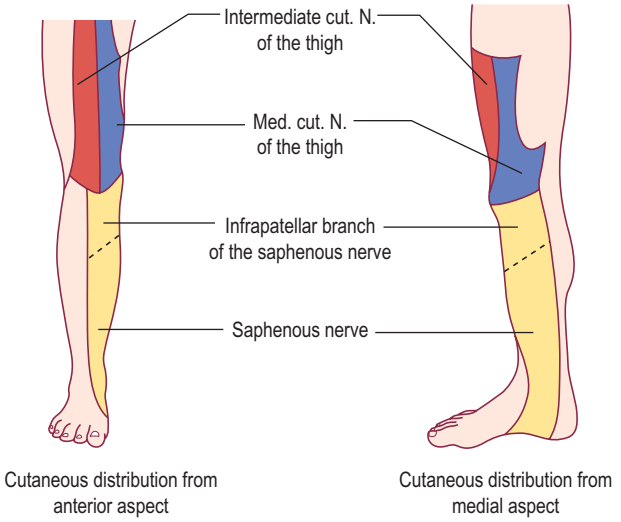

FIGURE 23–2 Cutaneous territory of the sensory branches of the femoral nerve.
(Adapted from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia. with permission.)

examination may show sensory disturbance over the medial or anterior thigh. Sensory disturbance also may occur over the medial calf, extending just distal to the medial malleolus (saphenous sensory nerve territory). Sensation is spared over the lateral thigh (territory of the lateral femoral cutaneous nerve) and the very proximal medial thigh (obturator nerve sensory territory). Abnormalities in these areas implicate a lesion of the lumbar plexus or roots.

Box 23–1. Etiology of Femoral Neuropathy

- Compression
  - Iliopsoas, pelvic, or retroperitoneal hematoma
  - Anticoagulation
  - Hemophilia
- Pelvic mass (tumor, abscess, cyst)
- Aortic or iliac aneurysm
- Inguinal lymph node
- Hyperextension stretch injury
  - Dancing
  - "Hanging leg syndrome"
- Direct injury
  - War injuries
  - Pelvic fracture
  - Iatrogenic
    - Surgical laceration
    - Arteriography
    - Misplaced injection
- Radiation injury
- Ischemia
  - Diabetes
  - IV drug abuse
  - Common iliac artery occlusion
  - Intraoperative hypotension
  - Aortic clamping during vascular surgery
- Surgical operations or procedures
  - Abdominal hysterectomy
  - Bone grafting
  - Hip arthroplasty
  - Herniorrhaphy
  - Iliac bone biopsy
  - Laparoscopy
  - Transurethral endoscopic surgery
  - Pelvic surgery
  - Radical prostatectomy
  - Renal transplantation
  - Spinal surgery (transabdominal approach)
  - Tuboplasty
  - Vaginal hysterectomy
- Vaginal delivery

Adapted from Al Hakim, M., Katirji, M.B., 1993. Femoral mononeuropathy induced by the lithotomy position: a report of 5 cases and a review of the literature. Muscle Nerve 16, 891.

ETIOLOGY

There are many reported etiologies of femoral neuropathy, although most cases result from positioning or compression during abdominal or pelvic surgery (Box 23–1). Most often implicated are self-retaining surgical retractors that are used in many pelvic and abdominal operations that compress the femoral nerve against the pelvis. In addition, there are increasing reports of femoral neuropathy occurring as a complication of total hip arthroplasty (THA), especially in THA revision surgery. While sciatic neuropathy remains the most common perioperative neuropathy associated with THA, it is now followed by femoral neuropathy. The mechanism of injury to the femoral nerve during THA is not always clear. In some cases, it may be due to a retraction injury, especially with an anterior or anterior lateral approach. In other cases, it may be due to compression arising posteriorly to the femoral nerve from the hip prosthesis itself. In other cases, similar to those reported for the sciatic nerve, excessive cement used to fix the prosthesis may damage the femoral nerve.

The other very common cause of femoral neuropathy occurs from compression at the inguinal ligament when the hip is flexed and externally rotated. This situation is encountered most often when patients are placed in the lithotomy position for prolonged periods of time during surgical procedures. Most common are labor/delivery and gynecologic and urologic procedures.

Rare reports of femoral neuropathy following renal transplantation are thought to occur from nerve ischemia. During renal transplantation, an anastomosis of the graft renal artery is made to the internal, external, or common iliac artery. Because the middle and distal portions of the femoral nerve depend on the internal or external iliac artery for their blood supply, the possibility of significant localized "steal" exists, potentially shunting blood away from the vasa nervosum of the femoral nerve.

Otherwise, isolated femoral neuropathies are uncommon. Iatrogenic femoral neuropathy can occur in the inguinal region as a consequence of hematoma formation from misguided femoral catheterizations. Femoral neuropathy may also occur in patients with diabetes mellitus, presumably from nerve infarction. However, this usually occurs in the setting of a more widespread polyradiculoplexopathy (i.e., diabetic amyotrophy). Likewise, retroperitoneal hemorrhage, often from excessive anticoagulation, may result in a lumbar plexopathy with prominent femoral involvement (see Chapter 32). Rare cases of tumor or other mass lesions may affect the femoral nerve as well.

DIFFERENTIAL DIAGNOSIS

The differential diagnosis of femoral neuropathy includes lumbar plexopathy and L2–L4 radiculopathy (Table 23–1).

Table 23–1. Clinical Differentiating Factors in Femoral Neuropathy

	Femoral Neuropathy (Distal Lesion)	Femoral Neuropathy (Above Inguinal Ligament)	Lumbar Plexopathy	L2–L4 Radiculopathy
Weakness of knee extension	X	X	X	X
Weakness of hip flexion		X	X	X
Weakness hip adduction			X	X
Weakness of ankle dorsiflexion			X	X
Reduced knee tendon reflex	X	X	X	X
Sensory loss in anterior medial thigh	X	X	X	X
Sensory loss in medial calf	X	X	X	X
Sensory loss in proximal medial thigh			X	X
Sensory loss in lateral thigh			X	X

X, may be present.

Superficially, these three entities may appear very similar. All three may involve weakness of the quadriceps muscle and a depressed or absent quadriceps reflex. In an isolated femoral neuropathy, however, non-femoral-innervated L2–L4 muscles are normal. Specifically, the adductor muscles innervated by the obturator nerve and the ankle dorsiflexors (tibialis anterior) innervated by the peroneal nerve (L4–L5) are spared. By contrast, however, these muscles may be weak in lesions of the lumbar plexus or lumbar nerve roots. If pain is a major component, demonstrating slight weakness of the adductor muscles may be difficult. Pain radiating from the back or exacerbated with back motion suggests radiculopathy. The area of sensory abnormalities may be quite similar in femoral neuropathy, lumbar plexopathy, and L2–L4 radiculopathy. However, abnormal sensation over the lateral thigh (lateral femoral cutaneous nerve territory) or the very proximal medial thigh (obturator nerve territory) does not occur in isolated femoral neuropathy; either of these findings suggests a plexus or root lesion.

Box 23–2. Recommended Nerve Conduction Protocol for Femoral Neuropathy

Routine studies:

1. Femoral motor study recording rectus femoris, stimulating femoral nerve below the inguinal ligament; bilateral studies
2. Saphenous sensory studies, recording medial ankle and stimulating medial calf; bilateral studies

To exclude a more generalized plexopathy or polyneuropathy:

1. Ipsilateral tibial motor study, recording abductor hallucis brevis, stimulating medial ankle and popliteal fossa
2. Ipsilateral peroneal motor study, recording extensor digitorum brevis, stimulating ankle, below fibular neck, and lateral popliteal fossa
3. Ipsilateral tibial and peroneal F responses
4. Ipsilateral sural sensory response, recording posterior ankle and stimulating calf

ELECTROPHYSIOLOGIC EVALUATION

Nerve Conduction Studies

The nerve conduction evaluation of suspected femoral neuropathy is somewhat limited (Box 23–2). Surface recording electrodes can be placed over one of the quadriceps muscles (usually the rectus femoris) and the femoral nerve stimulated below the inguinal ligament (Figure 23–3). Comparison of compound muscle action potential (CMAP) amplitude from side to side is useful in assessing the degree of axonal loss (Figure 23–4). If the CMAP amplitude is reduced, it usually signifies axonal loss. Of course, low CMAP amplitudes can also occur in disorders of the motor neuron, neuromuscular junction associated with block, and myopathies. For example, a patient with inclusion body myositis and a wasted quadriceps muscle may show a diminished femoral CMAP amplitude. A purely demyelinating lesion at or above the inguinal ligament will result in a normal CMAP amplitude, despite clinical weakness, when the nerve is stimulated below the lesion.

On the sensory side, studying the saphenous sensory nerve is the most helpful study for differentiating a femoral neuropathy or lumbar plexopathy from an L2–L4 radiculopathy (Figure 23–5). The saphenous sensory nerve is the terminal extension of the femoral nerve and is expected to be abnormal in any postganglionic lesion with axonal loss (i.e., lumbar plexus or femoral nerve). The saphenous nerve can be stimulated in the groove between the medial gastrocnemius and tibia 10 to 14 cm proximal to the recording electrodes, which are placed halfway between the tibialis anterior tendon and the medial malleolus. As with other uncommonly performed sensory studies, comparing the

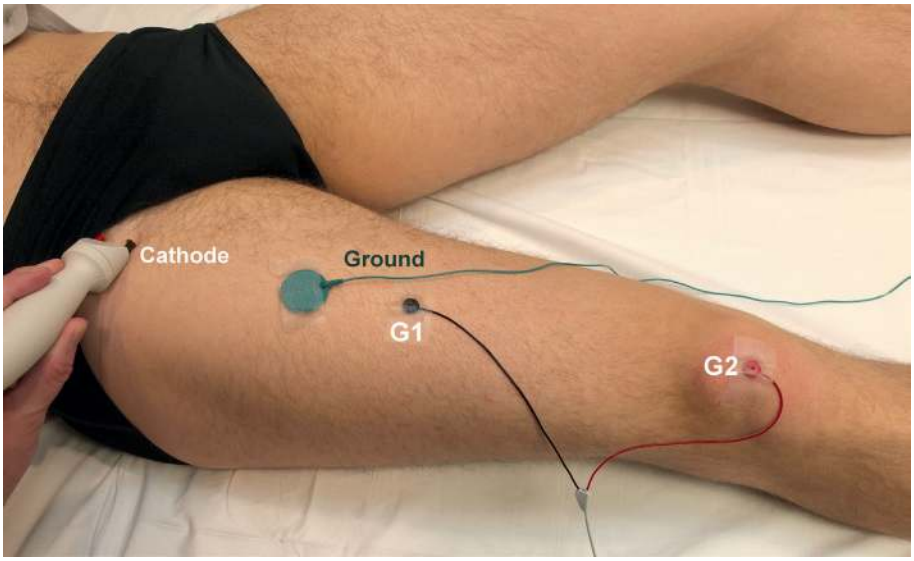

FIGURE 23–3 Femoral motor study. The femoral nerve can be stimulated inferior to the inguinal ligament, recording the rectus femoris (G1 over the muscle belly and G2 over the quadriceps tendon at the patella).

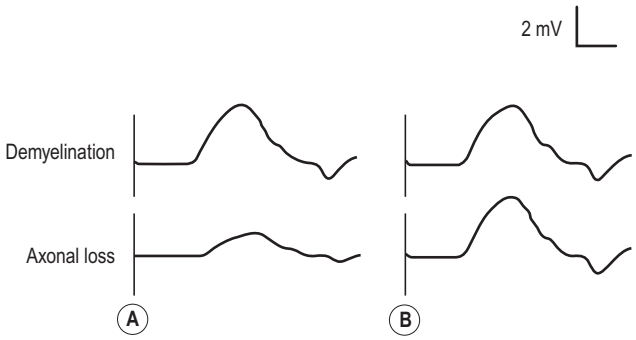

FIGURE 23–4 Femoral motor studies. For lesions older than 1 week, the amplitude of the femoral compound muscle action potential (CMAP) on the symptomatic side (A) compared with that on the contralateral asymptomatic side (B) reflects the number of intact axons. In a purely demyelinating lesion, the femoral CMAP will be normal if the nerve is stimulated distal to the lesion. In axonal loss lesions, the CMAP amplitude will decrease in proportion to the amount of axonal loss. Prognosis and recovery time depend on the amount of axonal loss.

sensory nerve action potential (SNAP) amplitude between the symptomatic and asymptomatic sides often is useful. Even in normal individuals, the saphenous sensory potential usually is small (5–10 μV) and becomes very difficult to elicit in older patients. Therefore, a saphenous sensory study should not be considered abnormal unless there is a clear side-to-side asymmetry. No diagnostic significance should be given to bilaterally absent saphenous SNAPs, especially in middle-aged or older individuals.

Electromyographic Approach

The EMG evaluation (Box 23–3) is directed toward differentiating between a femoral neuropathy, lumbar plexopathy and L2–L4 radiculopathy. First, the quadriceps muscles are examined. It is useful to evaluate at least two heads; the vastus lateralis and either the vastus medialis or rectus femoris are the easiest muscles to examine (Figure 23–6). The vastus lateralis and medialis are activated by straightening the knee and extending the leg. However, the rectus femoris is more easily activated by flexing the hip with the leg extended. Neurogenic abnormalities found here are consistent with a femoral neuropathy, lumbar plexopathy, or L2–L4 radiculopathy. Next, the iliacus muscle is checked, looking for similar findings that would indicate a lesion proximal to the inguinal ligament. Non-femoral-innervated muscles that have some L4 innervation are sampled next. Both the thigh adductors (L2–L4) and tibialis anterior (L4–L5) should be examined. Needle examination of both these muscles should be normal in an isolated femoral neuropathy. In lesions of the lumbar roots or plexus, they may be abnormal. If abnormalities are discovered in L2–L4-innervated muscles beyond the femoral distribution, it is important to examine other muscles innervated by the peroneal, tibial, and sciatic nerves to ensure that the abnormalities are not secondary to a more widespread neuropathy or polyradiculopathy. Finally, evaluation of the paraspinal muscles at the L2, L3, and L4 levels is very important because abnormalities there signify a lesion at or proximal to the root level.

The combination of NCS abnormalities and findings on the needle EMG usually allows one to distinguish between an isolated femoral neuropathy, a lumbar plexopathy, and an L2–L3–L4 lumbar radiculopathy (Table 23–2). In addition, one can assess the degree of axonal loss from the amplitudes of the femoral motor and saphenous sensory studies, and the presence of denervation and reinnervation on the needle EMG.

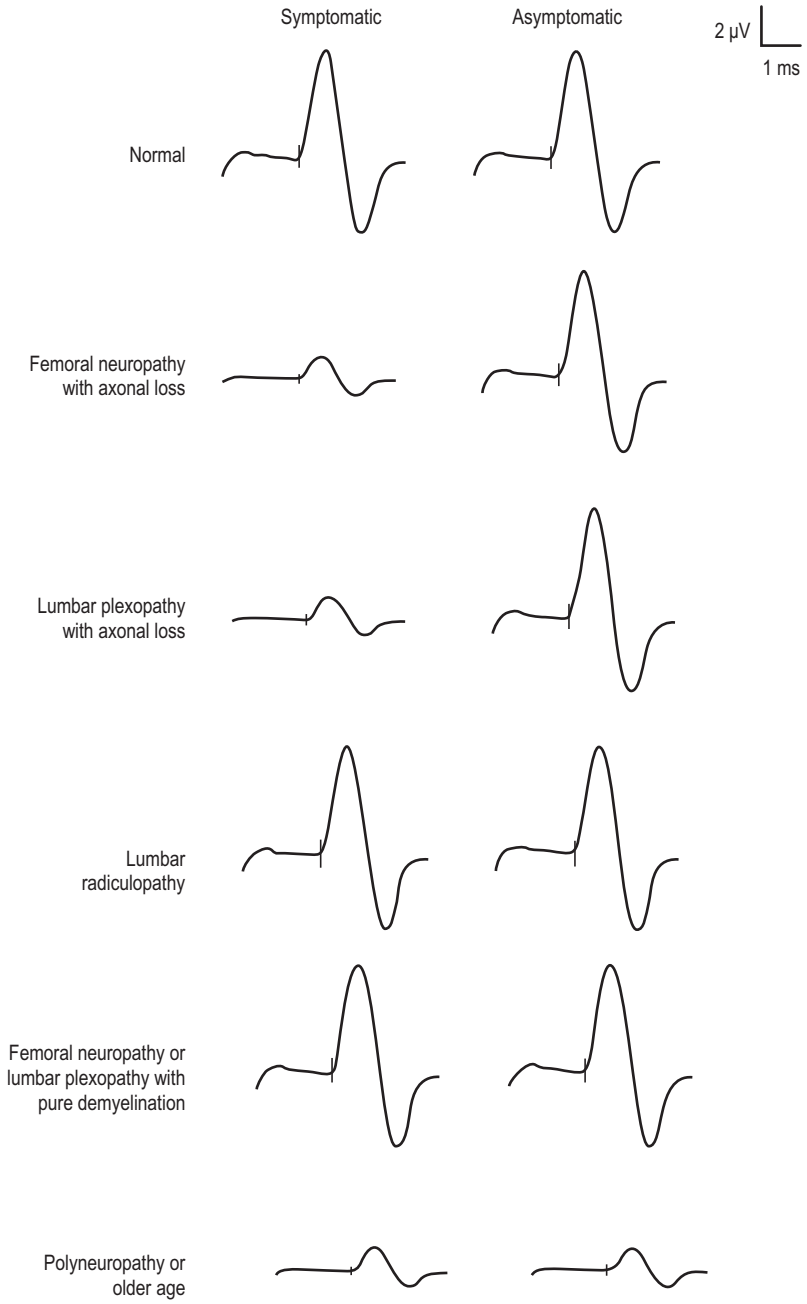

FIGURE 23–5 Saphenous sensory studies: normal and pathologic patterns. Comparison of the symptomatic with the contralateral asymptomatic side is always necessary, especially in older individuals or patients with a mild polyneuropathy, in whom saphenous sensory potentials may be difficult or impossible to elicit.

Table 23–2. Electromyographic and Nerve Conduction Abnormalities Localizing the Lesion Site in Femoral Neuropathy

	Femoral Neuropathy (Distal Lesion)	Femoral Neuropathy (Above Inguinal Ligament)	Lumbar Plexopathy	L2–L4 Radiculopathy
Electromyographic Findings				
Vastus medialis	X	X	X	X
Vastus lateralis	X	X	X	X
Rectus femoris	X	X	X	X
Iliacus		X	X	X
Thigh adductors			X	X
Tibialis anterior			X	X
Lumbar paraspinals				X
Nerve Conduction Study Findings				
Abnormal saphenous SNAP (if axonal)†	X	X	X	
Low femoral CMAP (if axonal)	X	X	X	X

X, abnormalities may be present. CMAP, compound muscle action potential; SNAP, sensory nerve action potential.

†In individuals older than 40 years, saphenous potentials can be difficult to obtain; in these individuals, the saphenous response should not be considered abnormal unless it is asymmetric compared to the other side.

Box 23–3. Recommended Electromyographic Protocol for Femoral Neuropathy

Routine muscles:

1. At least two heads of the quadriceps (vastus lateralis, vastus medialis, or rectus femoris)
2. Iliacus
3. At least one obturator-innervated adductor muscle (adductor brevis, longus, or magnus)
4. Tibialis anterior
5. L2, L3, and L4 paraspinal muscles
6. At least two non-femoral and non-L2–L4-innervated muscles to exclude a more generalized process (e.g., medial gastrocnemius, tibialis posterior, biceps femoris, gluteus maximus)

Special considerations:

- If any of the above muscles are equivocal, comparison to the contralateral side is useful.
- If the lesion is purely demyelinating, the only abnormality on needle electromyography will be decreased recruitment of normal configuration motor unit action potentials in weak muscles.

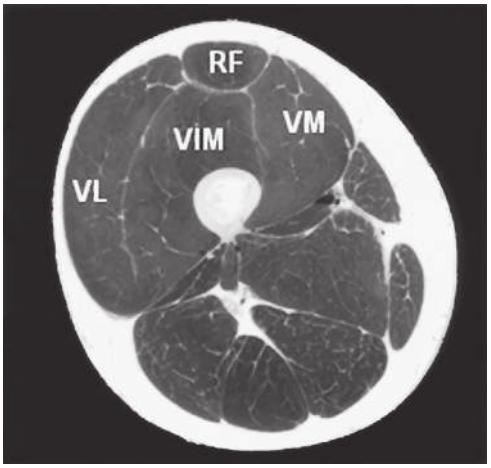

FIGURE 23–6 Quadriceps. Axial cross-section of the mid-thigh. Of the four heads of the quadriceps, the vastus lateralis (VL), vastus medialis (VM), and rectus femoris (RF) are the most superficial and easy to sample with needle electromyography. The vastus intermedialis (VIM) is much deeper and less accessible.

EXAMPLE CASE

Case 23–1

History and Physical Examination

A 38-year-old woman was referred for persistent difficulty walking 5 weeks after she underwent surgery. She had been admitted for an elective vaginal hysterectomy 4 weeks previously. Epidural anesthesia was used; the surgery lasted two and a half hours and was without complication. She was discharged 3 days after the operation. Just after surgery, the patient noted that her left leg would buckle occasionally, and she had nearly fallen several times. She experienced a pins-and-needles sensation over the front of the thigh that radiated to the inner calf. There was no significant pain in the leg. She had mild discomfort in the back where the epidural catheter had been placed. There were no symptoms in the right leg.

On examination, muscle bulk and tone were normal. The left knee jerk was absent; the right was normal. All other reflexes were normal. Strength testing at bedside showed normal strength in all muscles, including hip flexion, ankle dorsiflexion, and thigh adduction. One examiner thought there was a question of mild weakness of left knee extension. When the patient subsequently was asked to arise from a kneeling position, she was unable to do so leading with the left leg but could easily

CASE 23–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F Wave latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Femoral (m)	Groin	Rectus femoris	8.6	7.3	≥3	6.5	7.0							
Saphenous (s)	Medial calf	Medial ankle	8	2	≥4	3.6	3.8	≤4.4	49	47	≥40			
Tibial (m)	Ankle	AHB		12.2	≥4		5.3	≤5.8					48	≤56
	Popliteal fossa	AHB		10.1						50	≥41			
Peroneal (m)	Ankle	EDB		4.3	≥2		5.8	≤6.5					47	≤56
	Below fibula	EDB		4.2			9.2			47	≥44			
	Lateral popliteal fossa	EDB		4.0			12.3			49	≥44			
Sural (s)	Calf	Posterior ankle		12	≥6		3.8	≤4.4		48	≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 23–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Left vastus lateralis	↑	+1	0	NL	↓↓	NL	NL	NL
Left iliacus	NL	0	0	NL	NL	NL	NL	NL
Left vastus medialis	↑	+1	0	NL	↓↓	NL	NL	NL
Left tibialis anterior	NL	0	0	NL	NL	NL	NL	NL
Left thigh adductors	NL	0	0	NL	NL	NL	NL	NL
Left L3 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Left L4 paraspinal	NL	0	0	NL	NL	NL	NL	NL

↑= increased; ↓↓ = moderately reduced; NL = normal.

do so on the right side. Sensory examination showed hypesthesia over the anterior thigh and medial calf. The lateral thigh, lateral calf, and sole of the foot had normal sensation.

Summary

This 38-year-old woman noted buckling of her left knee along with abnormal sensation over the anterior thigh and medial calf following pelvic surgery. Her symptoms and signs suggest a femoral nerve problem. The left knee jerk is absent, whereas the right is normal, suggesting a lesion of the femoral nerve, lumbar plexus, or L2–L4 nerve roots. It is important to point out that many times it is difficult to discern mild weakness with bedside testing of muscles that are normally very strong. As in this case, putting the quadriceps at a mechanical disadvantage was necessary to demonstrate subtle weakness. When the patient was asked to arise from a kneeling position, she was unable to do so leading with the left leg, suggesting weakness of the left quadriceps muscles. Intact hip flexion suggests that the iliopsoas muscle, a more proximal femoral-innervated muscle, is spared. The normal examination of the adductors and ankle dorsiflexors is important, signifying that non-femoral L2–L4-innervated muscles may be normal.

The nerve conduction studies show a slightly reduced femoral motor potential on the left side compared with the right, although in an absolute sense the potential is clearly within the normal range. The slight asymmetry on its own would not be considered significant. However, there is a clear asymmetry between the saphenous sensory potentials. The left side is significantly reduced compared with the right (>50% difference in amplitudes). This is a key piece of information because it strongly implies that the lesion is at or distal to the dorsal root ganglion, either in the lumbar plexus or in the femoral nerve. Additional routine nerve conduction studies in the lower extremity are performed, including tibial and peroneal motor studies and the sural sensory study, to rule out a coexistent polyneuropathy or a possible lumbosacral plexopathy. The fact that those studies are normal makes the diagnosis of plexopathy or polyneuropathy unlikely.

The needle EMG examination reveals fibrillation potentials in the quadriceps muscles (specifically the vastus lateralis and vastus medialis) with decreased recruitment of normal configuration motor unit action potentials (MUAPs). Notably, the iliacus muscle is normal. Non-femoral lumbar-innervated muscles, specifically the thigh adductors (L2–L4) and the tibialis anterior (L4–L5), are normal, as are the L3 and L4 paraspinal muscles.

At this point we are ready to formulate an electrophysiologic diagnosis.

IMPRESSION: *There is electrophysiologic evidence of a subacute femoral neuropathy, most probably at the inguinal ligament, that is predominantly demyelinating in nature, with some secondary axonal loss.*

This case raises several important questions.

How Does One Determine that the Pathology is Predominantly Demyelinating?

The lesion is predominantly demyelinating because the CMAP amplitudes are fairly symmetric from side to side, yet the patient is clearly weak. Because more than 5 days have passed, any wallerian degeneration along motor fibers that is going to occur has already taken place. Therefore, the relatively normal CMAP amplitude distal to the lesion implies that most of the axons of the femoral nerve remain intact. The predominant cause of the weakness must be demyelination of the femoral nerve at the inguinal ligament, which is proximal to the stimulation site (just inferior to the inguinal ligament). With demyelination, axons are blocked and weakness follows. On

the needle EMG, this manifests mostly as moderately decreased recruitment of MUAPs. The MUAP configuration is normal, however, for the following reasons: (1) the lesion is predominantly demyelinating, and (2) not enough time has transpired for reinnervation to occur. Note that there are fibrillation potentials in the vastus lateralis and vastus medialis. Most demyelinating lesions result in some secondary axonal loss. Axonal loss also is indicated by the low saphenous sensory potential. The best way to assess axonal loss, however, is not by the degree of fibrillation activity but by the amplitude of the CMAP. In this case, the CMAP amplitude on the symptomatic side is approximately 85% that on the asymptomatic side, indicating roughly 15% loss of axons. This is only an estimate, however; this degree of side-to-side asymmetry may well fall within the normal range.

Is the EMG Helpful in Determining the Etiology and Prognosis of the Femoral Neuropathy?

The nerve conduction studies and EMG clearly demonstrate a postganglionic lesion of the femoral nerve, most likely at the inguinal ligament. The preserved hip flexion strength correlates with the normal EMG examination of the iliacus. This finding is important in excluding a lesion proximal to the inguinal ligament. By suggesting that the lesion is at the inguinal ligament, the EMG is helpful in determining that the most likely etiology of the neuropathy is compression that occurred while the patient was in the lithotomy position during surgery.

The EMG also is very helpful in assessing the prognosis. Because the CMAP amplitude is relatively intact and the likely pathophysiology is one of demyelination, the prognosis for recovery is quite good. Remyelination in such cases usually occurs over several weeks. Therefore, the duration of the patient's disability will likely be short. Remyelination undoubtedly will occur over the next several weeks to months, accompanied by the return of full strength.

Suggested Readings

Al-Ajmi, A., Rousseff, R.T., Khuraibet, A.J., 2010. Iatrogenic femoral neuropathy: two cases and literature update. J Clin Neuromusc Dis 12, 66–75.

Al Hakim, M., Katirji, M.B., 1993. Femoral mononeuropathy induced by the lithotomy position: a report of 5 cases and a review of the literature. Muscle Nerve 16, 891.

Dawson, D.M., Hallet, M., Wilbourn, A.J., 1999. Entrapment neuropathies, third ed. Lippincott Raven, Philadelphia.

Sharma, K.R., Cross, J., Santiago, F., et al., 2002. Incidence of acute femoral neuropathy following renal transplantation. Arch Neurol 59, 541–545.

Tarsal Tunnel Syndrome 24

Patients with pain and numbness in the foot often are referred to the electromyography (EMG) laboratory for evaluation of possible tarsal tunnel syndrome (TTS). TTS results from entrapment of the distal tibial nerve under the flexor retinaculum at the medial ankle. Superficially, it might seem that tibial nerve entrapment under the flexor retinaculum at the ankle would be analogous to median nerve entrapment under the flexor retinaculum at the wrist [i.e., carpal tunnel syndrome (CTS)]. However, in contrast to CTS, which is very common, TTS is exceptionally rare. Although electrophysiology can be useful in demonstrating focal slowing at the tarsal tunnel in those rare cases of true TTS, every electromyographer should be aware that significant technical difficulties are often encountered when studying the distal tibial nerve and the muscles it innervates, especially in older patients.

ANATOMY

As the tibial nerve descends distal to the medial malleolus, it runs beneath the flexor retinaculum on the medial side of the ankle, through the tarsal tunnel (Figure 24–1). The tarsal tunnel is a fibro-osseous tunnel below the medial malleolus with a bony floor and a roof formed by the flexor retinaculum. In addition to the tibial nerve, the tibial artery and tendons of the flexor hallucis longus, flexor digitorum longus, and tibialis posterior pass through the tarsal tunnel. The distal tibial nerve then divides into three or four branches. One or two branches (*medial and lateral calcaneal sensory nerves*) are purely sensory and provide sensation to the heel of the sole (Figure 24–2). The other two branches, the *medial and lateral plantar nerves*, contain both motor and sensory fibers that supply the medial and lateral sole of the foot, respectively. Typically, the medial plantar nerve supplies the first three and a half toes (including the great toe), whereas the lateral plantar nerve supplies the little toe and the lateral fourth toe. Both plantar nerves innervate the intrinsic muscles of the foot. The muscles that are most accessible to study using needle EMG are the abductor hallucis brevis (AHB), flexor hallucis brevis (FHB), and flexor digitorum brevis (FDB) for the medial plantar nerve, and the abductor digiti quinti pedis (ADQP) for the lateral plantar nerve.

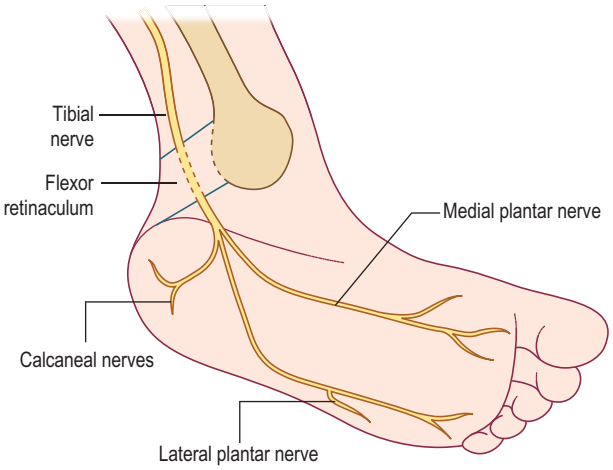

FIGURE 24–1 Anatomy of the distal tibial nerve at the ankle and sole of the foot. The distal tibial nerve runs posterior to the medial malleolus under the flexor retinaculum on the medial side of the ankle (i.e., through the tarsal tunnel), before dividing into the medial plantar, lateral plantar, and calcaneal nerves. The calcaneal nerves are purely sensory and provide sensation to the heel of the sole. The medial and lateral plantar branches both contain motor fibers to supply the intrinsic muscles of the foot and sensory fibers to supply the medial and lateral sole, respectively.

CLINICAL

The most frequent symptom in patients with TTS is perimalleolar pain. Ankle and sole pain often is described as burning and often is worse with weight bearing or at night. Paresthesias and sensory loss involving the sole of the foot may occur due to compression of the plantar or calcaneal nerves (Figure 24–3). There are few other reliable clinical signs. Intrinsic foot muscle atrophy may occur but is not specific to TTS. For example, atrophy of intrinsic foot muscles may occur in L5–S1 radiculopathy, proximal tibial neuropathy, or polyneuropathy. It is extremely difficult to assess strength of the intrinsic foot musculature, because most of the important toe and ankle functions are subserved by the long extensors and flexors in the lower leg, which are innervated by the proximal peroneal and tibial nerves. Finally, many consider a Tinel's sign over the tarsal tunnel to be suggestive of TTS. Unfortunately, like Tinel's

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signs elsewhere, this is a nonspecific sign and may occur in some normal subjects. Significantly, the ankle tendon reflex, which is mediated by the tibial nerve proximal to the tarsal tunnel, is normal in TTS, as is sensation over the lateral foot (sural nerve) and the dorsum of the foot (superficial peroneal nerve).

ETIOLOGY

The incidence of TTS is widely debated. Some podiatrists believe that TTS is rather common, whereas most neurologists and electrophysiologists believe that it is quite rare. Lesions of the medial and lateral plantar nerves most often occur as a result of trauma (including sprain and fracture) or occasionally from degenerative bone or connective tissue disorders. Rare cases of TTS are caused by varicosities or other unusual mass lesions (e.g., lipomas, ganglions, cysts, exostoses). TTS caused by hypertrophy of the flexor retinaculum from repetitive use (akin to CTS) is unusual. One or more of the three nerve branches (calcaneal, medial plantar, and lateral plantar) may be involved.

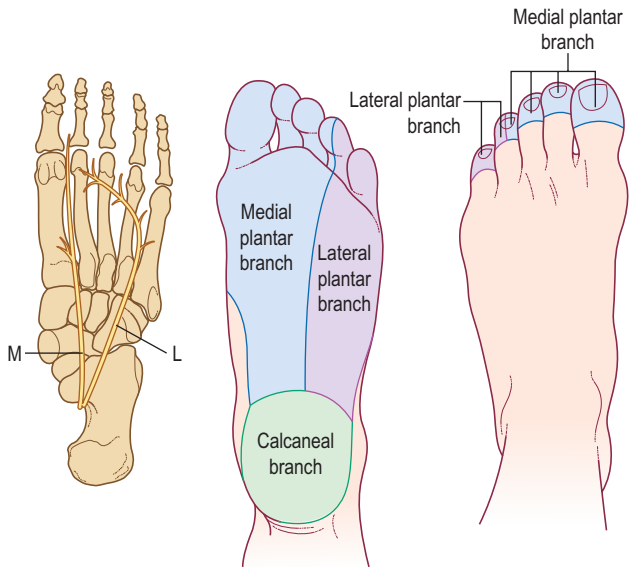

FIGURE 24–2 Tibial sensory innervation of the foot. The distal tibial nerve supplies sensation to the sole of the foot via the medial plantar, lateral plantar, and calcaneal sensory nerves.
(Adapted from Omer, G.E., Spinner, M., 1980. Management of peripheral nerve problems. WB Saunders, Philadelphia.)

DIFFERENTIAL DIAGNOSIS

The differential diagnosis of TTS includes local orthopedic problems of the foot (especially tendinitis and fasciitis), proximal tibial neuropathy, and, especially early on, mild polyneuropathy. S1 radiculopathy or lumbosacral plexopathy may cause sensory loss over the sole, but neither is typically associated with local foot pain. It is not unusual for patients who first present with polyneuropathy to be misdiagnosed with TTS. Most patients studied in our laboratory referred for possible TTS had either a normal electrophysiologic examination (and may have had a local orthopedic problem) or were found to have a mild distal polyneuropathy.

ELECTROPHYSIOLOGIC EVALUATION

Nerve Conduction Studies

Evaluation of suspected TTS is greatly simplified if one side is symptomatic and the other side is normal. This situation allows for side-to-side comparison studies (Box 24–1). The important nerve conduction studies to perform include bilateral tibial distal motor latencies to both the AHB and ADQP, for the medial and lateral plantar nerves, respectively, stimulating the tibial nerve proximal to the tarsal tunnel at the medial malleolus (Figure 24–4). Compound

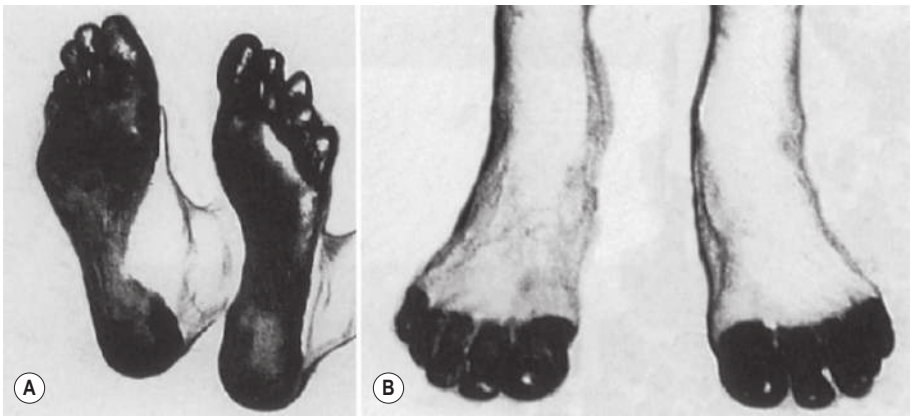

FIGURE 24–3 Sensory loss in tarsal tunnel syndrome. **A:** The first case of tarsal tunnel syndrome was reported by Captain Keck in an army recruit who developed pain in the feet and anesthesia in the distribution of the distal tibial nerve. **B:** Black shading indicates areas of anesthesia from the original case report.
(From Keck, C., 1962. The tarsal tunnel syndrome. J Bone Joint Surg 44, 180.)

Box 24–1. Recommended Nerve Conduction Study Protocol for Tarsal Tunnel Syndrome

Routine studies:

1. Distal tibial motor (medial and lateral plantar) studies, stimulating tibial nerve at medial malleolus and recording abductor hallucis brevis (medial plantar) and abductor digiti quinti pedis (lateral plantar). Comparison with contralateral side is required
2. Routine tibial motor study, recording abductor hallucis brevis, stimulating medial ankle and popliteal fossa
3. Routine peroneal motor study, recording extensor digitorum brevis and stimulating ankle, below fibular neck, and lateral popliteal fossa
4. Medial and lateral plantar mixed or sensory studies (plantar mixed and sensory responses usually require averaging several potentials). For mixed studies, stimulate medial sole and record medial ankle (medial plantar mixed); stimulate lateral sole and record medial ankle (lateral plantar mixed). For sensory studies, stimulate great toe and record medial ankle (medial plantar sensory); stimulate little toe and record medial ankle (lateral plantar sensory). Comparison with the contralateral side is required, using identical distances between the stimulating and recording sites
5. Sural sensory response, stimulating posterior calf, recording posterior ankle
6. Tibial and peroneal F responses
7. H reflexes, bilateral studies (may be abnormal in S1 radiculopathy or polyneuropathy but not in tarsal tunnel syndrome)

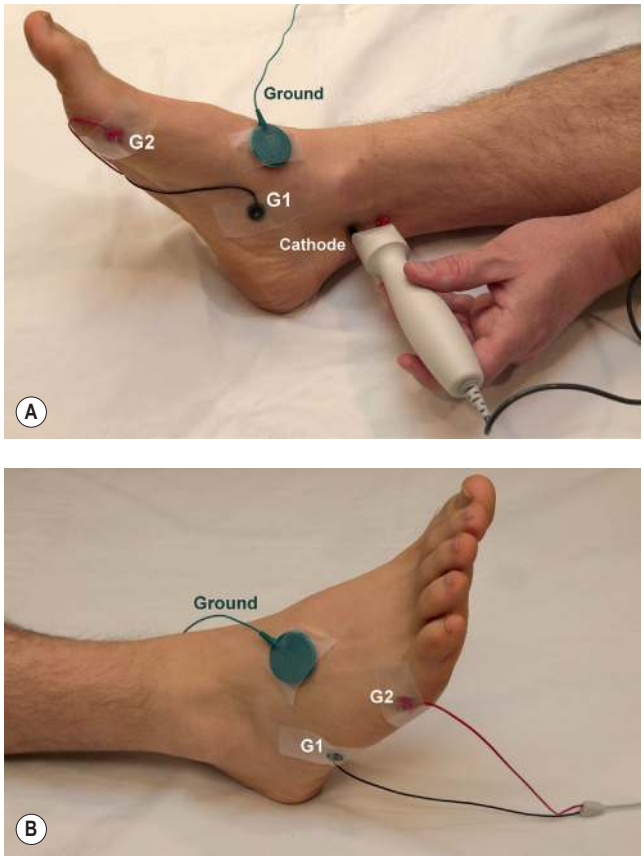

FIGURE 24–4 Distal tibial motor studies. The medial and lateral plantar distal motor latencies can be measured by recording the abductor hallucis brevis (**A**) and abductor digiti quinti pedis (**B**), respectively, and stimulating the tibial nerve behind the medial malleolus.

muscle action potential (CMAP) amplitudes and distal latencies are compared from side to side. Theoretically, if there is demyelination across the tarsal tunnel, the distal latencies on the involved side should be markedly prolonged. In axonal loss lesions, the CMAP amplitudes will be reduced, and the latencies will be normal or only slightly prolonged.

Surface sensory and mixed nerve studies are difficult to perform, even in normal healthy subjects, but they increase the sensitivity of making the electrodiagnosis of TTS. Orthodromic surface sensory studies can be performed stimulating the great and little toes (medial and lateral plantar sensory nerves, respectively) and recording over the tibial nerve at the medial ankle proximal to the tarsal tunnel. The potentials are usually extremely small in amplitude, making it necessary to average many potentials. Antidromic surface sensory studies also can be performed, but they have similar technical limitations. Surface recording of the mixed plantar nerves is slightly easier (Figure 24–5). Both the medial and lateral plantar mixed nerves can be stimulated in the sole, recording over the tibial nerve at the medial ankle (proximal to the tarsal tunnel). Averaging is still required to measure these small potentials, and in older individuals they may be absent. *Often, medial and lateral plantar sensory and mixed nerve potentials are unobtainable even in normal subjects*. Consequently, an absent or low-amplitude potential should not be considered abnormal unless a clear side-to-side difference is found using identical distances between the stimulating and recording sites. No diagnostic significance should be attributed to bilaterally absent plantar mixed or sensory nerve responses, especially in middle-aged or older individuals. It is important to emphasize that the plantar mixed and sensory nerves are the most distal nerves in the lower extremities. As such, their conduction velocities normally are slower than those of more proximal nerves and are more susceptible to the effects of temperature and cooling.

In addition to bilateral plantar motor, sensory, and mixed nerve studies, further nerve conductions should be performed routinely, especially to exclude a polyneuropathy. Routine peroneal and tibial motor studies and their respective F responses should be obtained along with the sural sensory response. If the sural sensory response is abnormal, any abnormalities in the plantar nerves are likely secondary to either a polyneuropathy or, less often, a sciatic or lumbosacral plexus lesion. In some situations, assessment of bilateral H reflexes can yield useful information. H reflexes are normal in TTS but may be abnormal in polyneuropathy, proximal tibial neuropathy, sciatic and lumbosacral plexus lesions, and S1 radiculopathy, all of which clinically may cause sensory abnormalities over the sole of the foot.

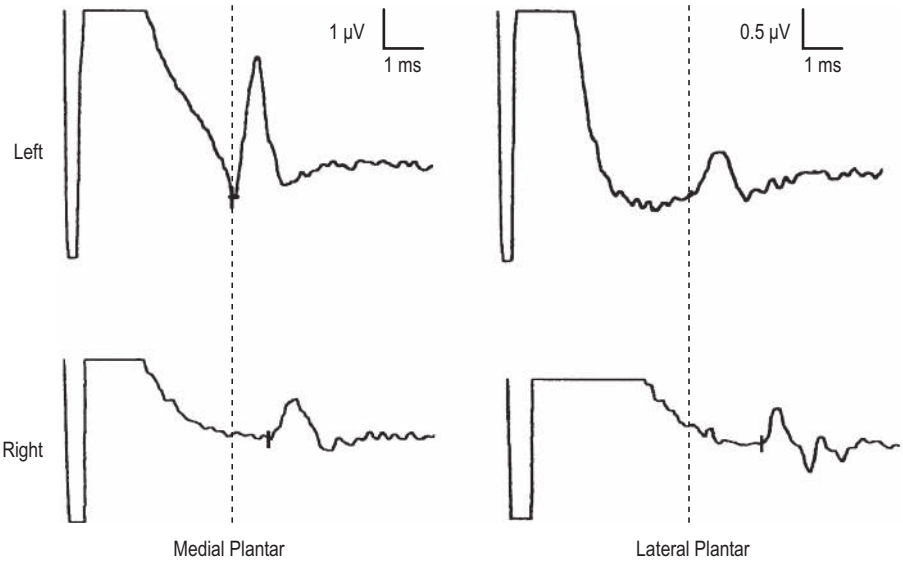

FIGURE 24–5 Medial and lateral plantar mixed nerve responses: value of comparing symptomatic side to asymptomatic contralateral side. The medial and lateral sole are stimulated while recording over the tibial nerve at the medial ankle. Sensory and mixed nerve potentials are very low in amplitude and must be averaged to be discerned from background noise. Although the right medial plantar mixed nerve potential is two to three times lower in amplitude than the left, the absolute difference is only 2 to 3 µV. However, the right medial and lateral plantar mixed nerve potentials are significantly prolonged in comparison to the left.

Box 24–2. Recommended Electromyographic Protocol for Tarsal Tunnel Syndrome

Routine muscles:

1. Abductor hallucis brevis and abductor digiti quinti pedis (must be compared with the contralateral side)
2. At least two distal tibial-innervated muscles proximal to the tarsal tunnel (e.g., medial gastrocnemius, soleus, tibialis posterior, flexor digitorum longus)
3. At least one distal peroneal-innervated muscle in the lower leg (tibialis anterior, extensor hallucis longus)

Special considerations:

- If any muscle proximal to the tarsal tunnel is abnormal, additional muscles must be sampled to determine whether the lesion represents a more proximal tibial or sciatic neuropathy, lumbosacral plexopathy, radiculopathy, or polyneuropathy.
- From a practical point of view, it is nearly impossible to diagnose tarsal tunnel syndrome in the presence of a polyneuropathy.
- Examination of intrinsic foot muscles often is painful for patients and these muscles are difficult to activate. Increased insertional activity and occasionally fibrillation potentials, associated with large, long duration motor unit action potentials, are frequently found in normal subjects without symptoms. Interpreting the electromyographic findings in an intrinsic foot muscle as abnormal requires that (1) the abnormalities be fairly marked or (2) the contralateral asymptomatic muscle is distinctly different on EMG from the symptomatic side.

Electromyographic Approach

EMG often is quite problematic in the assessment of TTS (Box 24–2). An EMG study of the intrinsic foot muscles is fraught with problems. First is the limited ability of patients to tolerate the examination. The sole is quite sensitive, and placement of the EMG needle into the intrinsic foot muscles is painful for most patients. Second, activating these muscles is difficult; therefore, it frequently is difficult to assess a sufficient number of motor unit action potentials (MUAPs). Finally, the interpretation of what is normal may be difficult. Intrinsic foot muscles commonly show increased insertional activity and occasionally fibrillation potentials associated with large, long-duration MUAPs, as one would expect in a neurogenic lesion. *Such findings are not unusual in normal subjects without symptoms*, however, and are thought to be due to everyday wear and tear on the feet. Therefore, interpretation of these abnormalities is problematic. Interpreting the EMG findings in an intrinsic foot muscle as abnormal requires that (1) the abnormalities be fairly marked or (2) the contralateral asymptomatic muscle is distinctly different on EMG from the symptomatic side.

In addition to the plantar-innervated intrinsic foot muscles (AHB, FHB, and ADQP), tibial- and peroneal-innervated muscles in the lower leg should be sampled to exclude a more proximal lesion or polyneuropathy. If abnormalities are found in these muscles, a more extensive evaluation should be performed to sort out whether the changes are due to a proximal tibial neuropathy, sciatic neuropathy, lumbosacral plexopathy, radiculopathy, or polyneuropathy.

EXAMPLE CASE

Case 24–1

History and Physical Examination

A 41-year-old woman was referred for persistent foot pain after an ankle fracture. Four months previously, she sustained a non-displaced fracture of the right ankle and wore a cast for 6 weeks. She continued to experience ankle pain, which worsened with walking.

Examination showed tenderness over the medial ankle. There was mild atrophy of the right intrinsic foot muscles. Toe and ankle flexion and extension were normal. Sensation was intact over the lateral foot and the dorsum of

CASE 24–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F Wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Tibial (m)	Ankle	AHB	6.5	10.6	≥4	5.3	4.8	≤5.8				54	51	≤56
	Popliteal Fossa	AHB	5.0	8.5		12.1	11.1		44	48	≥41			
Tibial (m)	Ankle	ADQP	4.2	5.3	≥3	5.8	5.2	≤6.3						
Peroneal (m)	Ankle	EDB	4.1		≥2	4.7		≤6.5				55		≤56
	Below fibula	EDB	4.0			10.7			50		≥44			
	Lateral popliteal fossa	EDB	3.9			12.9			51		≥44			
Sural (s)	Calf	Posterior ankle	17		≥6	3.0		≤4.4	52		≥40			
Peroneal (s)	Lateral calf	Ankle	27		≥6	3.2		≤4.4	50		≥40			
Medial plantar (mixed study)	Medial sole	Medial ankle	1	8	≥3	4.1	3.3	≤3.7						
Lateral plantar (mixed study)	Lateral sole	Medial ankle	0.5	4	≥3	4.4	3.5	≤3.7						

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; AHB = abductor hallucis brevis; ADQP = abductor digiti quinti pedis; EDB = extensor digitorum brevis.

Note: All sensory and mixed latencies are peak latencies. All sensory and mixed-nerve conductions are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 24–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right AHB	↑	+1	0	Poor	NL	+1	+1	NL
Right ADQP	↑	0	0	Poor	NL	NL/+1	NL	NL
Left AHB	↑	+1	0	Poor	NL	NL/+1	NL/+1	NL
Left ADQP	NL	0	0	Poor	NL	NL/+1	NL	NL
Right medial gastrocnemius	NL	0	0	Fair	NL	NL	NL	NL
Right tibialis posterior	NL	0	0	NL	NL	NL	NL	NL
Right tibialis anterior	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; NL = normal; AHB = abductor hallucis brevis; ADQP = abductor digiti quinti pedis.

the foot. Hypesthesia to pinprick and temperature was present over the sole of the right foot. The deep tendon reflexes, including the ankle reflexes, were present and symmetric.

Summary

There is little in this patient's history to suggest a nerve injury. Persistent pain following trauma and an ankle fracture could very well be of local orthopedic origin. However, the neurologic examination reveals mild abnormalities. There is mild atrophy of the intrinsic foot muscles on the right, although, with the history of recent casting, this finding could be due to disuse alone. The sensory examination shows normal sensation over the lateral foot and the dorsum of the foot, but pinprick and temperature sensation are decreased over the sole of the right foot. This pattern of abnormal sensation over the sole of the foot with complete sparing of the lateral foot and dorsum of the foot would be unusual for a typical polyneuropathy, in which all the distal fibers are affected first. This finding raises the possibility of a lesion of the plantar nerves. Numbness over the sole may be seen in disorders other than polyneuropathy, including proximal tibial neuropathy, sciatic neuropathy, lumbosacral plexopathy, or lesions of the S1–S2 nerve roots. The bilaterally intact ankle reflex is a helpful piece of information. For example, a lesion of the S1 nerve root, lumbosacral plexus, sciatic nerve, or more proximal tibial nerve may

well result in an abnormal ankle reflex on the symptomatic side.

When reviewing the nerve conduction studies, particular attention must be paid to whether the results correlate with the clinical examination. First, tibial motor studies recording the AHB muscle are performed bilaterally; the results are normal. There is a slight asymmetry, i.e., the amplitude on the symptomatic right side is slightly smaller with a slightly longer distal latency, but the differences would not be considered significant. Note that routine tibial motor studies recording the AHB muscle check only the medial plantar nerve. Tibial motor studies recording the ADQP muscle are next performed bilaterally to assess the lateral plantar nerves. The amplitudes and latencies are normal, although again there is a slight asymmetry, with the right side slightly smaller in amplitude and longer in latency than the left side. Peroneal motor studies are performed next on the symptomatic side; they are normal.

After the motor studies are completed, the sensory studies are performed, including the sural and then the superficial peroneal sensory responses on the right side. Both are entirely normal. The normal sural sensory response correlates with the normal sensation over the lateral foot, and the normal superficial peroneal sensory response likewise correlates well with the normal sensation over the dorsum of the foot. As for the plantar responses, when the medial and lateral plantar mixed nerves are recorded, only small-amplitude responses are obtained from the right side. This finding alone would not necessarily be considered abnormal, because plantar mixed and sensory responses often are very small or difficult to obtain in normal subjects. When these responses are compared with the asymptomatic contralateral side, however, the amplitudes are clearly and significantly asymmetric (>50% difference from side to side). In addition, the latencies are somewhat prolonged on the right side compared to the left. The degree of prolongation is not in the unequivocally demyelinating range and may be consistent with axonal loss and dropout of the fastest-conducting fibers.

When the nerve conduction studies are completed, there is strong evidence for a lesion affecting the distal tibial nerve and involving the medial and lateral plantar nerves. Polyneuropathy seems less likely, given the intact and robust sural and superficial peroneal sensory responses, and the asymmetry of the plantar mixed nerve studies from side to side. However, the reduced amplitude of the medial and lateral plantar mixed nerve responses and the borderline prolonged latencies are well within the range that would indicate axonal loss. Thus, there still is the possibility of a proximal tibial neuropathy in the calf. However, the fact that the sural sensory response, which is derived proximally from the tibial and peroneal nerves in the popliteal fossa, is normal argues against a proximal lesion of the tibial nerve. The needle EMG examination should be helpful in confirming the location of the lesion; particular attention should be paid to tibial muscles in the calf above the level of the tarsal tunnel.

Moving on to the needle EMG findings, fibrillation potentials are present in the right AHB muscle. There is poor activation of MUAPs, which is not unusual even in normal subjects. The few MUAPs seen appear to be of slightly increased duration and amplitude. These findings usually are associated with neuropathic lesions. However, one must always be cautious in assessing the intrinsic foot muscles. Normal subjects without any complaints may have mild active denervation or reinnervation (or both) in the intrinsic foot muscles. Indeed, when the contralateral AHB muscle is checked, there are also sparse fibrillation potentials with borderline large and long MUAPs. Therefore, although we might have initially interpreted the right AHB as abnormal, after examining the contralateral side, we determine that the findings on the right side are of dubious significance. A similar lack of asymmetry is seen in the ADQP muscles; both sides are slightly abnormal. Next, two tibial-innervated muscles that arise above the tarsal tunnel are sampled (the medial gastrocnemius and the tibialis posterior), and both are entirely normal. Finally, the tibialis anterior muscle is sampled. This is a peroneal-innervated muscle, and it is completely normal.

At this time, we are ready to formulate our electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are consistent with a distal tibial neuropathy affecting the medial and lateral plantar nerves.*

An important question should be addressed at this point.

How Does One Localize the Lesion to the Plantar Nerves?

The electrophysiologic abnormalities are limited to the distal tibial nerve, that is, the medial and lateral plantar nerves. Both plantar mixed nerve responses are low compared with the contralateral side, with mild prolongation of peak latency. This type of abnormality can be seen in TTS, but it also can be seen in proximal tibial neuropathy, sciatic neuropathy, or lumbosacral plexopathy. The fact that the EMG study does not demonstrate any abnormality of peroneal- or tibial-innervated muscles proximal to the tarsal tunnel argues against a lesion of the proximal tibial nerve, sciatic nerve, or lumbosacral plexus. Note that the asymmetric abnormalities in the mixed nerve responses seen in this case would not be expected in a sacral radiculopathy, because sensory potentials (which make up the majority of mixed nerve potentials) are spared in lesions proximal to the dorsal root ganglion. The clinical findings of intact sensation over the lateral and dorsal foot also argue strongly against a polyneuropathy, sciatic neuropathy, or lumbosacral plexopathy. These findings are later substantiated on the nerve conduction studies, which show normal sural and superficial peroneal

sensory responses. Therefore, although the electrophysiology fails to definitively localize the lesion, the weight of the evidence favors a lesion of the distal tibial nerve at the ankle (medial and lateral plantar nerves), especially considering the site of the trauma and the site of the persistent pain.

Suggested Readings

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25 Facial and Trigeminal Neuropathy

Although nerve conduction and electromyography (EMG) studies are used most often to evaluate peripheral nerve and muscle disorders, they also can be used to evaluate lesions of the cranial nerves. Outside of the brainstem, the cranial nerves, other than cranial nerves I (olfactory) and II (optic), are essentially the same as peripheral nerves, carrying motor, sensory, and autonomic fibers.

Mononeuropathies affecting cranial nerves VII (facial) and V (trigeminal) are the most common cranial nerve lesions evaluated in the EMG laboratory. The facial nerve can be directly stimulated and recorded using standard nerve conduction techniques. The blink reflex can be used to evaluate both the facial and trigeminal nerves. Facial and masticatory muscles, supplied by cranial nerves VII and V, respectively, can easily be examined with an EMG needle. As in other neuromuscular disorders, the electrophysiologic evaluation of facial and trigeminal neuropathies is used to confirm localization of the lesion, assess the underlying pathophysiology and severity of the lesion, and offer a prognosis. In fact, assessment of severity and prognosis are often the key issues addressed by the electromyographer in the most common cranial neuropathy of all, idiopathic facial palsy (i.e., Bell's palsy).

ANATOMY

Facial Nerve

The facial nerve, cranial nerve VII, is a complex nerve that carries several different fiber bundles, including the following:

- Motor fibers to all muscles of facial expression, as well as to the posterior belly of the digastric, stapedius, and stylohyoid muscles
- Parasympathetic motor fibers supplying the mucosa of the soft palate and the salivary and lacrimal glands
- Taste fibers to the anterior two thirds of the tongue
- Parasympathetic sensory fibers for visceral sensation from the salivary glands and the nasal and pharyngeal mucosa
- Somatic sensory fibers supplying a small part of the external auditory meatus and skin of the ear
- Proprioceptive sensory afferents from facial muscles

The facial nerve is formed by the conjoining of the *facial motor root* and the adjacent *nervus intermedius*. The facial motor root supplies the muscles of facial expression and arises from the facial motor nucleus located in the ventral lateral tegmentum of the lower pons. The nervus intermedius carries taste, sensory, and parasympathetic fibers and arises from the solitary nucleus/tract (medulla), trigeminal sensory nuclei (medulla–pons), and superior salivatory nucleus (pons), respectively.

The facial nerve, including the motor root and nervus intermedius, emerges from the brainstem at the cerebellopontine angle and enters the internal auditory meatus, next passing through the geniculate ganglion before traversing the facial canal. Within the bony facial canal, several branches arise from and leave the main facial nerve (Figure 25–1). First, parasympathetic fibers are given off to the *greater and lesser petrosal nerves*, bound for the pterygopalatine and otic ganglia. A small motor branch arises next, to innervate the stapedius muscle in the inner ear. The *chorda tympani* then arises to carry taste fibers to the anterior two thirds of the tongue and parasympathetic fibers to the submandibular and sublingual salivary glands.

The facial nerve exits the skull at the stylomastoid foramen before coursing through the parotid gland. After the stylomastoid foramen, the nerve supplies the stylohyoid and the posterior belly of the digastric muscles, then gives off a cutaneous posterior auricular branch before dividing into its five major peripheral branches: temporal (a.k.a., frontal), zygomatic, buccal, mandibular, and cervical branches, which innervate the muscles of facial expression (Figure 25–2).

Trigeminal Nerve

The trigeminal nerve, cranial nerve V, carries sensory fibers to the face and motor fibers to the muscles of mastication. It arises from several different nuclei in the brainstem, including one motor nucleus (mid-upper pons) and three separate sensory nuclei. The sensory nuclei include the main sensory nucleus (mid-upper pons), which mediates light touch; the nucleus of the spinal tract of V (pons to upper cervical cord), which mediates pain and temperature; and the mesencephalic nucleus of V (lower midbrain), which mediates proprioception from facial muscles. Exiting

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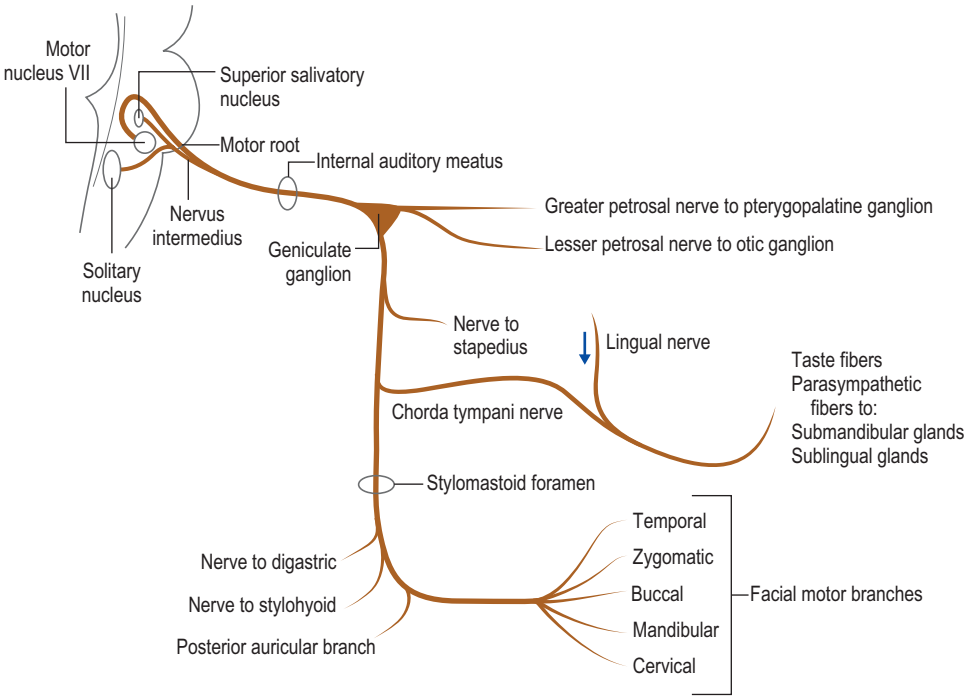

FIGURE 25–1 Course of the facial motor root and nervus intermedius branches of the facial nerve in the facial canal. The facial nerve is formed by the merging of the facial motor root and the adjacent nervus intermedius. The motor root supplies the muscles of facial expression. The nervus intermedius carries taste, sensory, and parasympathetic fibers. Within the bony facial canal, several branches arise from and leave the main facial nerve. Parasympathetic fibers are given off to the greater and lesser petrosal nerves, bound for the pterygopalatine and otic ganglia. A small motor branch arises next to innervate the stapedius muscle in the inner ear. The chorda tympani then arises to carry taste fibers to the anterior two thirds of the tongue and parasympathetic fibers to the submandibular and sublingual salivary glands.

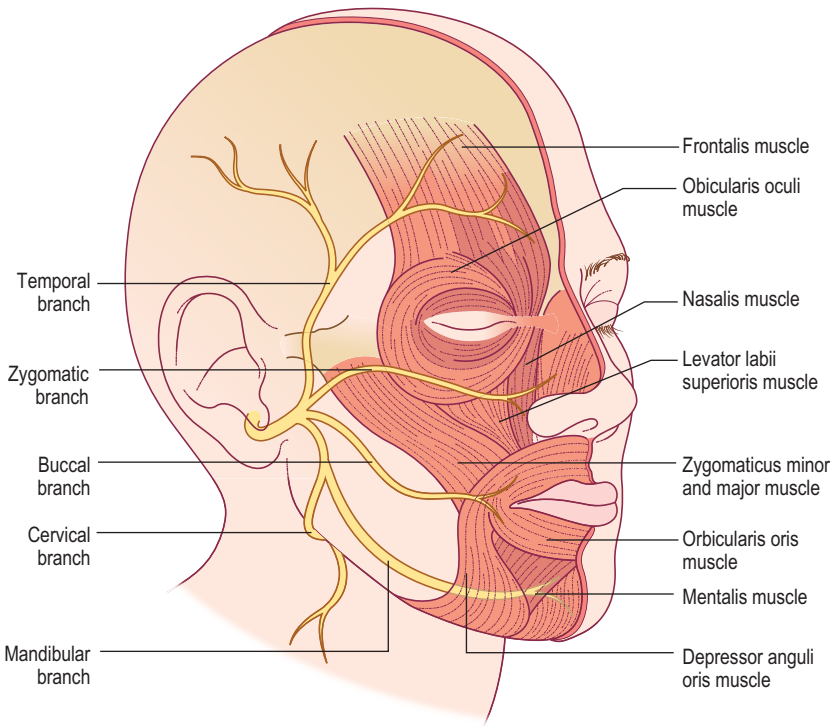

FIGURE 25–2 Major peripheral branches of the facial nerve. After exiting the stylomastoid foramen, the facial nerve bifurcates into five major peripheral branches: temporal, zygomatic, buccal, mandibular, and cervical to supply the muscles of facial expression.
(From Oh, S.J. 1993. Clinical electromyography: nerve conduction studies, 2nd ed. Williams & Wilkins, Baltimore, with permission.)

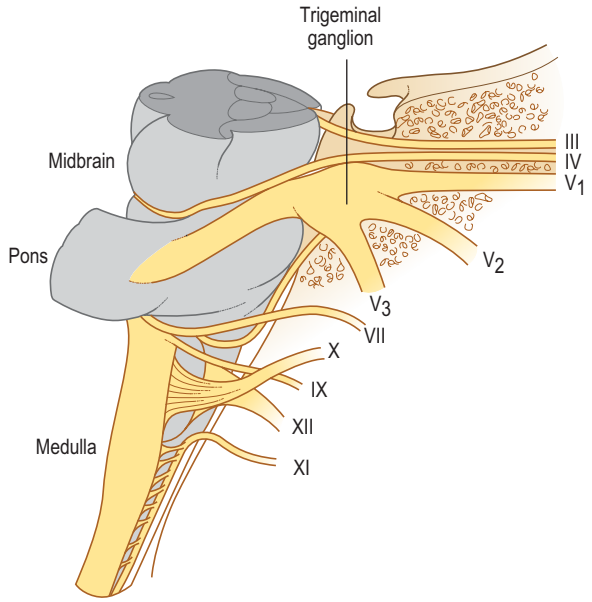

FIGURE 25–3 Trigeminal ganglion and origin of the three major peripheral nerve branches. Exiting from the lateral mid-pons, the trigeminal nerve divides into three major peripheral nerves – ophthalmic (V_1), maxillary (V_2), and mandibular (V_3) – which arise from the trigeminal ganglion, located just outside the brainstem on the petrous bone in the middle cranial fossa.
(Adapted with permission from Montgomery, E.B., Wall, M., Henderson, V.W., 1986. Principles of neurologic diagnosis. Little, Brown, Boston.)

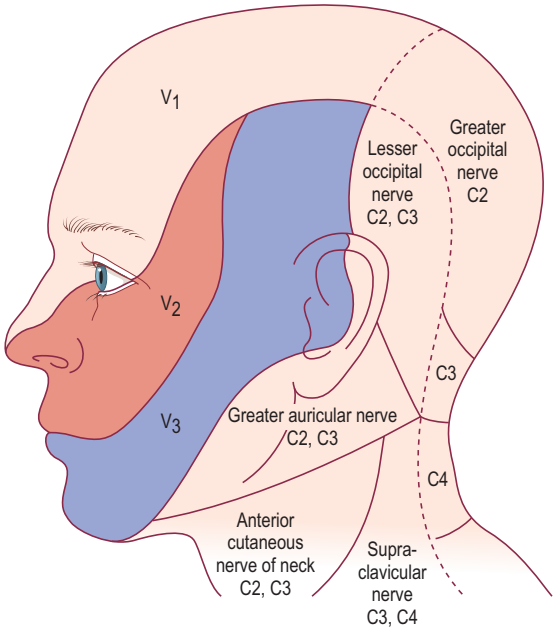

FIGURE 25–4 Trigeminal sensory distribution. The three branches of the trigeminal nerve – ophthalmic nerve (V_1), maxillary nerve (V_2), and mandibular nerve (V_3) – supply sensation to the face and anterior scalp.
(Adapted with permission from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia.)

from the lateral mid-pons, the nerve is called trigeminal because it branches into three major peripheral nerves that arise from the trigeminal ganglion (also known as the *semilunar* or *gasserian ganglion*), located just outside the brainstem on the petrous bone in the middle cranial fossa (Figure 25–3). The cavity formed by the folds of dura that contain the trigeminal ganglion, surrounded by cerebrospinal fluid, is known as Meckel's Cave. Whereas the trigeminal ganglion contains cell bodies of the sensory fibers from both the main sensory nucleus and the nucleus of the spinal tract of V, the cell bodies of proprioceptive sensory fibers from muscle spindles of trigeminal motor fibers are contained within the mesencephalic nucleus of V in the midbrain.

The three major peripheral nerve divisions of the trigeminal nerve are the ophthalmic (V_1), maxillary (V_2), and mandibular (V_3) nerves. Each nerve exits the skull through a distinct opening: (1) the ophthalmic nerve through the superior orbital fissure, (2) the maxillary nerve through the foramen rotundum, and (3) the mandibular nerve through the foramen ovale. Each of the three major nerve branches contains sensory fibers, whereas motor fibers are carried solely in the mandibular nerve branches that supply innervation to the muscles of mastication (masseter, temporalis, medial, and lateral pterygoid muscles) and to the anterior belly of the digastric muscle, the mylohyoid, tensor veli palatini, and tensor tympani muscles. Branches of the trigeminal nerve supply light touch, pain, and temperature sensation to the skin of the face, the anterior half of the scalp, most of the oral and nasal mucosa, the anterior two thirds of the tongue, and the dura mater of the anterior and middle cranial fossae (Figure 25–4).

CLINICAL

Facial Neuropathy

The most common cranial mononeuropathy is facial nerve palsy, which usually presents as idiopathic *Bell's palsy*. Some cases are post-infectious, although a growing amount of evidence suggests that Bell's palsy is a viral-induced cranial neuritis caused by herpes simplex virus-1 in many cases. In addition, the risk of Bell's palsy is increased in patients with hypertension or diabetes and in pregnant women (the latter especially late in the pregnancy or in the early postpartum period).

Unilateral facial nerve dysfunction can also be seen in association with several disorders, most commonly in the setting of diabetes. In addition, facial palsy occurs with herpes zoster involving the geniculate ganglion (Ramsay Hunt syndrome), lymphoma, leprosy, cerebellopontine angle tumors such as acoustic neuroma, multiple sclerosis, stroke, and a host of other disorders (Box 25–1). Bilateral facial weakness is less common; it may be seen in Guillain–Barré syndrome, Lyme disease, sarcoid, Melkersson–Rosenthal syndrome, tuberculous meningitis, and leptomeningeal lymphomatosis/carcinomatosis. Bifacial weakness also is noted in some neuromuscular junction disorders and in various muscular dystrophies.

Box 25–1. Differential Diagnosis of Facial Weakness

- Idiopathic Bell's palsy
- Associated with systemic disorders
  - Guillain–Barré syndrome*
  - Lyme disease*
  - Diabetes
  - Herpes zoster (Ramsay Hunt syndrome)
  - Vasculitis
- Infiltrative lesions
  - Lymphoma
  - Leptomeningeal lymphomatosis/carcinomatosis*
  - Tuberculous meningitis*
  - Leprosy
  - Sarcoid*
  - Melkersson–Rosenthal syndrome*
- Multiple sclerosis
- Associated with tumors
  - Cerebellopontine angle tumor
  - Nasopharyngeal carcinoma
- Associated with neuromuscular junction disorders
  - Myasthenia gravis*
  - Lambert–Eaton myasthenic syndrome*
- Muscular dystrophies
  - Facioscapulohumeral dystrophy*
  - Oculopharyngeal dystrophy*
  - Myotonic dystrophy*
- Stroke

*Often bilateral involvement.

The clinical presentation of facial nerve palsy depends on the location, pathophysiology, and severity of the lesion. A central lesion (proximal to the facial nerve nuclei) causes contralateral weakness primarily of the lower facial musculature, with relative sparing of the orbicularis oculi and frontalis muscles, which are bilaterally innervated. Furthermore, with central lesions there may be facial movement during laughing or crying because the pathways that mediate responses to emotional stimuli are different from those that mediate voluntary facial movement. Peripheral lesions (at or distal to the facial nerve nuclei) cause ipsilateral facial paralysis that affects both the upper and lower facial musculature, resulting in an inability to wrinkle the forehead, close the eye, or smile. In addition, there may be dysfunction and absent taste sensation over the anterior two thirds of the tongue, depending on which branches are involved as the nerve courses through the facial canal.

In patients with idiopathic Bell's palsy, complete facial paralysis involving the upper and lower face generally occurs within 24 hours and inevitably is accompanied by pain behind the ipsilateral ear. The etiology is thought to be inflammation of the facial nerve, which causes swelling and compression of the nerve in the facial canal.

In most patients, the prognosis is excellent, with full recovery of function over several weeks to months. However, in more severe cases, usually those associated with significant axonal loss, some permanent facial weakness remains, or aberrant reinnervation may occur as the nerve regenerates. Aberrant reinnervation can take one of two forms: (1) an axon that previously innervated a particular muscle grows down a different fascicle and innervates a different muscle than the original one, or (2) a single axon branches into two or more axons that go to two or more different muscles. Either type of aberrant reinnervation can result in synkinesis of facial movements. For example, closing the eye (orbicularis oculi) may be accompanied by movement of the lips (orbicularis oris). Clinically, these reinnervation abnormalities may vary from being very subtle to very severe. In the most extreme case, synkinesis may lead to massive contractions on one side of the face. As most people blink spontaneously every few seconds, synkinesis involving the orbicularis oculi and other facial muscles can clinically appear very similar to hemifacial spasm (see below), although the etiology is quite different.

Aberrant reinnervation may also occur between the motor axons of the facial nerve and the parasympathetic axons (i.e., nerve fibers derived from the facial motor root and nerve fibers derived from the nervus intermedius). Thus, parasympathetic axons may innervate motor endplates, and, conversely, motor axons may innervate the parasympathetic endplates. This may result in lacrimation, salivation, and/or hemifacial sweating when the facial muscles are activated. One can imagine the embarrassing situation wherein tears rather than saliva are produced while eating.

Hemifacial Spasm

Hemifacial spasm is a chronic and often progressive disorder usually associated with chronic compression of or injury to the facial nerve. The disorder is characterized by involuntary contractions that affect one or multiple muscles on one side of the face. The spasms typically occur initially around the eye, and later spread to involve other ipsilateral facial muscles. The contractions are often irregular and persist during sleep. Although several unusual causes of chronic irritation have been reported in the literature, the most common etiology is an aberrant blood vessel lying in contact with the facial nerve near its exit zone from the brainstem. The spasms are thought to be generated by damage to some axons of the facial nerve with ephaptic transmission to other nearby axons. Surgical decompression of the blood vessel away from the facial nerve often results in complete recovery.

As noted above, massive reinnervation and subsequent synkinesis of the facial muscles may occur following an idiopathic facial palsy, leading to a pattern nearly identical clinically to hemifacial spasm. However, the underlying pathophysiology of hemifacial spasm (damage to the facial nerve with ephaptic transmission) differs from that of postparalytic facial syndrome (massive synkinesis that occurs with spontaneous blinking, due to aberrant reinnervation of muscles following idiopathic facial palsy).

Trigeminal Neuropathy

Trigeminal neuropathy is less common than facial palsy. It generally occurs as a purely sensory neuropathy in

association with connective tissue disorders, most notably Sjögren syndrome or systemic lupus erythematosus. In addition, trigeminal neuropathy can be seen in association with toxic neuropathies, sometimes in isolation. Rarely, patients with local or metastatic cancer present with isolated involvement of the mentalis branch of V_3 (so-called "numb chin syndrome"). Isolated motor involvement of the trigeminal nerve is seen occasionally, usually in association with mass lesions or after surgery.

Patients with purely sensory dysfunction of cranial nerve V present with numbness over the ipsilateral face. The distribution of numbness depends on the extent of nerve involvement and on which branches of the trigeminal nerve are involved. Involvement of the motor branch causes difficulty chewing and deviation of the jaw to the contralateral side when opening the mouth.

Trigeminal Neuralgia

Trigeminal neuralgia, also known as *tic douloureux*, is a condition characterized by episodes of severe pain in the distribution of one or more branches of the trigeminal nerve. It occurs most frequently in the maxillary division. Inconsequential stimuli, such as light touch over the cheek, eating, or brushing the teeth can trigger excruciating pain. There is no associated sensory or motor dysfunction in the fifth nerve distribution and standard nerve conduction and EMG evaluations will be normal. Blink reflex studies usually are normal, although rarely the R1 component may be abnormal on the affected side (found in <5% of patients).

Box 25–2. Electrophysiologic Evaluation of Facial and Trigeminal Nerve Lesions

Facial nerve:

1. Facial nerve studies:
   a. Stimulation of the whole facial nerve, stimulating below and anterior to the mastoid or directly anterior to the tragus, recording a facial muscle (typically the nasalis or orbicularis oculi); bilateral studies; OR
   b. Stimulation of facial branches:
      i. Frontal branch. Stimulating three to four fingerbreadths lateral to the eye, recording the frontalis muscle; bilateral studies.
      ii. Zygomatic branch. Stimulating over the zygomatic bone just anterior to the ear, recording the nasalis muscle; bilateral studies.
      iii. Mandibular branch. Stimulating over the angle of the jaw, recording the mentalis muscle; bilateral studies.
2. Blink reflex studies, stimulating the supraorbital nerve, recording orbicularis oculi muscles; bilateral studies
3. Needle electromyographic examination, examining muscles from the major branches, including frontalis (temporal branch), orbicularis oculi (zygomatic branch), orbicularis oris (buccal branch), and mentalis (mandibular branch)

Trigeminal nerve:

1. Blink reflex studies, stimulating the supraorbital nerve, recording orbicularis oculi muscles; bilateral studies
2. Needle electromyographic examination, examining the masseter and temporalis muscles

ELECTROPHYSIOLOGIC EVALUATION

Facial Neuropathy

The facial nerve can be evaluated using a combination of direct facial nerve stimulation, the blink reflex, and needle EMG examination (Box 25–2). The electrophysiologic evaluation is directed toward answering four major questions:

1. Is the lesion central or peripheral?
2. If the lesion is peripheral, what is the extent of involvement? That is, are all branches of the nerve involved, or is the lesion selective?
3. What is the underlying pathophysiology: demyelinating, axonal loss, or elements of both?
4. What is the prognosis for recovery?

Nerve Conduction Studies

Using a handheld stimulator, the facial nerve can be stimulated either below the ear anterior to the mastoid or directly anterior to the tragus (Figure 25–5). The patient should be in a relaxed state, lying supine on the examining table. The stimulating cathode should be placed anterior and superior to the anode, although it may be necessary to rotate the anode to reduce the stimulus artifact or to avoid direct

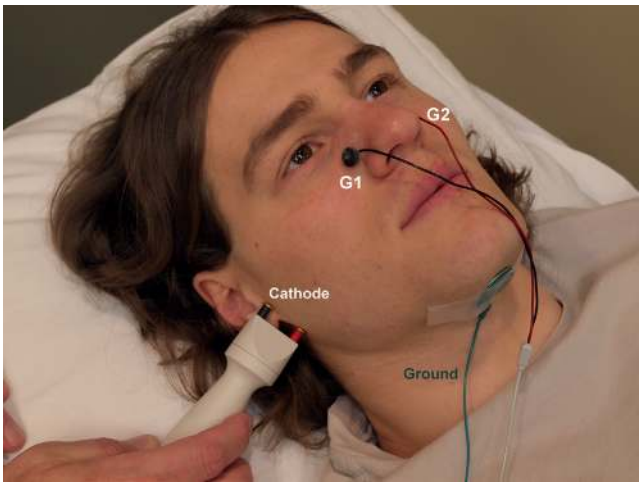

FIGURE 25–5 Facial nerve stimulation. Using a handheld bipolar prong stimulator, the facial nerve can be stimulated either below the ear anterior to the mastoid or directly anterior to the tragus. The patient should be lying supine on the examining table. The active recording electrode is a standard disk electrode placed on the skin over the nasalis muscle, with the reference electrode placed over the contralateral nasalis muscle. The orbicularis oculi and other facial muscles also can be used for recording. A surface ground electrode is placed over the forehead or chin.

stimulation of the masseter. The active recording electrode consists of a a standard disk electrode placed over the nasalis muscle, with the reference electrode placed over the contralateral nasalis. The inferior orbicularis oculi also is commonly used for recording, with the active electrode placed on the skin just lateral and inferior to the pupil at midposition, with the reference electrode placed on the skin over the lateral canthus of the eye. The nasalis muscle also is commonly used for recording, with the reference electrode placed on the contralateral nasalis muscle. Any of the following muscles can be used for recording: the frontalis, nasalis, orbicularis oculi or oris, mentalis, or platysma, although a needle recording electrode may be necessary for some muscles. The reference electrode can be placed over the same muscle on the contralateral side of the face. A surface ground electrode is placed over the forehead or chin.

Selective branches of the facial nerve can be stimulated more distally, including the temporal branch recording the frontalis muscle, the zygomatic branch recording the nasalis, the buccal branch recording the orbicularis oris, the mandibular branch recording the mentalis, or the cervical branch recording the platysma. Avoiding direct stimulation of the masseter muscle is important and can be accomplished by watching for contraction of the masseter during nerve stimulation.

As in any other motor conduction study, the amplitude of the distal compound muscle action potential (CMAP) is proportional to the number of intact motor axons, whereas the distal latency reflects conduction time along the fastest-conducting fibers of the distal segment of the facial nerve. The degree of axonal loss has direct implications for the prognosis and the time required for recovery. In general, amplitudes 50–75% lower than the contralateral side are associated with a poorer prognosis, a prolonged recovery time, and aberrant reinnervation. Note that it is important to check the facial CMAP at least 6 days after facial weakness develops so that enough time will have passed for wallerian degeneration to have occurred for motor fibers. If a patient with a facial palsy is evaluated before the symptoms are 3 days old, wallerian degeneration will not have begun. If evaluated between 3 and 5 days, wallerian degeneration may not be complete, and thus the degree of axonal loss and the prognosis will not be assessed accurately.

Blink Reflex Studies

Direct facial nerve stimulation evaluates only the distal segments of the nerve. The blink reflex study measures the entire reflex arc between the trigeminal and facial nerves, including proximal segments of the facial nerve (see Chapter 5). Therefore, to evaluate the proximal facial nerve segments, the blink reflex study is used in combination with direct facial nerve stimulation. Lesions of the facial nerve result in abnormalities of the ipsilateral R1 and R2 components of the blink reflex, whereas the contralateral R2 response remains normal. When the contralateral normal side is stimulated, the opposite pattern is seen: normal ipsilateral R1 and R2 responses and an abnormal contralateral R2 response.

The blink reflex can also be used in chronic facial palsies to look for electrophysiologic evidence of aberrant reinnervation. One can perform a blink reflex study stimulating the supraorbital nerve, co-recording the orbicularis oculi and mentalis muscles. If ipsilateral R1 and R2 responses are present in both muscles, aberrant reinnervation likely is present because the mentalis muscle does not usually participate in the blink reflex.

Electromyographic Approach

A small, fine, concentric needle should always be used to study the facial muscles, with muscles from the major branches being sampled. The easiest muscles to sample include the frontalis (temporal branch), orbicularis oculi (zygomatic branch), orbicularis oris (buccal branch), and mentalis (mandibular branch). Muscles innervated by cranial nerve V (masseter, temporalis) should also be sampled to look for evidence of more widespread cranial nerve dysfunction. The motor unit action potentials (MUAPs) in facial muscles tend to be smaller and shorter than those in limb muscles. In addition, the onset firing frequency is higher than in most limb muscles (8–10 Hz as opposed to 4–5 Hz). Accordingly, one should become well practiced in the needle examination of facial muscles so as not to mistake the normally small MUAPs for myopathic motor unit potentials.

On needle EMG, myokymic discharges may be seen in the facial muscles of patients with multiple sclerosis, brainstem tumors (especially pontine gliomas), or Guillain–Barré syndrome, or in patients who have received prior irradiation to the face and neck area.

Needle EMG can also be used to look for evidence of synkinesis that results from aberrant reinnervation. Small concentric needle electrodes can be placed simultaneously in muscles innervated by different facial nerve branches, with the electromyographer looking for co-contraction. For example, if MUAPs fire in the mentalis when the patient is asked to close the eyes, synkinesis is likely present. One must always take care not to confuse simultaneous co-contraction of muscles under voluntary control with involuntary co-contraction of muscles, which indicates synkinesis.

Hemifacial Spasm

Nerve Conduction Studies and Blink Reflex

Direct facial nerve conduction studies are usually normal in hemifacial spasm. However, the blink reflex and other specialized nerve conduction studies looking for *lateral spread* (ephaptic transmission) may be useful in demonstrating abnormalities. Selective facial nerve conduction studies can be done by stimulating an individual facial nerve branch and co-recording muscles innervated by different branches. For example, the zygomatic branch can be stimulated in a patient with hemifacial spasm, with the orbicularis oculi (zygomatic branch) and mentalis (mandibular branch) simultaneously recorded. One looks for a delayed lateral spread response (presumably ephaptic) in the

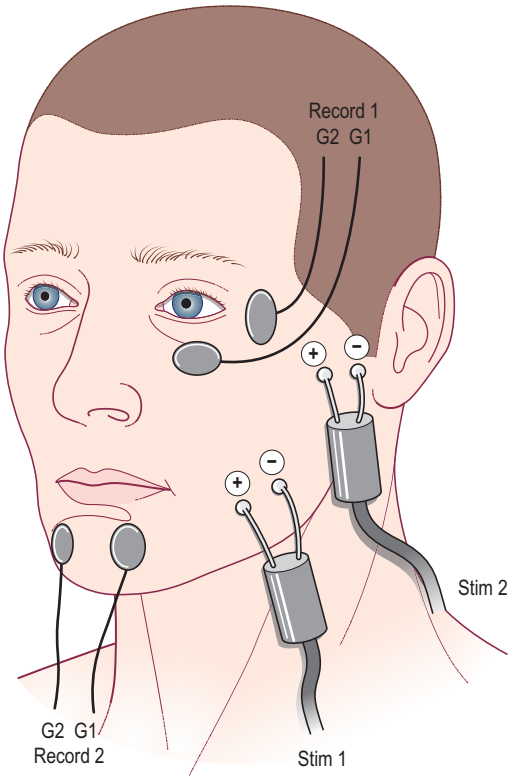

FIGURE 25–6 Technique for recording the lateral spread response. Two sets of recording electrodes are used, each set placed over a facial muscle innervated by a different facial branch, with the appropriate reference electrode. In the example shown here, recording electrodes are placed over the orbicularis oculi (record 1), innervated by the zygomatic branch, with another set of recording electrodes placed over the mentalis (record 2), innervated by the mandibular branch. The muscles are co-recorded while each individual facial branch (zygomatic or mandibular) is stimulated. In normal individuals, only the muscle innervated by the branch being stimulated will result in a potential. In patients with hemifacial spasm, a delayed response is also seen in the muscle innervated by the branch not being directly stimulated, presumably from ephaptic spread at the site of nerve injury or compression.
(From Harper, C.M., 1991. AAEM case report no. 21: hemifacial spasm: preoperative diagnosis and intraoperative management. Muscle Nerve 14, 213. Reprinted by permission of Wiley.)

mentalis that occurs just after the response at the orbicularis oculi (Figure 25–6). As in other nerve conduction studies, when a facial nerve branch is stimulated, the depolarization travels both orthodromically and antidromically. In hemifacial spasm, the antidromic volley presumably travels to the area of nerve injury and spreads ephaptically to adjacent fiber branches, resulting in a delayed response in muscles innervated by adjacent facial nerve branches. After successful decompression of the facial nerve, this lateral spread response disappears.

Similarly, one can perform a blink reflex study stimulating the supraorbital nerve, co-recording the orbicularis oculi and mentalis muscles. Ipsilateral R1 and R2 responses may be present in both muscles. This finding is similar to those seen with aberrant reinnervation in chronic facial palsy. In patients with hemifacial spasm, however, the response obtained recording the mentalis often is impersistent or varies in latency, whereas in patients with old facial palsy, this response is more often consistent and reproducible. Note that this finding is not seen in blepharospasm or other central movement disorders.

Electromyographic Approach

During a hemifacial spasm, the needle EMG study usually reveals MUAPs firing repetitively at high rates (e.g., 80–150 Hz), often in irregular bursts. MUAP morphology typically is normal. In many ways, the pattern is similar to that of myokymic discharges. This firing pattern differentiates hemifacial spasm from blepharospasm and other central movement disorders, wherein EMG reveals normal MUAPs firing in a pattern indistinguishable from that produced by voluntary contraction.

Trigeminal Neuropathy

The trigeminal nerve can be evaluated using a combination of the blink reflex and needle EMG examination (Box 25–2).

Blink Reflex Studies

The afferent limb of the blink reflex is used to evaluate the sensory fibers of the supraorbital branch of the ophthalmic nerve (V_1), the main sensory nucleus of cranial nerve V in the mid-pons, the nucleus of the spinal tract of cranial nerve V in the lower pons and medulla, and interneurons in the lower pons and lateral medulla. Lesions along the supraorbital branch of the trigeminal nerve result in abnormalities of the ipsilateral R1 and R2 components and the contralateral R2 component of the blink reflex.

Electromyographic Approach

The masseter and temporalis muscles are the most easily accessible to evaluate the motor function of cranial nerve V_3, with use of a small, fine concentric needle. As already noted the MUAPs of facial muscles are small and brief and should not be confused with myopathic motor unit potentials.

EXAMPLE CASES

Case 25–1

History and Physical Examination

A 50-year-old woman was well until 3 days before presentation, when she developed pain behind the left ear. The next day the left side of her face began to droop, and she was unable to blink her eye, keep food in her mouth, or pronounce certain words. She drooled from the left side of the mouth and noticed diminished taste sensation. Past medical history was notable for hypertension and diabetes.

On examination at day 3, she had a complete left facial palsy involving the upper and lower face. She was unable to wrinkle her forehead, blink her eye, or smile on the left side. She had difficulty pronouncing words beginning with "b" or "p" sounds and could not identify sugar on

CASE 25–1. Nerve Conduction Studies 2 Weeks After Presentation

Nerve Stimulated	Stimulation Site	Recording Site	Motor Amplitude (mV)			Latency (ms)		
			RT	LT	NL	RT	LT	NL
Facial (motor study)	Anterior mastoid	Orbicularis oculi	1.8	0.3	≥1	2.0	2.5	≤3.1

RT = right; LT = left; NL = normal.

CASE 25–1. Blink Reflex Studies 2 Weeks After Presentation

Nerve Stimulated	Stimulation Site	Recording Site	R1 Latency (ms)			R2 Latency (ms)		
			RT	LT	NL	RT	LT	NL
Right supraorbital (V_1)	Superior orbital fissure	Orbicularis oculi	9.0	–	≤13	34.1	NR	≤41 (ipsilateral) ≤44 (contralateral)
Left supraorbital (V_1)	Superior orbital fissure	Orbicularis oculi	–	NR	≤13	31.8	NR	≤41 (ipsilateral) ≤44 (contralateral)

RT = right; LT = left; NL = normal; NR = no response.

CASE 25–1. Electromyography 2 Weeks After Presentation

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Left frontalis	↑	+2	0	NONE				
Left orbicularis oculi	↑	+2	0	NL	↓↓↓	NL	NL	NL
Left orbicularis oris	↑	+1	0	NONE				
Left mentalis	↑	+1	0	NONE				
Left temporalis	NL	0	0	NL	NL	NL	NL	NL
Left masseter	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓↓↓= markedly decreased; NL = normal.

the left anterior tongue. On corneal reflex testing, no blink was elicited on the left with either left or right corneal stimulation. Hearing and lacrimation were normal. She denied hyperacusis. The palate elevated symmetrically, and the tongue was midline on protrusion. The remainder of the cranial nerve examination was normal, including sensation over the face and scalp and masseter strength. The remainder of the neurologic examination also was normal. No vesicular lesions were noted in the external auditory canal.

Electrophysiologic evaluation was performed 2 weeks after the onset of symptoms and again 6 months later.

Summary

This 50-year-old woman presented with an acute left facial palsy affecting the upper and lower facial muscles and associated with pain behind the ipsilateral ear, consistent with idiopathic Bell's palsy. The complete left facial palsy involving the upper and lower face suggests a peripheral lesion. There is altered taste sensation, with normal hearing and lacrimation, suggesting a distal lesion in the facial canal. There are no other neurologic findings suggesting a more widespread cranial neuropathy.

Beginning with the nerve conduction studies done 2 weeks after presentation, direct facial motor nerve stimulation recording orbicularis oculi reveals a markedly low CMAP amplitude on the left side (one sixth the amplitude of the contralateral side) with a normal distal latency. On the blink reflex study, left supraorbital stimulation shows an absent R1 and ipsilateral R2 response. The contralateral R2 response, which reflects efferent fibers along the right facial nerve, is normal. In contrast, right supraorbital stimulation produces a normal R1 and ipsilateral R2, but the contralateral R2 response, which reflects efferent fibers along the left facial nerve, is absent. At this point, there is electrophysiologic evidence of a lesion affecting the facial nerve on the left side, given the combination of findings from the facial nerve

conduction studies and the blink reflex study. The markedly low CMAP amplitude with direct facial nerve stimulation indicates severe axonal loss.

EMG examination is performed next to confirm the findings of the nerve conduction and blink reflex studies, to determine which branches of the facial nerve are involved, and to look for possible evidence of more widespread involvement of nearby nerves. The EMG study shows increased insertional activity and fibrillation potentials in the left frontalis, orbicularis oculi, orbicularis oris and mentalis muscles, with markedly reduced recruitment of normal configuration MUAPs in the orbicularis oculi. No MUAPs can be activated in other muscles innervated by the facial nerve. The masseter and temporalis muscles, innervated by cranial nerve V_3, are normal.

With this information, we are ready to formulate an electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are consistent with a severe acute axonal lesion involving several branches of the facial nerve on the left side. Continuity of the nerve is demonstrated to the orbicularis oculi. Repeat study is recommended in 3 to 6 months to look for evidence of reinnervation.*

The combination of direct facial nerve stimulation, blink reflex studies, and needle EMG examination can be used to answer four critical questions regarding the patient's facial palsy.

Is the Lesion Central or Peripheral?

The findings of a low CMAP amplitude, absent ipsilateral left R1 and R2 responses with a normal contralateral R2 on the blink reflex study, and fibrillation potentials with poor recruitment of normal configuration MUAPs are all consistent with an acute peripheral lesion of cranial nerve VII. In an acute central lesion, direct facial stimulation studies should be normal. Likewise, needle EMG of the facial muscles also should be normal in a central lesion, although activation of MUAPs may be reduced while recruitment of MUAPs remains normal.

How Extensive is the Lesion?

All of the abnormalities noted with direct facial nerve stimulation, the blink reflex, and needle EMG implicate an isolated lesion of the left facial nerve. The abnormal findings include the low CMAP amplitude while recording over the left orbicularis oculi with direct facial stimulation and the absent ipsilateral R1 and R2 responses and normal contralateral R2 response with left-sided stimulation on the blink reflex. The needle examination reveals abnormalities in the distribution of at least four branches of the left facial nerve, including active denervation in muscles supplied by the temporal, zygomatic, buccal, and mandibular branches. No activation of MUAPs is noted in muscles supplied by three of these branches. The blink reflex findings of an intact contralateral R2 response with left-sided stimulation and intact ipsilateral R1 and R2 responses with right-sided stimulation suggest that cranial nerve V_1, the main sensory nucleus of V, and the nucleus of the spinal tract of V are intact bilaterally, along with cranial nerve VII on the right side. Needle examination of the left masseter and temporalis muscles is normal, suggesting that the motor component of the fifth cranial nerve (V_3) on the left side is intact as well.

What is the Underlying Pathophysiology?

The low CMAP amplitude, normal distal latency, and diffuse fibrillation potentials noted 2 weeks after onset of the facial palsy all point toward an acute axonal loss lesion. At this point, there has been enough time for wallerian degeneration to occur, resulting in the low CMAP amplitude. The fibrillation potentials noted 2 weeks after the onset of symptoms have appeared relatively early (before 3 weeks). They probably are seen so early because of the short length of the facial nerve.

What is the Prognosis for Recovery?

The prognosis for recovery is based on the underlying pathophysiology. The best prognostic indicator is the amplitude of the CMAP obtained from direct facial nerve stimulation, which is directly proportional to the number of intact motor axons. The markedly low CMAP amplitude and normal distal latency, obtained on day 14, after wallerian degeneration has taken place, suggests severe axonal degeneration. Comparison of this amplitude (0.3 mV) with that on the contralateral side (1.8 mV) can be used to estimate the number of intact motor axons. In this case, the amplitude is one sixth that of the normal side. A CMAP amplitude of less than half that of the contralateral normal side indicates a poor prognosis, with slow and generally incomplete recovery.

In the repeat study at 6 months, needle examination reveals reduced recruitment of small, short, polyphasic MUAPs. These are known as nascent motor unit potentials, which are newly reinnervated MUAPs that are seen after severe denervation. As an axon regrows after a severe lesion, there is a certain point at which only a few of the muscle fibers have been reinnervated. At this

CASE 25–1. Nerve Conduction Studies 6 Months After Presentation

Nerve Stimulated	Stimulation Site	Recording Site	Motor Amplitude (mV)			Latency (ms)		
			RT	LT	NL	RT	LT	NL
Facial (motor study)	Anterior mastoid	Orbicularis oculi	1.3	0.8	≥1	2.0	2.0	≤3.1

RT = right; LT = left; NL = normal.

CASE 25–1. Blink Reflex Studies 6 Months After Presentation

Nerve Stimulated	Stimulation Site	Recording Site	R1 Latency (ms)			R2 Latency (ms)		
			RT	LT	NL	RT	LT	NL
Right supraorbital (V_1)	Superior orbital fissure	Orbicularis oculi	9.0	–	≤13	33.4	35.6	≤41 (ipsilateral) ≤44 (contralateral)
		Mentalis	NR	–		NR	NR	NR
Left supraorbital (V_1)	Superior orbital fissure	Orbicularis oculi	–	10.4	≤13	34.7	32.8	≤41 (ipsilateral) ≤44 (contralateral)
		Mentalis		11.6			36.2	NR

RT = right; LT = left; NL = normal; NR = no response.

CASE 25–1. Electromyography 6 Months After Presentation

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Left frontalis	NL	0	0	NL	↓↓	–2	–2	+2
Left orbicularis oculi	NL	0	0	NL	↓↓	–2	–2	+2
Left orbicularis oris*	NL	0	0	NL	↓↓	–1/+1	–2	+2
Left mentalis	NL	0	0	NL	↓↓	–1/+1	–1	+2

NL = normal;↓↓ = moderately reduced.
*When patient closed eyes, voluntary motor unit action potentials were seen in this muscle as well.

point, the MUAPs are small, short, and polyphasic, similar to those seen in myopathy. The major factor that differentiates between the two is the recruitment pattern. In early reinnervation, one sees moderately to markedly reduced recruitment of nascent MUAPs; in myopathy, recruitment of MUAPs is normal or early. Although the finding of nascent motor unit potentials in all branches of the facial nerve studied at 6 months indicates continuity of the nerve, reinnervation is incomplete at this point.

The blink reflex studies at 6 months show ipsilateral R1 and R2 responses when the left supraorbital nerve is stimulated and the orbicularis oculi and mentalis muscles are simultaneously recorded. The mentalis muscle does not generally participate in the blink reflex. The response from the mentalis muscle with supraorbital nerve stimulation indicates synkinesis that is likely secondary to aberrant reinnervation of the facial nerve. Similarly, the needle examination finding of co-activation of MUAPs in the orbicularis oculi and orbicularis oris muscles on voluntary contraction of the orbicularis oculi indicates synkinesis. These findings parallel the clinical findings at 6 months, wherein attempted eye closure on the left side resulted in the corner of the mouth turning up on the left side.

Case 25–2

History and Physical Examination

A 60-year-old woman noted the onset of right facial numbness that developed insidiously over the past 5 months. She had no complaints of facial pain, weakness, double vision, difficulty with swallowing or speech, or numbness in areas other than the right side of the face. She had noted a dry mouth and dry eyes over the past year. Past medical history and review of systems were otherwise unremarkable.

The neurologic examination was notable for decreased sensation to light touch and pinprick in the right V_1 and V_2 distributions. The corneal reflex was depressed on the right. There was no ptosis. Bulbofacial strength was normal, including masseter strength. The jaw did not deviate when opening the mouth. The remainder of the cranial nerve and neurologic examination was normal, with the exception of moderately decreased vibration to the mid-shins, mild wasting of the intrinsic foot muscles, and absent ankle reflexes bilaterally.

Summary

This patient presented with the subacute onset of right facial numbness involving the ophthalmic (V_1) and maxillary (V_2) divisions of the trigeminal nerve. There are no other neurologic complaints, although she has a history of a dry mouth and dry eyes for the past year. Neurologic examination confirms the presence of sensory loss in the V_1 and V_2 distributions. In addition, she has signs consistent with a mild peripheral neuropathy, including distal vibratory loss in the lower extremities, mild wasting of the intrinsic foot muscles, and absent ankle reflexes in the lower extremities bilaterally.

Nerve conduction studies in the lower extremities show absent sural potentials, slightly low CMAP

CASE 25–2. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F-wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Tibial (m)	Ankle	AHB	4.2	3.7	≥4	4.7	4.8	≤5.8				56	57	≤56
	Popliteal fossa	AHB	3.6	3.2		11.8	12.1		42	41	≥41			
Peroneal (m)	Ankle	EDB	1.8	2.2	≥2	5.2	5.4	≤6.5				57	58	≤56
	Below fibula	EDB	1.7	2.1		12.1	12.2		43	44	≥44			
	Lateral popliteal fossa	EDB	1.6	2.1		14.5	14.7		42	40	≥44			
Sural (s)	Calf	Posterior ankle	NR	NR	≥6	NR	NR	≤4.4	NR	NR	≥40			
H reflex	Popliteal fossa	Soleus	NR	NR		NR	NR	≤34						

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.
Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 25–2. Blink Reflex Studies

Nerve Stimulated	Stimulation Site	Recording Site	R1 Latency (ms)			R2 Latency (ms)		
			RT	LT	NL	RT	LT	NL
Right supraorbital (V_1)	Superior orbital fissure	Orbicularis oculi	NR	–	≤13	NR	NR	≤41 (ipsilateral) ≤44 (contralateral)
Left supraorbital (V_1)	Superior orbital fissure	Orbicularis oculi	–	9.6	≤13	33.8	32.6	≤41 (ipsilateral) ≤44 (contralateral)

RT = right; LT = left; NL = normal; NR = no response.

CASE 25–2. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Left tibialis anterior	NL	0	0	NL	↓	+1	+1	+1
Left extensor hallucis longus	↑	+1	0	NL	↓	+1	NL	+1
Left medial gastrocnemius	NL	+1	0	NL	NL	+1	NL	NL
Left gluteus medius	NL	0	0	NL	NL	NL	NL	NL
Left vastus lateralis	NL	0	0	NL	NL	NL	NL	NL
Left L5 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right medial gastrocnemius	↑	+1	0	NL	↓	+1	+1	NL
Right extensor hallucis longus	NL	+1	0	NL	↓	+1	+1	+1
Right vastus lateralis	NL	0	0	NL	NL	NL	NL	NL
Right L5 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right masseter	NL	0	0	NL	NL	NL	NL	NL
Right temporalis	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓ = slightly decreased; NL = normal.

amplitudes, mildly slowed conduction velocities, mildly prolonged tibial and peroneal F-wave latencies, and absent H reflexes bilaterally. These findings are consistent with a sensorimotor peripheral neuropathy. Moving next to the blink reflex studies, stimulation of the right supraorbital nerve reveals an absent R1 response and absent bilateral R2 responses. Left supraorbital stimulation produces a normal R1 response and normal bilateral R2 responses. Because right supraorbital nerve stimulation fails to produce an ipsilateral R1 or R2 responses on either side, and left supraorbital nerve stimulation produces a normal R1 and bilateral R2 responses, there must be a lesion along the sensory fibers of the V_1 branch of the trigeminal nerve on the right side. Thus far, the electrophysiologic studies demonstrate a peripheral neuropathy, with a superimposed trigeminal neuropathy on the right side.

Moving next to the needle examination, the distal muscles of both lower extremities have sparse fibrillation potentials with mildly reduced recruitment of slightly large, prolonged MUAPs. The proximal lower extremity muscles, including lumbar paraspinal muscles, are normal. These findings are consistent with the nerve conduction studies showing a peripheral neuropathy. Needle examination of the right masseter and temporalis muscles, which are innervated by cranial nerve V_3, is normal. Therefore, there is no evidence of involvement of the motor fibers of the trigeminal nerve, despite the findings on the blink reflex studies.

At this point, we are ready to formulate our electrophysiologic impression.

IMPRESSION: *There is electrophysiologic evidence consistent with a mild generalized axonal sensorimotor peripheral neuropathy. In addition, there is electrophysiologic evidence of a superimposed lesion of the trigeminal sensory fibers on the right side.*

Further laboratory investigations including sedimentation rate, antinuclear antibodies, rheumatoid factor, anti-Ro and anti-La antibodies, Schirmer test, and lip biopsy revealed evidence consistent with Sjögren syndrome. Neurologic complications of that disorder include trigeminal neuropathy and a generalized sensorimotor peripheral neuropathy.

Suggested Readings

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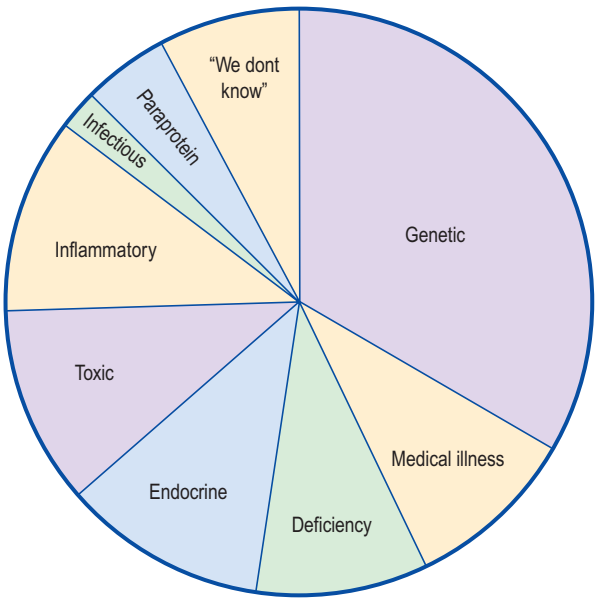
26 Polyneuropathy

Nerve conduction studies and electromyography (EMG) play key roles in the evaluation of patients with suspected polyneuropathy. Although polyneuropathy has hundreds of potential causes, they can be grouped into several large categories (Figure 26–1). The first step in the evaluation of a patient with polyneuropathy is to reduce the differential diagnosis to a smaller, more manageable number of possibilities. This usually can be accomplished by acquiring several critical pieces of information from the history, physical examination, and electrophysiologic studies.



Overview of polyneuropathy

FIGURE 26–1 Overview of polyneuropathy. Although there are literally hundreds of causes of polyneuropathy, they can be grouped into several large categories. Note that even after a complete evaluation, there remain a sizable number (approximately 20%) of patients in whom the diagnosis remains uncertain. Disclaimer: the various categories are for illustrative purposes only, and their relative sizes in the chart should not be interpreted as authoritative, as there are insufficient prevalence data on the various categories of polyneuropathies. However, genetic neuropathies are very common, as are toxic, deficiency (such as vitamin deficiency), endocrine, and other medical conditions that may result in a polyneuropathy. In addition, paraproteins account for a small number (5–10%) of polyneuropathies, especially in patients with difficult to diagnose polyneuropathy.

Electrophysiologic studies can be used (1) to confirm the presence of a polyneuropathy, (2) to assess its severity and pattern, (3) to determine whether motor, sensory, or a combination of fibers are involved, and, most importantly, (4) to assess whether the underlying pathophysiology is axonal loss or demyelination. In cases in which a demyelinating polyneuropathy is found, further differentiation between an acquired and inherited condition can often be made. The information obtained from electrophysiologic testing, in conjunction with key pieces of clinical information, usually allows the differential diagnosis to be narrowed considerably so that further laboratory testing can be more appropriately applied and a final diagnosis reached.

CLINICAL

Polyneuropathy literally means dysfunction or disease of many or all peripheral nerves. Because peripheral nerves can react to disease in only a limited number of ways, polyneuropathies of many different causes may present with similar symptoms and signs. Indeed, most patients with polyneuropathy first present with a combination of sensory and motor symptoms and signs in the feet and lower legs, which later spread proximally in the legs and then into the hands and arms. Despite the many similarities, one can always limit the differential diagnosis of a polyneuropathy by determining the answers to seven key questions.

Key Question No. 1: What is the Temporal Course and Progression of the Polyneuropathy (Acute, Subacute, Chronic; Progressive, Stepwise, Relapsing/Remitting)?

The temporal course and progression can be obtained by the history alone and often confirmed by electrophysiologic studies. Most polyneuropathies are chronic, and their onset cannot be easily determined. Acute polyneuropathies are notably less common (Box 26–1). Among them, Guillain–Barré syndrome (and its most common variant, *acute inflammatory demyelinating polyneuropathy* [AIDP]) is the most distinctive, with an onset over a few days or a few weeks at most. Similarly, most polyneuropathies are slowly progressive (Figure 26–2). Polyneuropathies that progress

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Box 26–1. Acute Polyneuropathies

Guillain–Barré syndrome
Porphyria
Diphtheria
Drugs (e.g., dapsone, nitrofurantoin, vincristine)
Toxins (e.g., arsenic, thallium, triorthocresylphosphate)
Tick paralysis
Vasculitis

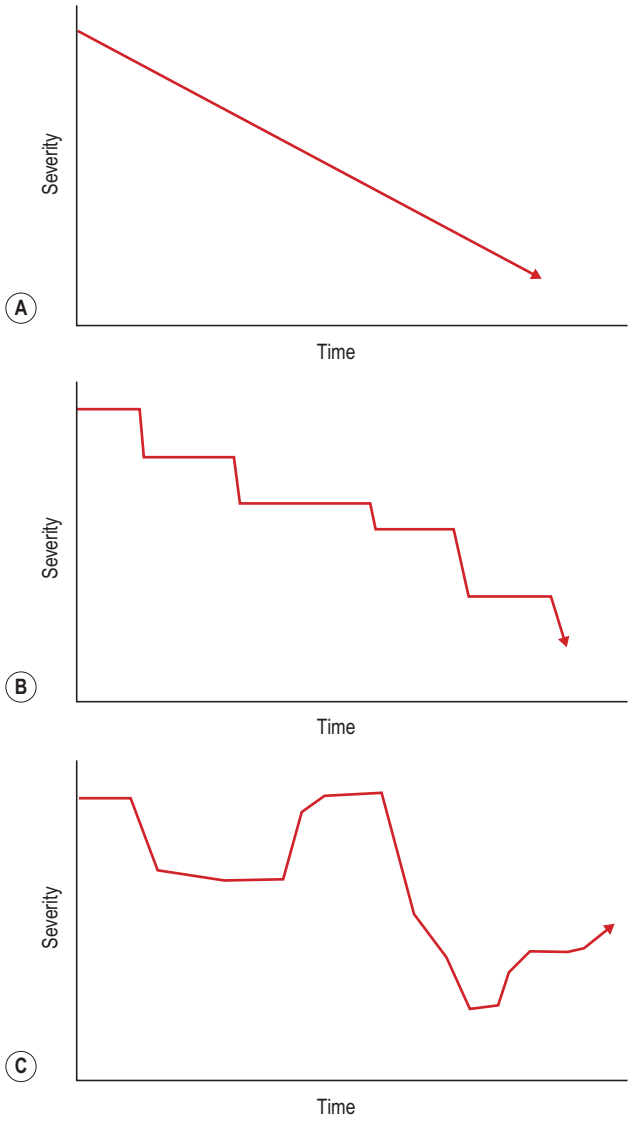


FIGURE 26–2 Temporal progression of polyneuropathy. The pattern of the temporal progression is one of the key historical points in determining the etiology of a polyneuropathy (n.b., worsening severity is denoted as going downward). **A:** Slowly progressive; **B:** Stepwise progressive; **C:** Relapsing / remitting.

in a stepwise fashion are infrequent and are often associated with a mononeuropathy multiplex pattern (discussed later). Likewise, the history of a relapsing/remitting course is distinctly unusual and suggests either an intermittent exposure/intoxication or a variant of chronic inflammatory demyelinating polyneuropathy (CIDP).

Key Question No. 2: Which Fiber Types are Involved (Motor, Large Sensory, Small Sensory, Autonomic)?

The next step is to determine which fiber types are involved. This information is obtained primarily from the history and confirmed by physical examination and electrophysiologic tests. Nerve fibers can be categorized either by the modality carried (motor, sensory, autonomic) or by fiber size. All motor fibers are large-diameter, myelinated fibers, whereas all autonomic fibers are small-diameter, mostly unmyelinated fibers. However, sensory fibers may be either large or small in diameter. Large sensory fibers mediate vibration, proprioception, and touch, whereas small sensory fibers convey pain and temperature sensations.

When nerve is diseased, it can react in a limited number of ways. Thus, many peripheral nerve disorders present with similar symptoms despite different etiologies. Symptoms and signs of nerve dysfunction result either from lack of function (*negative* symptoms and signs) or from abnormal function or overfunctioning (*positive* symptoms and signs). For example, anyone who has "fallen asleep" on his or her arm can remember the initial numbness or lack of feeling (negative symptoms), followed by intense pins-and-needles paresthesias (positive symptoms) as circulation is restored. Characteristic positive or negative sensory symptoms and signs caused by diseased nerves help one recognize which fiber types are involved (Table 26–1).

Determining which fiber types are involved has important diagnostic implications. Most polyneuropathies involve both sensory and motor fibers on electrophysiologic testing, even though, clinically, most distal axonal polyneuropathies exhibit sensory symptoms and findings long before the disease process becomes sufficiently severe to cause actual weakness. Patients with certain hereditary polyneuropathies (e.g., Charcot–Marie–Tooth polyneuropathy) and conditions such as lead poisoning, porphyria, and Guillain–Barré syndrome may exhibit predominantly motor symptoms and signs. On the sensory side, pure sensory neuropathies also are unusual and often suggest a primary process affecting the dorsal root ganglia. These *sensory neuronopathies* are quite rare and are characteristically seen acutely or subacutely as a paraneoplastic syndrome, postinfectious process, or associated with Sjögren's syndrome or pyridoxine (B_6) intoxication. Chronic sensory neuronopathies may be seen in the inherited sensory neuropathies and as a component of some inherited neurodegenerative conditions (e.g., Friedreich's ataxia).

Large and small fibers are affected in most polyneuropathies. Only a few polyneuropathies preferentially affect small fibers (Box 26–2). Manifestations include autonomic dysfunction and a distal sensory deficit, particularly for pinprick, often associated with painful, burning dysesthesias. It is essential to appreciate that routine nerve conduction studies assess only large myelinated fibers. A patient who has a pure small-fiber polyneuropathy, *with complete sparing of the large fibers*, may have completely normal electrophysiologic studies. Conversely, large-fiber

Table 26–1. Negative and Positive Symptoms and Signs of Peripheral Nerve Disease

	Negative	Positive
Motor	Weakness Fatigue Hyporeflexia or areflexia Hypotonia Orthopedic deformities (e.g., pes cavus, hammer toes)	Fasciculations Cramps Myokymia Restless legs "Tightness"
Sensory		
Large fiber	Decreased vibration sensation Decreased joint position sensation Hyporeflexia or areflexia Ataxia Hypotonia	"Tingling" "Pins and needles"
Small fiber	Decreased pain sensation Decreased temperature sensation	"Burning" "Jabbing" "Shooting"
Autonomic	Hypotension Arrhythmia Decreased sweating Impotence Urinary retention	Hypertension Arrhythmia Increased sweating

Box 26–2. Small-Fiber Peripheral Polyneuropathies

Diabetes
Amyloidosis (inherited and acquired)
Toxins (especially alcohol)
Drugs (especially ddI, ddC)
Hypertriglyceridemia
Hereditary sensory neuropathies
Tangier disease
Fabry disease
Acquired immunodeficiency syndrome
Idiopathic (especially in the elderly)

polyneuropathies always show abnormalities on electrophysiologic testing. Predominantly large-fiber polyneuropathies result in clinical sensory deficits (particularly for vibration and touch), weakness, and loss of tendon reflexes, with little or no autonomic and pain/temperature sensation loss.

Key Question No. 3: What is the Pattern of the Polyneuropathy (Distal Dying Back [Distal-To-Proximal Gradient], Short Nerves, Multiple Nerves; Symmetry, Asymmetry)?

The overall pattern of the polyneuropathy is determined largely based on the clinical examination and is supplemented and confirmed by electrophysiologic studies. In most polyneuropathies, there is a distal-to-proximal gradient of symptoms and signs. Distal symptoms and findings occur in most polyneuropathies, in part indicating the frequency with which axonal loss is the underlying pathologic process. Most axonal polyneuropathies exhibit a distal-to-proximal, dying back pattern, reflecting that the chance of damage to a nerve is length dependent (Figure 26–3). Thus, the longest nerves are affected first, resulting in a stocking-glove distribution of symptoms. Patients initially develop numbness or weakness of the toes and feet, which then slowly progresses up the leg. When the process reaches the upper calf, the fingertips become involved as well, because the distance from the lumbosacral spinal cord to the upper calf is the same as that from the cervical spinal cord to the fingertips. Only rarely will polyneuropathies preferentially affect the shorter, more proximal nerves before the distal ones (e.g., in porphyria, proximal diabetic neuropathy, and some cases of inflammatory demyelinating polyneuropathy).

After determining whether a distal-to-proximal gradient is present, one should next assess the polyneuropathy for symmetry. Nearly all polyneuropathies are symmetric. *The*

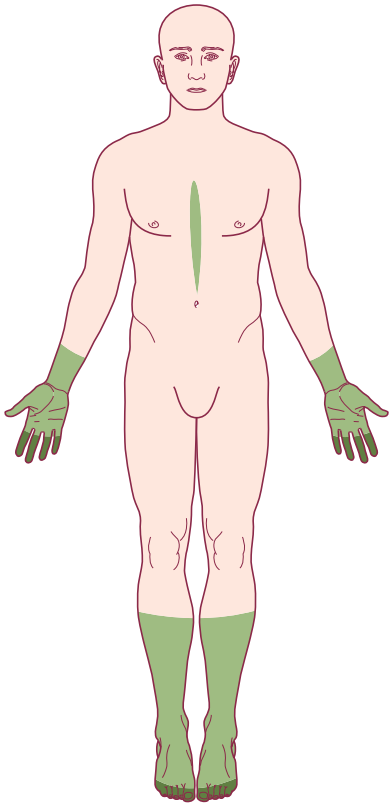


FIGURE 26–3 Stocking-glove pattern of polyneuropathy. Most polyneuropathies, especially axonal polyneuropathies, are length dependent, resulting in a stocking-glove distribution of symptoms and signs. Symptoms first present in the toes and then progress up the leg. When the polyneuropathy reaches the upper calves, the fingertips become involved as well. As the polyneuropathy worsens, symptoms may develop over the anterior chest and abdomen, representing distal degeneration of the thoracic intercostal nerves.
(Reprinted with permission from Schaumburg, H.H., Spencer, P.S., Thomas, P.K., 1983. Disorders of peripheral nerves. FA Davis, Philadelphia.)

presence of any significant asymmetry is a key finding; it usually excludes a large number of toxic, metabolic, and genetic conditions that cause only a symmetric pattern. Asymmetry implies the possibility of (1) a mononeuropathy multiplex pattern, (2) a superimposed radiculopathy or entrapment neuropathy, or (3) a variant of CIDP. Nerve conduction studies and EMG frequently are useful in sorting out these possibilities.

The pattern of a *mononeuropathy multiplex* is one of the most important patterns to recognize and differentiate from the length-dependent, dying-back, axonal polyneuropathy. The clinical presentation is distinctive: there is an asymmetric, stepwise progression of individual cranial and/or peripheral neuropathies (Figure 26–4). Over time, a confluent pattern may develop, which may be difficult to distinguish from a generalized polyneuropathy. In most cases, the individual neuropathies are of named nerves (i.e., median, ulnar, peroneal, etc.) as opposed to small nerve twigs. Mononeuropathy multiplex has a limited differential diagnosis (Box 26–3) and most often occurs in the setting of vasculitis and vasculitic neuropathy. As each subsequent nerve is infarcted, pain develops (often severe), followed hours or days later by weakness and numbness in the nerve's distribution. Although other organ systems are often involved, the initial clinical presentation of systemic vasculitis may involve only the peripheral nervous system. Indeed, there are now well-recognized cases in which vasculitis remains confined to the peripheral nervous system.

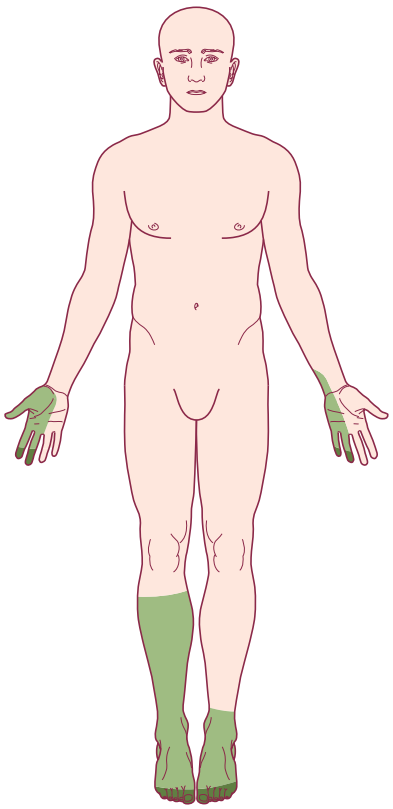


FIGURE 26–4 Mononeuropathy multiplex pattern of polyneuropathy. Mononeuropathy multiplex is a distinctive pattern, presenting as an asymmetric, stepwise progression of individual cranial or peripheral neuropathies, usually of named nerves. As time passes, a confluent pattern may develop that often is difficult to distinguish from a generalized polyneuropathy. Mononeuropathy multiplex is characteristically seen in vasculitic polyneuropathy. The pattern shown here is an asymmetric polyneuropathy with involvement of the left ulnar, right median, left distal peroneal, right saphenous, and right peroneal nerves.
(Adapted and reprinted with permission from Schaumburg, H.H., Spencer, P.S., Thomas, P.K., 1983. Disorders of peripheral nerves. FA Davis. Philadelphia.)

Box 26–3. Differential Diagnosis of Mononeuropathy Multiplex

- Vasculitis (e.g., polyarteritis nodosa, Churg–Strauss syndrome, Wegener's syndrome, hypersensitivity, cryoglobulinemia, systemic lupus erythematosus, rheumatoid arthritis, Sjögren's syndrome, chronic active hepatitis)
- Diabetes
- Inflammatory demyelinating polyneuropathy (Lewis–Sumner variant)
- Multiple entrapments (hereditary and acquired)
- Infection (e.g., Lyme, leprosy, human immunodeficiency virus)
- Infiltration (e.g., granulomatous disease [sarcoid], neoplasm [lymphoma, leukemia])

Key Question No. 4: What is the Underlying Nerve Pathology (Axonal, Demyelinating, or Mixed)?

Pathologically, injury to nerves consists of two major processes: axonal loss or demyelination. The vast majority of polyneuropathies are primarily axonal. In demyelinating polyneuropathies, the initial injury to the nerves reflects damage to or dysfunction of the Schwann cells and the myelin sheaths. As a consequence of demyelination, conduction is impaired with marked slowing of conduction velocity or frank conduction block. In establishing the differential diagnosis of a peripheral nerve disorder, the presence of demyelination is always a key finding (see later). Demyelination may be demonstrated either by nerve biopsy and pathologic examination or, more easily, by electrophysiologic testing. When nerve conduction studies demonstrate a polyneuropathy to be predominantly demyelinating, the differential diagnosis is readily narrowed to a small group of disorders (Box 26–4).

Key Question No. 5: Is there a Family History of Polyneuropathy?

For any patient with a polyneuropathy, especially when the diagnosis is not clear, particular attention must be paid to family history. There are a large number of inherited polyneuropathies. Although for most of them only symptomatic therapy is available, correct diagnosis is important for genetic counseling and prognosis, and to avoid unnecessary or inappropriate further testing and treatment. Charcot–Marie–Tooth (CMT) neuropathy refers to a group

Box 26–4. Demyelinating Polyneuropathies

Hereditary
- Charcot–Marie–Tooth, Type I (CMT1)
- Charcot–Marie–Tooth, Type IV (CMT4)
- Charcot–Marie–Tooth, X-linked (CMTX)
- Dejerine–Sottas disease*
- Refsum disease
- Hereditary neuropathy with liability to pressure palsy (HNPP)
- Metachromatic leukodystrophy
- Krabbe disease
- Adrenoleukodystrophy/adrenomyeloneuropathy
- Cockayne syndrome
- Niemann–Pick disease
- Cerebrotendinous xanthomatosis
- Mitochondrial neurogastrointestinal encephalomyopathy (MNGIE)

Acquired
- Acute inflammatory demyelinating polyradiculoneuropathy (AIDP, the most common variant of Guillain–Barré syndrome)
- Chronic inflammatory demyelinating polyradiculoneuropathy (CIDP)
  - Idiopathic
  - Associated with human immunodeficiency virus (HIV) infection
  - Associated with MGUS (especially IgM)
  - Associated with anti-MAG antibodies
  - Associated with osteosclerotic myeloma
  - Associated with Waldenström macroglobulinemia
- Multifocal motor neuropathy with conduction block ($\pm GM_1$ antibodies)
- Diphtheria
- Toxic (i.e., amiodarone, perhexiline, arsenic, glue sniffing, buckthorn shrub poisoning)

*Dejerine–Sottas disease is a historical term used to denote a severe demyelinating neuropathy in children. The classic phenotype described a hypotonic infant with areflexia and hypertrophic nerves; on nerve conduction studies, conduction velocities were extremely slow, typically around 6 m/s. Formerly considered a distinct entity with autosomal recessive inheritance, genetic analysis has demonstrated that Dejerine–Sottas is a syndrome with either recessive inheritance or autosomal dominant inheritance with de novo mutations. The recessive forms are now incorporated into the CMT4 group. The de novo autosomal dominant forms have mutations on the same genes implicated for CMT1 (*P0, PMP22,* and *EGR2*), but with the genetic defect resulting in a much more severe demyelinating neuropathy.

of inherited disorders characterized by a chronic motor and sensory polyneuropathy. CMT accounts for the majority of inherited polyneuropathies and, in many large series, represents a significant proportion of the patients with difficult-to-diagnose polyneuropathies. Four major types of CMT are defined based on their inheritance and physiology: the demyelinating autosomal dominant form is CMT1; the axonal autosomal dominant form is CMT2; the autosomal recessive demyelinating form is CMT4; and the X-linked demyelinating form is CMTX. Within each type, there are several subtypes based on the specific genetic defect. In contrast to CMT, there are a smaller group of inherited polyneuropathies associated with defects of metabolism that have been described. Most are extremely rare and are associated with other systemic abnormalities.

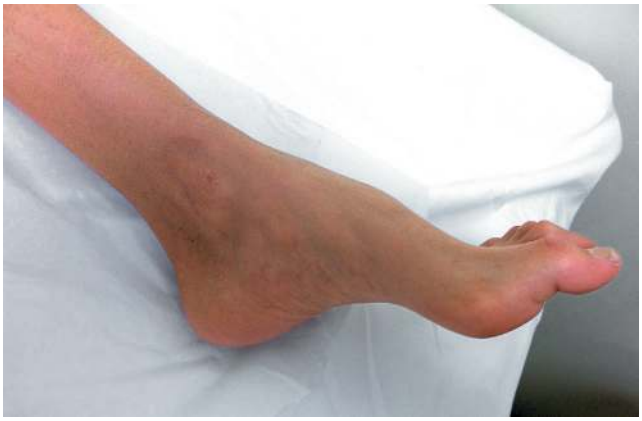


FIGURE 26–5 Pes cavus. Pes cavus is an orthopedic deformity of the foot, recognized as a foreshortened foot with a high arch and hammer toes. Pes cavus develops during childhood from the combination of intrinsic foot muscle weakness and relative preservation of the long flexors and extensor muscles in the calves. Because most polyneuropathies preferentially affect distal muscles, polyneuropathies that are present during development as a child commonly result in this deformity. As the vast majority of polyneuropathies that are present as a child are genetic, the presence of pes cavus in a patient with a peripheral neuropathy likely indicates that the neuropathy has been present since childhood and is most likely inherited.

Inherited polyneuropathies may affect certain individuals so minimally or may progress so slowly over an individual's lifetime that the person never seeks medical attention. Therefore, it often is beneficial to examine family members, both clinically and with nerve conduction studies and EMG, to help determine whether the underlying etiology of the patient's polyneuropathy is genetic. Several clinical clues, however, suggest the possibility of an inherited polyneuropathy (Figure 26–5):

- Foot deformity (pes cavus, hammer toes, high arches)
- History of a long-standing polyneuropathy (many years and often decades)
- History of very slow progression
- Few positive sensory symptoms
- Family history of "polio," "rheumatism," "arthritis," or other disorders that actually might have been inherited polyneuropathy

Key Question No. 6: Is there a History of Medical Illness or are there Signs Suggesting A Medical Illness Associated with Polyneuropathy?

A careful history and general physical examination are essential in evaluating a patient with polyneuropathy. Several medical conditions are strongly associated with polyneuropathy. Most prominent among them are diabetes and other endocrine disorders, cancer, connective tissue disorders, porphyria, vitamin and other deficiency states, and human immunodeficiency virus (HIV) infection.

Key Question No. 7: Is there any History of Occupational or Toxic Exposure To Agents Associated with Polyneuropathy?

Finally, it is always important to ask about occupational and exposure history. Among drugs, most notable are cancer chemotherapeutic agents, which frequently result in polyneuropathy that is detectable either clinically or electrically. In addition, a large number of prescription drugs, as well as over-the-counter medicines, can cause polyneuropathy. A careful review of all medicines is always important.

Asking about a patient's occupational and recreational activities occasionally elicits a toxic source for the neuropathy. One should always inquire about the patient's use of alcohol, which is one of the most frequent causes of toxic polyneuropathy.

AXONAL POLYNEUROPATHY

The underlying pathology of the vast majority of polyneuropathies is axonal degeneration, usually affecting both motor and sensory fibers. Axonal polyneuropathies include nearly all diabetic, toxic, metabolic, drug-induced, nutritional, connective tissue, and endocrine-associated polyneuropathies. In addition, there are a small number of inherited CMT neuropathies that are axonal. The autosomal dominant axonal form of CMT is now known as CMT2. CMT2 is further divided into several subtypes based on the specific genetic defect, and accounts for approximately 10–15% of the CMT inherited neuropathies.

Clinical

Clinically, the patient with an axonal polyneuropathy usually presents with a stocking-glove distribution of symptoms and signs, including distal sensory loss and weakness. Ankle reflexes usually are absent, whereas knee and upper extremity reflexes are preserved, unless the polyneuropathy is severe.

In severe cases, the pattern of abnormalities may become more complex. Sensory symptoms and signs may develop not only over the limbs but also over the anterior chest and abdomen (escutcheon sign, which is the shape of a shield), reflecting distal degeneration of the thoracic intercostal nerves, which originate from the back and run around the abdomen and chest. If this pattern is not appreciated, a mistaken impression of a spinal level may result. (*Note*: A level will only be found examining the front, not the back.) In the most extreme cases, sensory loss may develop over the top of the head due to degeneration of the distal trigeminal and cervical nerves.

Electrophysiology

Axonal polyneuropathies are associated with a characteristic pattern of nerve conduction results, provided the polyneuropathy has been present long enough for wallerian degeneration to have occurred (i.e., 3–9 days). In general, motor and sensory amplitudes decrease, with normal or only slightly slowed distal latencies, late responses, and conduction velocities. The changes are always more marked in the lower extremities, where the pathology is the greatest.

Likewise, evidence of axonal loss is found on needle EMG examination, more prominent distally than proximally, with the lower extremities more affected than the upper extremities. Of course, EMG findings are dependent on the length of time a polyneuropathy has been present. Denervation typically develops within weeks and reinnervation after weeks to months. Different patterns also develop depending on the tempo of the illness. If the process is relatively active and progressive, a combination of denervation and reinnervated motor unit action potentials (MUAPs) with decreased recruitment will be seen and again will be more prominent distally. In cases where the polyneuropathy is long-standing and only very slowly progressive, reinnervation may completely keep pace with denervation. In such cases, only reinnervated MUAPs with decreased recruitment will be seen distally, with little or no active denervation.

Most polyneuropathies have been present for several months or years before coming to evaluation. Accordingly, when a patient with an axonal polyneuropathy is first seen in the EMG laboratory, a combination of denervation and reinnervation is usually present.

Special Situations in Axonal Polyneuropathy: The Use of the Sural/Radial Amplitude Ratio in Mild Polyneuropathy

Nearly all axonal polyneuropathies are characterized by a distal pattern of abnormalities. Thus, the lower extremities are affected first and most prominently. Accordingly, the amplitude of the sural sensory study (normal or abnormal) takes on great significance in the EDX evaluation of most axonal polyneuropathies. However, interpretation of the sural amplitude has several limitations, especially in the following scenarios:

1. Younger individuals have much higher baseline sural amplitudes than older individuals. Thus, if a young patient had a sural amplitude of 30 μV, then developed an axonal polyneuropathy and the sural amplitude decreased to 15 μV, this value would still be considered normal in most EMG labs.
2. Older individuals may have low or difficult to obtain sural sensory responses at baseline. Thus, in an 80-year-old patient with numbness of the feet and a sural amplitude of 3 μV, it is difficult to know whether this value indicates a neuropathy or is simply consistent with age.
3. In obese individuals, the additional adipose tissue between the skin and the underlying nerve may result in an attenuation of the sensory nerve amplitude. Thus, in an obese patient with a sural amplitude of

5 μV, it may be difficulty to know if this value indicates a neuropathy or simply denotes a reduced amplitude from technical issues related to increased intervening adipose tissue in the lower leg.

In these situations, the use of the sural/radial amplitude ratio (SRAR) may be helpful. The SRAR is especially helpful in those patients with a "borderline normal" sural amplitude. The rationale for using the SRAR is straightforward: in a distal dying-back axonal neuropathy, the sural amplitude should be disproportionally affected compared to the radial amplitude. In the original description of this technique by Rutkove et al., a SRAR <0.40 had a specificity of 90% and a sensitivity of 90% in detecting an axonal polyneuropathy. In addition, the SRAR was less dependent on age than the sural amplitude alone, and also did not appear to be affected by body mass index (BMI). A latter study using a larger cohort of normal subjects suggested that a cutoff value of 0.4 may have been too high, and a more appropriate cutoff should be 0.21. Dropping the cutoff to 0.21 improved the specificity to 95% (i.e., reduced the number of false positives to under 5%).

Thus, the SRAR can be a useful adjunct in the EDX evaluation of axonal polyneuropathy. Of course, like all nerve conduction data, it relies on obtaining valid data. One needs to be sure that the amplitude of each nerve has been maximized and that the recording electrodes are optimally placed over each nerve. Moreover, in the rare situation wherein there is a superimposed sural or radial mononeuropathy, the SRAR cannot be considered valid for the electrodiagnosis of axonal polyneuropathy.

Special Situations in Axonal Polyneuropathy: Acute Presentation

The pattern of an acute or subacute axonal polyneuropathy is distinctly unusual. If the polyneuropathy is very acute (less than several weeks' duration) and denervation is not yet present, the only abnormality on needle EMG examination will be normal-appearing MUAPs with reduced recruitment. *However, this is the same pattern on needle EMG that occurs in an acute demyelinating polyneuropathy*. If an axonal polyneuropathy is subacute (more than several weeks but less than several months), active denervation will also be present. MUAPs again will be normal in morphology, but with reduced recruitment. These two patterns are very unusual in the EMG laboratory because very few polyneuropathies are acute or subacute, and of the ones that are acute/subacute, most are associated with demyelination and not axonal loss. Acute axonal polyneuropathies include those associated with porphyria or vasculitis and those rare cases of Guillain–Barré syndrome that are axonal and not demyelinating.

Special Situations in Axonal Polyneuropathy: Asymmetric Presentation

Nerve conduction studies and EMG are also used to assess the pattern of an axonal polyneuropathy. Nearly all axonal polyneuropathies are symmetric and distal. Any asymmetry is distinctly unusual and implies either (1) a mononeuropathy multiplex pattern or (2) a second superimposed process, such as an entrapment neuropathy or radiculopathy. Of course, patients with polyneuropathy of any kind are more susceptible to mononeuropathies at typical entrapment sites, especially median neuropathy at the wrist and ulnar neuropathy at the elbow. Any significant asymmetry found on nerve conduction studies and EMG that is not explained by an entrapment neuropathy or superimposed radiculopathy should seriously raise the possibility of an underlying mononeuropathy multiplex pattern and should lead one to consider the possibility of vasculitic polyneuropathy.

Special Situations in Axonal Polyneuropathy: Non-length-dependent Presentation

Like the finding of asymmetry, that of proximal more than distal abnormalities has important diagnostic significance in an axonal polyneuropathy. Proximal changes (e.g., paraspinal muscles, shoulder and hip girdle muscles) suggest a non-length-dependent pattern, implying either the possibility of porphyria, which characteristically affects shorter nerves first, or the combination of both peripheral nerve and nerve root pathology (i.e., a polyradiculoneuropathy). Diabetic neuropathy is the best example of a true polyradiculoneuropathy, showing abnormalities both distally and proximally.

Diabetes

In any discussion of axonal neuropathies, special mention should be made of diabetic neuropathy. Peripheral nervous system manifestations of diabetes are numerous and varied. Isolated mononeuropathies of cranial nerves (e.g., facial palsy), intercostal nerves (known as diabetic thoracoabdominal neuropathy), or peripheral nerves may occur. Several types of polyneuropathy may occur. The most common, a distal sensorimotor polyneuropathy, is a typical axonal polyneuropathy affecting both large and small sensory fibers. On EMG, however, findings of a polyradiculoneuropathy are usually present. Diabetic patients may also present with a pure autonomic polyneuropathy or a small-fiber sensory polyneuropathy, with distal burning and pain. If large sensory and motor fibers are spared, such patients will have completely normal electrodiagnostic studies. Other patients with diabetes will present with more proximal nerve syndromes, either at the root or plexus level, especially in the lower extremity (i.e., proximal diabetic neuropathy, diabetic amyotrophy, etc.). Large-fiber diabetic neuropathies usually demonstrate axonal changes on nerve conduction studies. Although most axonal polyneuropathies, *including those associated with diabetes*, have some secondary demyelination, the electrophysiologic criteria for primary demyelination are not met. Only in some cases of uremic polyneuropathy, especially when combined with diabetic polyneuropathy, do nerve conduction velocities slow sufficiently to approach or exceed the criteria set for demyelinative slowing.

BORDERLINE CASES: DIFFERENTIATION BETWEEN AXONAL AND DEMYELINATIVE SLOWING

Slowing of conduction velocity to less than 75% of the lower limit of normal is one of the fundamental electrodiagnostic criteria for establishing primary demyelination in polyneuropathy. When compound muscle action potential (CMAP) amplitudes are markedly reduced secondary to axonal loss, however, conduction velocity slowing may be seen secondary to severe axonal loss with dropout of the fastest-conducting fibers. It is in this situation, when distal CMAP amplitudes are low and conduction velocity slowing nears 75% of the lower limit of normal, that it may be difficult to differentiate between a primary demyelinating polyneuropathy and a severe axonal polyneuropathy.

In such cases, one useful technique is to compare conduction velocities recording a distal and a proximal muscle across the same segment of nerve. In the leg, the peroneal nerve is most useful for this study. Peroneal motor studies are performed stimulating below the fibular neck and at the lateral popliteal fossa and recording simultaneously from the extensor digitorum brevis (EDB), a distal muscle, and the tibialis anterior, a proximal muscle (Figure 26–6). Conduction velocities across this same segment of nerve are then compared.

In patients with demyelinating polyneuropathies, conduction velocities typically are slowed at both recording sites, with no difference between proximal and distal sites (Figure 26–7). In patients with axonal polyneuropathies, however, conduction velocities may be slowed recording the EDB but usually are normal or only mildly reduced when measured from the tibialis anterior. This distal-to-proximal gradient of conduction velocity slowing in axonal polyneuropathies may be very helpful in differentiating a primary demyelinating from axonal polyneuropathy, especially when the distal conduction velocities are near the cutoff value for demyelinative slowing.

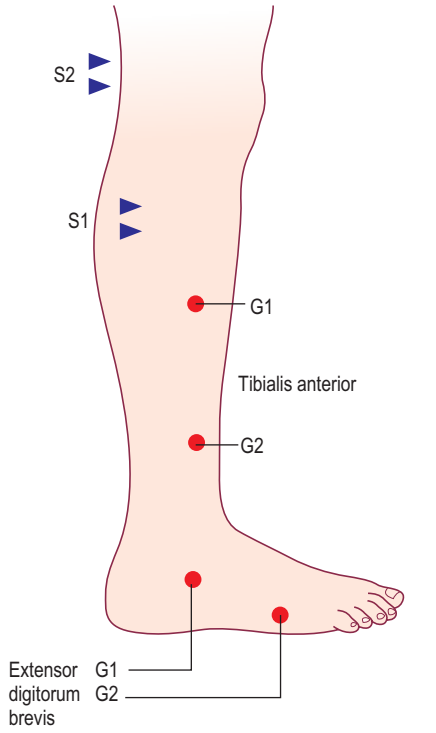


FIGURE 26–6 Recording proximal and distal muscles to differentiate axonal from demyelinative slowing. Co-recording a proximal and a distal muscle and comparing conduction velocities through the same segment of nerve may be helpful in differentiating axonal from demyelinative slowing in borderline cases. Here, recording electrodes are placed over the tibialis anterior and extensor digitorum brevis in the standard belly–tendon montage. The peroneal nerve is stimulated below the fibular neck and at the lateral popliteal fossa and conduction velocities computed across the same segment of nerve for the two recording sites.
(Reprinted with permission from Raynor, E.M., Ross, M.H., Shefner, J.M., et al., 1995. Differentiation between axonal and demyelinating neuropathies: identical segments recorded from proximal and distal muscles. Muscle Nerve 18, 402.)

DEMYELINATING POLYNEUROPATHY

For any patient with a polyneuropathy, the presence of demyelination as the primary pathology has special diagnostic significance. Nearly all polyneuropathies result in primary axonal loss, and any demyelination occurs as a secondary phenomenon. Few polyneuropathies are associated with demyelination as the primary pathologic process. Although demyelination usually is demonstrated most readily by nerve conduction studies and less often by nerve biopsy, several clinical clues may suggest primary demyelination:

- Global areflexia
- Hypertrophic nerves
- Moderate-to-severe muscle weakness with relative preservation of muscle bulk
- Motor symptoms and signs more prominent than sensory ones

On nerve conduction studies, disorders with primary demyelination are generally associated with markedly prolonged distal latencies (>130% of the upper limit of normal), markedly slowed conduction velocities (usually <75% of the lower limit of normal), and markedly prolonged or absent late responses (>130% of the upper limit of normal).

In addition, nerve conduction studies often can be used to distinguish between acquired and inherited demyelinating polyneuropathies. In a patient with an inherited condition, all myelin tends to be affected equally; thus, uniform slowing of conduction velocity occurs. Accordingly, nerve conduction studies usually are symmetric from side to side. In contrast, acquired conditions (e.g., Guillain–Barré syndrome, CIDP) are associated with patchy, often multifocal demyelination. As a result, asymmetry is found on nerve conduction studies (even in the face of clinical symmetry),

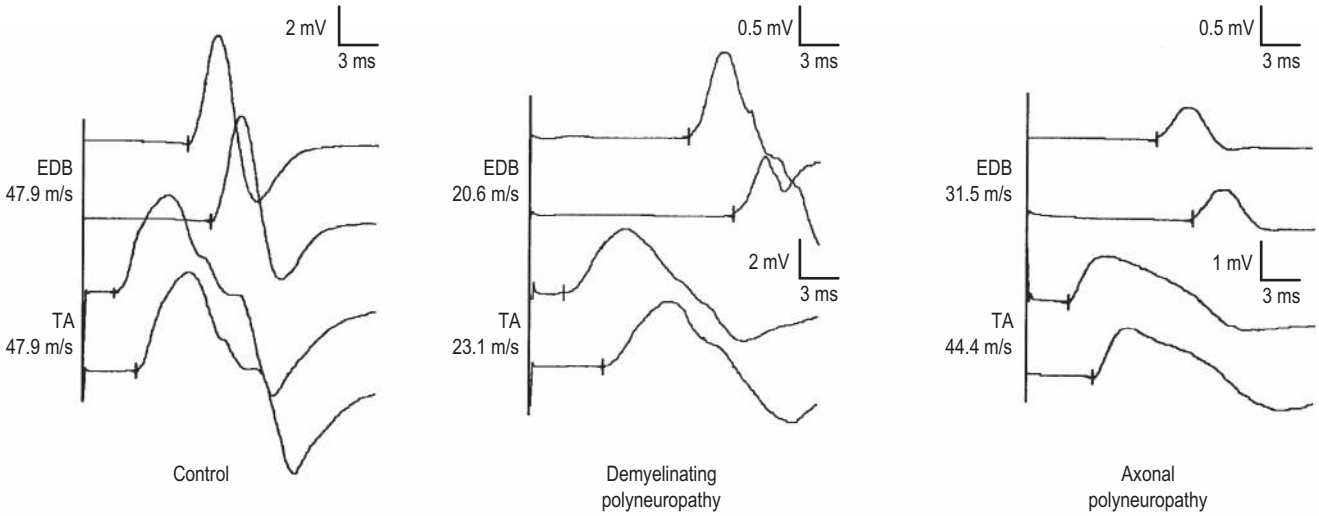
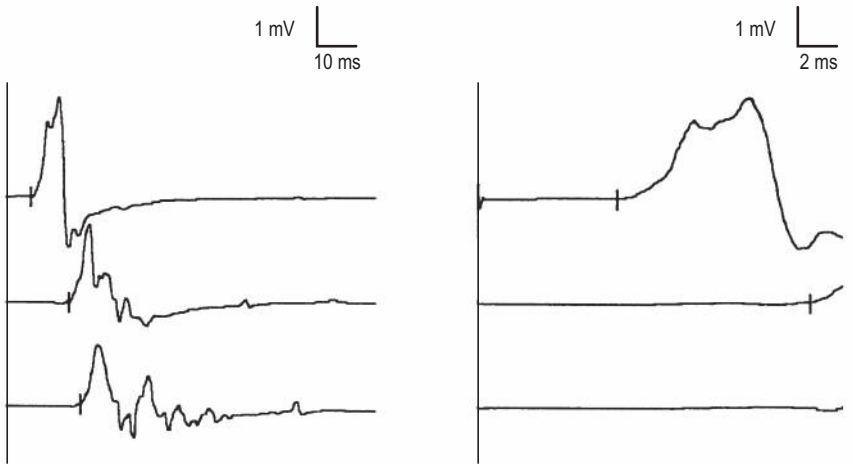


FIGURE 26–7 Proximal and distal recordings are used to differentiate demyelinative from axonal slowing. Conduction velocities below 75% of the lower limit of normal on nerve conduction studies usually imply primary demyelination. However, severe axonal polyneuropathies associated with loss of the faster fibers can approach this cutoff value, especially when distal compound muscle action potential amplitudes are very low. Comparing the conduction velocity across the same segment of nerve, recording proximal and distal muscles, can be useful in differentiating an axonal from a demyelinating polyneuropathy when conduction velocities are borderline. In normal individuals, there is no significant difference in conduction velocities when recording either the tibialis anterior (TA), a proximal muscle, or the extensor digitorum brevis (EDB), a distal muscle. In demyelinating polyneuropathies, there usually is marked slowing when recording both distal and proximal muscles. In severe axonal polyneuropathies associated with loss of the fastest axons, conduction velocity slowing may approach the cutoff in the leg value for demyelination (<30 m/s in the leg). However, conduction velocity usually is faster or normal when recording a more proximal muscle. This distal-to-proximal gradient of conduction velocity slowing and normalization of conduction velocity proximally are characteristic of axonal polyneuropathies.
(Reprinted with permission from Raynor, E.M., Ross, M.H., Shefner, J.M., et al., 1995. Differentiation between axonal and demyelinating neuropathies: identical segments recorded from proximal and distal muscles. Muscle Nerve 18, 402.)

FIGURE 26–8 Temporal dispersion in acquired demyelinating polyneuropathy. The presence of either conduction block or temporal dispersion marks a demyelinating polyneuropathy as acquired and not inherited. In the example shown here (stimulating the ulnar nerve at the wrist and below and above the elbow, recording the abductor digiti minimi muscle), there is marked temporal dispersion, at both the below-elbow and above-elbow sites. Note that when the sweep speed is set at 2 ms per division (routine setting), the proximal waveforms are off the screen.



along with evidence of conduction block and temporal dispersion. Conduction block and temporal dispersion at nonentrapment sites are key findings for differentiating acquired from inherited demyelinating polyneuropathies (Figure 26–8).

Guillain–Barré Syndrome (GBS)

Guillain–Barré syndrome is now most properly thought of as a syndrome that comprises several variants, with acute inflammatory demyelinating polyneuropathy (AIDP) being the most common in North America. GBS is an immune-mediated, rapidly progressive, predominantly motor polyneuropathy that often leads to bulbar and respiratory compromise. It is one of the most common of all neuromuscular emergencies. Although the overall prognosis is favorable in more than 80% of patients, the hospital course is frequently long, followed by a prolonged recuperation. Nerve conduction studies and EMG play an important role in the diagnosis of GBS because early recognition is necessary to begin appropriate treatment and avoid potential medical complications.

People of all ages can be affected, although GBS is most common in young adults. An antecedent event, often an upper respiratory infection or gastroenteritis, is found in approximately 60% of patients. Precipitating factors include campylobacter, cytomegalovirus, Epstein–Barr virus, and HIV infection, as well as vaccination, surgery, trauma, and malignancy (especially lymphoma).

Clinical

The classic presentation of GBS is a rapidly ascending paralysis. Many variants have also been seen, including proximal weakness, descending weakness, and the Miller–Fisher variant (ophthalmoplegia, ataxia, and areflexia). Early in the course, patients may complain of a sense of imbalance or poor coordination during walking. It is not unusual for a patient to be sent home from the emergency department with very mild gait ataxia as the only sign, only to return the next day with rapidly progressing weakness. Sensory symptoms with little objective sensory loss are common. Distal paresthesias in the fingers and toes typically are present simultaneously (an unusual finding in other polyneuropathies). A sensory level is not found. Hyporeflexia or areflexia develops early. Any weak limb with preserved reflexes should call the diagnosis of GBS into question. Bifacial weakness occurs in 50% of patients. Bulbar weakness with dysarthria and dysphagia are also frequent. Other cranial neuropathies are uncommon. Back and radicular pain occur in up to 25% of patients and may require narcotics. Autonomic dysfunction can occur. A fixed resting tachycardia is very common. Ileus, transient bladder dysfunction, arrhythmia, labile blood pressure, the syndrome of inappropriate secretion of antidiuretic hormone, and impaired thermoregulation can occur.

Most patients continue to progress for days to weeks and then experience a plateau before recovery commences. Intubation is required in one third of patients, usually between days 6 and 18. Progression beyond 4 weeks is rare for any patient with GBS.

Electrophysiology

During the first few days of the illness, all nerve conduction studies may be normal. The first changes in AIDP are often delayed, absent, or impersistent F and H responses, reflecting proximal demyelination. Indeed, pathologically, AIDP often starts at the root level as a polyradiculopathy. Later, routine motor nerve conduction studies show prolonged distal latencies, along with other evidence of segmental demyelination, especially conduction block and temporal dispersion. These changes are present in 50% of patients by 2 weeks and in 85% by 3 weeks. There is, however, a wide range of progression. Some patients have inexcitable nerves early on, due to either secondary wallerian degeneration or presumed distal demyelination. Notably, 10% of patients never fulfill criteria for acquired demyelination, sometimes because motor responses are absent. Although GBS is most often a demyelinating polyneuropathy in the form of AIDP, rare cases are associated with a similar clinical presentation but show axonal changes on nerve conduction studies. If the syndrome is pure motor and axonal, it is known as *acute motor axonal neuropathy* (AMAN). If both motor and sensory fibers are involved, the designation *acute motor sensory axonal neuropathy* (AMSAN) is used. Especially in the latter case, it is essential that these patients are screened for porphyria, which is another cause of a severe, acute axonal polyneuropathy.

To demonstrate segmental demyelination on motor nerve conduction studies, a combination of conduction block or temporal dispersion, or marked slowing of distal latencies, conduction velocities, or late responses must be seen. For acute polyneuropathies, the electrophysiologic criteria for segmental demyelination often are liberalized (Box 26–5).

Although almost 90% of patients will have motor abnormalities during the first few weeks, far fewer will have sensory nerve conduction abnormalities. Characteristically, sensory studies are normal early on. Later in the first week or two, sensory studies may show so-called *sural sparing* (i.e., the sural sensory response is normal whereas the median and ulnar sensory potentials are reduced or absent). This pattern is very unusual in the typical axonal, dying-back polyneuropathy. Many believe that sural sparing in the presence of a typical clinical picture is virtually diagnostic of AIDP. Why sural sparing occurs is not completely known, but it is likely related to the preferential, early involvement of the smaller myelinated fibers in AIDP. Although it is not intuitively obvious, the recorded sural sensory fibers are actually larger, and accordingly have more myelin, than the

Box 26–5. Electrophysiologic Criteria for Acute Demyelinating Polyneuropathy

Demonstrate at least three of the following in motor nerves:

1. Prolonged DLs (two or more nerves, not at entrapment sites)
   - DL >115% ULN (for normal CMAP amplitudes)
   - DL >125% ULN (for CMAP amplitudes <LLN)
2. CV slowing (two or more nerves, not across entrapment sites)
   - CV <90% LLN (for CMAP amplitudes >50% LLN)
   - CV <80% LLN (for CMAP amplitudes <50% LLN)
   - (*Note*: CVs are commonly preserved early in the course of acute inflammatory demyelinating polyneuropathy.)
3. Prolonged late responses: F response and H reflexes (one or more nerves)
   - >125% ULN
   - (*Note*: If distal CMAP amplitude is very low, absent F waves may not be abnormal.)
4. Conduction block/temporal dispersion (one or more nerves)
   - Unequivocal conduction block: Proximal/distal CMAP area ratio <0.50
   - Possible conduction block: Proximal/distal CMAP amplitude ratio <0.70
   - Temporal dispersion: Proximal/distal CMAP duration ratio >1.15

CMAP, compound muscle action potential; CV, conduction velocity; DL, distal latency; LLN, lower limit of normal; ULN, upper limit of normal.
Source: Adapted from Albers, J.W., Kelly, J.J., 1989. Acquired inflammatory demyelinating polyneuropathies: clinical and electrodiagnostic features. Muscle Nerve 12, 435. Reprinted by permission of John Wiley & Sons, Inc.

median and ulnar sensory fibers. The routine median and ulnar sensory potentials are recorded distally over the fingers, where the nerve diameters are more tapered than those of the sural nerve. The sural nerve actually has larger-diameter myelinated fibers where it is stimulated and recorded in the lower calf. These larger-diameter fibers presumably are relatively more resistant to the early inflammatory, demyelinating attack.

The needle EMG in early AIDP reveals the characteristic demyelinating pattern: no denervation, normal MUAP morphology, but with reduced recruitment in weak muscles. Exceptionally, somewhat larger MUAPs may be seen in early AIDP. These MUAPs are not reinnervated but occur for the same reason as does sural sparing: smaller myelinated fibers are affected first in AIDP. Thus, the normal, smaller MUAPs are blocked first because they are innervated by smaller-diameter, myelinated fibers. The normal, larger MUAPs may then be the only remaining, unblocked MUAPs. These larger MUAPs usually are not seen as individual potentials during the routine needle EMG examination. Because they are recruited last, usually with maximal contraction, they normally are buried in the interference pattern. With the smaller MUAPs blocked, however, these longer MUAPs are "uncovered" and more easily seen.

Early in the course of AIDP, there is usually no abnormal spontaneous activity at rest. The only exception may be the presence of occasional myokymic discharges. Myokymic discharges may be seen in the limbs, and especially in the face, even in the absence of clinical myokymia.

Despite the fact that AIDP has a predominantly demyelinating pathophysiology, there is always some secondary axonal loss. This leads to fibrillation potentials on needle EMG, usually developing within 2 to 5 weeks and becoming maximal at 6 to 10 weeks. Interestingly, fibrillation potentials are equally common in distal and proximal muscles, a finding that likely represents the random multifocal pathology. Fibrillation potentials may then persist for many months. After denervation, MUAPs can become more polyphasic (usually in the fourth week), followed by an increase in their amplitude and duration.

Although nerve conduction studies and EMG are principally used for diagnosis, they also are helpful in assessing prognosis. The best predictor of prognosis is the distal CMAP amplitude. Low distal CMAP amplitudes (<20% of the lower limit of normal at 3–5 weeks) are the best single predictor of a poor outcome or prolonged course. Other nerve conduction and EMG data (including the amount of fibrillation potentials) actually correlate quite poorly with prognosis. Indeed, some patients have nerve conduction results that appear to worsen despite clinical improvement. This likely represents the early recovery of fibers that previously were blocked and now are able to conduct, albeit very slowly.

Chronic Demyelinating Polyneuropathy

When a patient with a chronic polyneuropathy is found to have evidence of a primary demyelinating process on nerve conduction studies (Box 26–6), the differential diagnosis narrows considerably. However, some of the disorders that might be considered in the differential diagnosis (Box 26–4) are associated with other prominent symptoms outside of the peripheral nervous system, some of which involve the central nervous system or have an onset in early childhood. From a practical point of view, the differential diagnosis of an isolated chronic demyelinating polyneuropathy in an adult without central nervous system or systemic findings likely is limited to either an inherited polyneuropathy (most often CMT type 1A), or CIDP or one of its variants. Nerve conduction studies can often differentiate among these conditions.

Box 26–6. Electrophysiologic Criteria for Chronic Demyelinating Polyneuropathy

Demonstrate at least three of the following in motor nerves:

1. Prolonged DLs (two or more nerves, not at entrapment sites)
   DL >130% ULN
2. CV slowing (two or more nerves, not across entrapment sites)
   CV <75% LLN
3. Prolonged late responses: F response and H reflexes (one or more nerves)
   >130% ULN
   (*Note*: If distal CMAP amplitude is very low, absent F waves may not be abnormal.)
4. Conduction block/temporal dispersion (one or more nerves)
   Unequivocal conduction block: Proximal/distal CMAP area ratio <0.50
   Possible conduction block: proximal/distal CMAP amplitude ratio <0.70
   Temporal dispersion: proximal/distal CMAP duration ratio >1.15

(*Note*: These criteria are modified for inherited demyelinating polyneuropathy. At least two of the first three need to be demonstrated. Conduction block/temporal dispersion does not occur in inherited demyelinating polyneuropathies. One exception to this "rule" occurs in the severe demyelinating neuropathy of infancy and early childhood. This neuropathy was historically known in the literature as Dejerine–Sottas syndrome or HMSN-III. In these patients, the neuropathy is associated with such profound conduction velocity slowing (typically <10 m/s), there is often prominent temporal dispersion and phase cancellation resulting in dispersed, lower amplitude waveforms with proximal stimulation; however, the area does not drop >50% between distal and proximal stimulation sites.)

CMAP, compound muscle action potential; CV, conduction velocity; DL, distal latency; LLN, lower limit of normal; ULN, upper limit of normal.
Source: Adapted from Albers, J.W., Kelly, J.J., 1989. Acquired inflammatory demyelinating polyneuropathies: clinical and electrodiagnostic features. Muscle Nerve 12 (6), 435–451. Reprinted by permission of John Wiley & Sons, Inc.

Charcot–Marie–Tooth Neuropathy

Charcot–Marie–Tooth (CMT) is a group of inherited neuropathies that is comprised of several major types (CMT1, CMT2, CMT4, and CMTX) based on inheritance pattern (dominant, recessive, or X-linked) and whether the primary pathology is located in the myelin or axon. Each of these

CMT types are further divided based on their specific molecular and genetic findings. More than 40 different genes and loci associated with CMT have been identified. The most common type is CMT1, which accounts for approximately 40–50% of all patients with CMT. CMT1 comprises a group of demyelinating neuropathies, are among the most common demyelinating neuropathies seen in the EMG laboratory, and are by far the most common inherited demyelinating neuropathies. In the past, CMT1 was referred to in the literature as hereditary motor sensory neuropathy type I (HMSN-I), peroneal muscular atrophy, and hypertrophic or onion-bulb neuropathy of childhood. CMTX comprises a group of X-linked demyelinating neuropathies that account for approximately 10–15% of CMT cases. Rarely, females present with milder symptoms. Lastly, CMT4 encompasses a group of autosomal recessive demyelinating neuropathies which are extremely rare and unlikely to be encountered clinically.

Clinical

CMT is a slowly progressive, distal, motor more than sensory, neuropathy associated with pes cavus and hammer toes. Scoliosis and other skeletal deformities occur in some patients. The demyelinating types are CMT1, CMT4, and CMTX and may be associated with hypertrophic nerves. Sensory symptoms are uncommon, although mild sensory signs are usually discovered through careful examination. There are no cranial nerve signs in the more common CMT1 and CMTX phenotypes. CMT predominantly affects the intrinsic foot and lower leg anterior compartment musculature resulting in the typical appearance of distal leg wasting. The distal weakness results in prominent foot drops and a steppage gait. Later, the impairment spreads to the distal thighs and intrinsic hand muscles. Claw hands may develop. Ankle reflexes are always absent, and, in well-established cases, all reflexes are unobtainable. The onset is commonly in early childhood, typically presenting as a foot deformity or delay in achievement of motor milestones. Other patients may present in the first decades of life. Some patients are affected so minimally, however, that they may not come to medical attention until middle age or later.

Genetics

The genetics of the demyelinating CMT types are heterogeneous. In CMT1, the inheritance is autosomal dominant. At present, there are six subtypes of CMT1 (CMT1A, 1B, 1C, 1D, 1E, and 1F). The most common form is CMT1A which accounts for approximately 70–80% of all CMT1 cases. The genetic defect is a duplication error of a 1.5-megabase DNA region at chromosome 17p11.2. This region contains the peripheral myelin protein gene *PMP22* (this is the same gene location at which a deletion error results in hereditary neuropathy with liability to pressure palsies). Isolated patients without any family history have been found to have the same duplication, implying that some cases may be due to a *de novo* mutation. The second most common CMT1 is CMT1B which accounts for appropriately 10% of CMT1 cases. CMT1B is caused by a point mutation in the myelin protein zero (*MPZ*) gene on chromosome 1. The other CMT1 subtypes are extremely rare, each representing less than 1% of CMT1. While phenotypic differences between families with CMT1A and CMT1B is small, among large groups, patients with CMTIB are found to be more severely affected than patients with type IA, and have slower conduction velocities. DNA testing for the common CMT1 subtypes is widely commercially available.

CMT4, the autosomal recessive demyelinating type, is very rare. In contrast, CMTX, the X-linked form, is more common and occasionally seen in the EMG laboratory. The genetic defect in the most common form of CMTX, CMTX1, is a mutation of the gap-junction protein 1 gene (*GJB1*) which codes for connexin-32. Connexin-32 is important in forming the gap junctions in myelin at the paranodal regions.

Pathology and Imaging

The cerebrospinal fluid protein level is elevated in more than half of all patients with the demyelinating forms of CMT. Pathology of peripheral nerve shows segmental demyelination and Schwann cell proliferation with onion-bulb formation. Unmyelinated fibers are not affected. Imaging of the lumbar spine may show enlargement of the lumbosacral nerve roots and, in exceptional cases, may result in spinal stenosis.

Prognosis

The prognosis in many cases is relatively benign. Although rare patients eventually may require a wheelchair, most remain ambulatory with the use of simple bracing and have little impairment of functional strength.

Electrophysiology

In the demyelinating CMT neuropathies, nerve conduction studies show marked slowing of conduction velocity, usually below 75% of the lower limit of normal. Slowing is uniform in all nerves, without evidence of temporal dispersion or conduction block. Motor responses may be very low or absent in the lower extremities. In nearly all cases, slowing can be demonstrated in the upper extremities (median motor conduction velocity <38 m/s). Most patients with CMT1A have conduction velocities in the range of 20–25 m/s in the upper extremities. Patients with CMT1B, however, often have even slower velocities, in the range of 15 m/s or slower. In contrast, males with CMTX may have conduction velocities that are somewhat faster (e.g., 25–38 m/s). In females with CMTX, some may have a peripheral neuropathy clinically, but the conduction velocities are only slightly slow or are in the normal range.

There often is little correlation between the degree of slowing and the clinical symptoms. Maximal slowing evolves during the first 3 to 5 years, after which there is little change. Slowing has been documented in patients as young as 6 months. Distal latencies may increase during the first 10 years. Sensory studies are usually abnormal and

generally show low or absent amplitudes. As in most demyelinating polyneuropathies, there is some secondary axonal loss. Indeed, it is the secondary axonal loss that leads to the weakness and disability. Accordingly, EMG typically shows evidence of distal reinnervation, often with little spontaneous activity. Nerve conduction studies are extremely helpful in early diagnosis. Indeed, if a patient who is tested at several months of age or older has no clinical signs of CMT and normal conduction velocities, the diagnosis of a demyelinating form of CMT is essentially excluded.

Chronic Inflammatory Demyelinating Polyneuropathy

Clinical

CIDP is an acquired, demyelinating, motor and sensory neuropathy that is presumed to be immune mediated. All ages can be affected, but most patients present in their fifth to sixth decade. Both proximal and distal muscles are affected, and the clinical presentation is usually symmetric. The time course in CIDP is longer than AIDP (>6 weeks) and may follow a monophasic progression, a stepwise progression, or a relapsing and remitting course. Early in the illness, it may be impossible to differentiate AIDP from the initial presentation of CIDP. Patients with CIDP generally progress slowly (over weeks to months), with the major disability usually a gait disturbance. Areflexia or hyporeflexia is the rule. Large-fiber sensory loss (touch, vibration, position sense) is more common than small-fiber loss (pain, temperature). A Romberg sign is commonly present. Tremor may also be seen, especially in the upper extremities. Significant bulbar or respiratory weakness is unusual.

Etiology

CIDP may be idiopathic or may occur in association with HIV infection, osteosclerotic myeloma, Waldenström macroglobulinemia, lymphoma, monoclonal gammopathy of undetermined significance, or antibodies to myelin-associated glycoprotein (MAG). Therefore, all patients should undergo blood tests, including serum protein electrophoresis, immunoelectrophoresis, and tests for antibodies to MAG and HIV. Patients should undergo a skeletal survey to look for osteosclerotic myeloma and any patient who is found to have a monoclonal protein, should have further hematologic evaluation to identify a possible plasma cell dyscrasia.

Pathology

Cerebrospinal fluid studies commonly reveal protein elevation in the absence of a pleocytosis (except in HIV-associated CIDP, where a lymphocytic pleocytosis is common). Pathologic examination may demonstrate segmental demyelination with perivascular or diffuse mononuclear infiltration of nerve, without vasculitis, although many biopsies show nonspecific changes.

Prognosis

CIDP is an important diagnosis to recognize because patients may improve with plasma exchange, intravenous immunoglobulin (IVIG), or immunosuppressive therapy. Idiopathic CIDP may respond to prednisone, azathioprine (Imuran®), mycophenolate mofetil (CellCept®), cyclophosphamide (Cytoxan®), cyclosporine, or plasma exchange. In CIDP associated with monoclonal immunoglobulin M (IgM) antibodies, rituximab (Rituxan®) may be helpful. In patients whose CIDP is associated with osteosclerotic myeloma, surgery or radiation therapy directed at the plasmacytoma may result in improvement of the neuropathy.

Electrophysiology

On nerve conduction studies and EMG, CIDP is a chronic demyelinating polyneuropathy with secondary axonal features. Evidence of primary demyelination is present, with markedly prolonged distal latencies (>130% of the upper limit of normal), markedly slowed conduction velocities (<75% of the lower limit of normal), and markedly prolonged or absent late responses (>130% of the upper limit of normal). Because CIDP usually is a multifocal process affecting different segments of nerve differently, nerve conduction abnormalities often are asymmetric, despite the symmetric clinical presentation. Most importantly, there is usually conduction block, temporal dispersion, or both, marking the polyneuropathy as acquired.

Secondary axonal changes are the rule. Distal CMAP and sensory nerve action potential (SNAP) amplitudes are reduced, usually more markedly in the lower extremities. Needle EMG shows evidence of chronic and ongoing axonal loss with the typical neuropathic pattern: fibrillation potentials and long, large, polyphasic MUAPs with reduced recruitment. Because CIDP is actually a polyradiculoneuropathy, changes are often also seen in proximal muscles, including the paraspinal muscles.

Idiopathic CIDP and its variants usually display similar findings on nerve conduction studies and EMG. The only exceptions are multifocal motor neuropathy with conduction block (MMNCB, discussed in the following section) and some cases of anti-MAG polyneuropathy. Anti-MAG CIDP typically is a very slowly progressive, predominantly sensory polyneuropathy and is more common in older patients, especially men. Patients usually present with gait ataxia and marked large-fiber sensory loss. Some patients have a prominent action tremor. Although electrical studies demonstrate an acquired, demyelinating, motor and sensory polyneuropathy, often the most prominent change is markedly prolonged distal latencies (sometimes referred to as a distal myelinopathy). Anti-MAG polyneuropathy should be considered in any patient with a demyelinating polyneuropathy, especially when the distal latencies are prolonged out of proportion to the other abnormalities. Most anti-MAG polyneuropathies are associated with an IgM monoclonal protein.

Multifocal Motor Neuropathy with Conduction Block

In the early 1990s, attention was brought to patients with pure motor neuropathies, often associated with antiganglioside antibodies (especially anti-GM_1). A monoclonal protein was not present. These patients presented with a pure lower motor neuron syndrome, clinically similar to the progressive muscular atrophy variant of amyotrophic lateral sclerosis (ALS). However, their electrophysiologic studies

showed evidence of an acquired segmental demyelinating neuropathy with conduction block along motor nerves, similar to CIDP, although sensory nerves were minimally affected or completely spared. It was unclear whether these patients were a variant of CIDP or represented a unique syndrome. The recognition of this disorder, multifocal motor neuropathy with conduction block (MMNCB), now has important therapeutic and prognostic implications because most of these patients are treated successfully with intravenous immunoglobulin; cyclophosphamide or rituximab therapy have been used successfully in some refractory cases. It often falls to the electromyographer to make the differentiation between ALS, which usually is fatal, and MMNCB, which responds to immunomodulation.

Clinical

Patients with MMNCB present with progressive, asymmetric weakness and wasting, often affecting the distal upper extremity muscles first. Most patients are younger than 50 years, which is younger than patients with typical ALS. Males are more commonly affected than females. In some cases, it may be possible to detect weakness in the distribution of named motor nerves with sparing of other nerves in the same myotome (clinical multifocal motor neuropathy). This pattern is not seen in ALS or its progressive muscular atrophy variant, in which the entire myotome is characteristically affected at the same time. Occasional patients will have prominent weakness but without wasting, a finding usually associated with pure demyelination. Definite upper motor neuron signs are always absent, although retained or inappropriately brisk reflexes for the degree of weakness and wasting may be seen. Bulbar function and sensation are characteristically spared, although mild or transient sensory symptoms may be present.

Many believe that this disorder is a variant of CIDP. However, the asymmetry, upper extremity predominance, relative absence of sensory findings, and typical lack of response to prednisone all suggest the possibility of a unique disorder that differs from the usual presentation of CIDP.

Electrophysiology

Findings on motor nerve conduction studies in MMNCB often are similar to those seen in CIDP. There may be evidence of demyelinative slowing, including markedly prolonged latencies, slowed conduction velocities, and prolonged late responses. *The characteristic finding, however, is that of conduction block, temporal dispersion, or both, along the motor nerves*.

The precise electrophysiologic definition of conduction block remains controversial (see Chapter 3), and much of the interest in defining conduction block is due to this disorder. From results of computer simulation models, a drop in proximal CMAP area of more than 50% always signifies conduction block and cannot be explained by temporal dispersion alone. However, any abrupt drop in CMAP area or amplitude, especially over a short segment, usually signifies conduction block. Of course, conduction block across a known entrapment site (e.g., ulnar nerve at the elbow, peroneal nerve at the fibular neck) cannot be used to diagnose MMNCB or any other acquired demyelinating polyneuropathy.

Because MMNCB is potentially treatable and ALS is usually fatal, an exhaustive search for conduction blocks often is undertaken. Although such testing is worthwhile, it should be done only in patients with predominantly lower motor symptoms and signs. Patients with MMNCB do not have unequivocal upper motor signs (i.e., spasticity, extensor plantar responses, pathologic hyperreflexia) or bulbar dysfunction. Even if strict criteria for conduction block are not met, any markedly slowed conduction velocity or distal latency (excluding entrapment sites and recording from nerves where the recorded muscle is severely atrophic), or markedly prolonged F responses, should seriously put into question the diagnosis of ALS. Electrophysiologic evidence of demyelination does not occur in ALS.

In the search for conduction block, more proximal segments of nerve may be studied (e.g., stimulating axilla, Erb's point, cervical roots). In exceptional cases, conduction blocks may be demonstrated only proximally. However, conduction blocks in MMNCB typically are present distally in the routine segments of nerve usually studied. One must always remember that with proximal stimulation, technical problems become more marked, especially the problem of ensuring supramaximal stimulation. If supramaximal stimulation is not achieved proximally, a mistaken impression of a conduction block may occur. In addition, the normal effects of temporal dispersion become more marked when longer distances are studied. When patients with ALS are studied proximally, some drop in amplitude and area may occur, but a drop in area of more than 50% is never seen. Last, stimulation of proximal segments also carries the inherent problem of co-stimulation of adjacent nerves. This is especially true for the median and ulnar nerves, where collision studies are needed to exclude the contribution to the CMAP from proximal stimulation of adjacent nerves (see Chapter 30).

In MMNCB, sensory studies are usually completely normal (though mild sensory abnormalities have been seen). Indeed, sensory studies usually are normal, even if performed across the same segment of nerve where a motor conduction block is present (Figure 26–9). Of course, any sensory abnormalities should also put into question the diagnosis of ALS, unless there is a known secondary process resulting in a superimposed polyneuropathy.

Needle EMG findings characteristically show decreased recruitment of MUAPs in weak muscles as a result of proximal conduction blocks. As in CIDP, secondary axonal changes are not unusual; denervating potentials and reinnervated MUAPs are present in most patients.

ELECTROPHYSIOLOGIC EVALUATION OF POLYNEUROPATHY

The electrophysiologic evaluation of a polyneuropathy varies with its severity. In general, nerve conduction studies and EMG should progress from distal to proximal (from

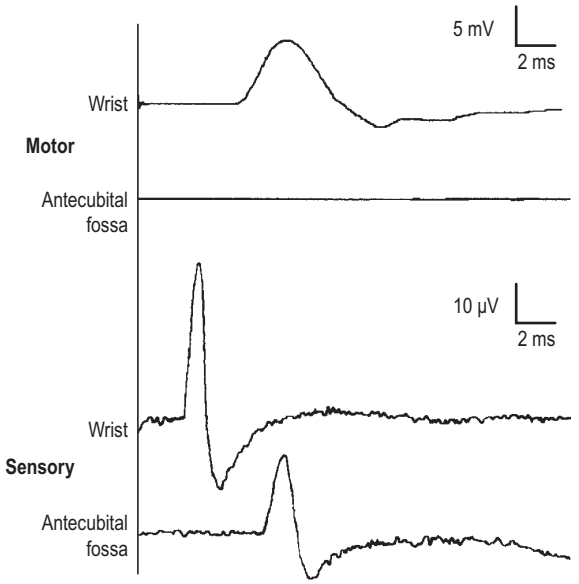


FIGURE 26–9 Motor conduction block in multifocal motor neuropathy with conduction block (MMNCB). Patients with MMNCB characteristically display conduction block of motor fibers, but often with complete sparing of sensory fibers, even through the same segment of nerve. Shown here are results of median nerve conduction studies in a patient with MMNCB, with the wrist and antecubital fossa stimulated and the abductor pollicis brevis muscle **(top)** for motor studies and the index finger **(bottom)** for sensory studies co-recorded. Note the complete block of motor conduction with intact sensory conduction. The amount of amplitude drop in the proximal sensory potential is within the normal range expected for the effects of normal temporal dispersion and phase cancellation for sensory potentials.

longer to shorter) nerves. In severe polyneuropathies, all responses may be absent distally in the lower extremities; in such cases nerve conduction studies must rely on the upper extremities. Testing should continue proximally from the lower to the upper extremities until normal or minimally affected nerves/muscles are encountered. As mentioned earlier, the goal of the electrophysiologic study is to confirm the presence of a polyneuropathy; assess its pattern and severity; determine whether motor, sensory, or a combination of fibers are involved; and, most importantly, assess whether the underlying pathology is primarily axonal loss or demyelination.

Nerve Conduction Studies

Nerve conduction studies should begin with motor conduction studies in a lower extremity (Box 26–7). The routine peroneal and tibial motor studies are performed along with their F responses. If motor responses are absent recording the usual distal muscles (i.e., EDB, abductor hallucis brevis), peroneal motor studies can be performed using the tibialis anterior, a more proximal muscle, for recording. Likewise, tibial motor studies can be performed proximally recording the soleus, using the same montage as for the H reflex. (*Note*: In this situation, only one stimulation site [i.e., the popliteal fossa] is possible; thus, an amplitude and distal latency can be obtained, but not a conduction

Box 26–7. Recommended Nerve Conduction Study Protocol for Polyneuropathy

Routine motor conduction studies:

1. Peroneal study, recording extensor digitorum brevis and stimulating ankle, below fibular neck, and lateral popliteal fossa
2. Tibial study, recording abductor hallucis brevis and stimulating ankle and popliteal fossa
3. Median study, recording abductor pollicis brevis and stimulating wrist and antecubital fossa
4. Ulnar study, recording abductor digiti minimi and stimulating wrist and below and above elbow

Routine sensory studies:

1. Sural SNAP, stimulating calf and recording posterior ankle
2. Median SNAP, stimulating wrist and recording digit 2
3. Ulnar SNAP, stimulating wrist and recording digit 5
4. Radial SNAP, stimulating forearm and recording snuffbox

Late responses:

1. F responses: median, ulnar, peroneal, and tibial
2. Soleus H reflexes

Special considerations:

- All of the above studies are performed on one side. In addition, in each extremity on the contralateral side, one motor and sensory study should be performed to assess symmetry. If there is a clinical suggestion of asymmetry, more nerves on the contralateral side should be studied.
- The yield of demonstrating conduction block and other evidence of demyelination increases as additional motor nerves or segments are studied. In selected patients, either the contralateral routine motor nerves can be studied or proximal stimulation studies can be performed.
- In borderline cases, comparing the ratio of the maximal radial sensory amplitude to the maximal sural sensory amplitude can be helpful. A ratio <0.21 is supportive of the electrical diagnosis of an axonal polyneuropathy.

SNAP, sensory nerve action potential.

velocity.) After the motor studies are completed in a lower extremity, one should obtain a lower extremity sensory response, either the sural or superficial peroneal, and often both. Averaging may be required, especially in polyneuropathy, where the responses may be very small. At least one motor and one sensory nerve conduction study should be performed in the contralateral leg to assess symmetry. In general, amplitude differences of more than 50% comparing side to side are considered abnormal (i.e., a 50% drop from the higher side to the lower; or a 100% increase from the lower side to the higher). Finally, in the lower extremities, the soleus H reflex can be performed. In most polyneuropathies where the ankle reflex is absent, so too is the H reflex, so the study adds little additional information. The H reflex, however, is more helpful in the assessment of very early polyneuropathies. Mild prolongation of the H reflex latency may be one of the first abnormalities seen in mild or early polyneuropathy.

After the lower extremity studies, an upper extremity is conducted. If only the lower extremities are studied, any abnormalities found could be just as consistent with the diagnosis of lumbosacral plexopathies as with that of polyneuropathy. In the upper extremity, median and ulnar motor conduction studies are performed first, with their F

responses. Their respective sensory studies are performed next. In axonal polyneuropathy, the median and ulnar sensory responses, although abnormal, usually are better preserved than the sural and superficial peroneal responses in the legs. Of course, one must ensure that these sensory responses are not abnormal secondary to a local entrapment neuropathy. In this regard, measuring the radial sensory response often is helpful, being much less commonly involved in entrapment neuropathy. Comparing the maximal radial sensory amplitude to the maximal sural amplitude can be especially useful (see discussion of the SRAR above). Any ratio <0.21 is supportive of the diagnosis of an axonal polyneuropathy. As with the lower extremities, comparison of one motor and sensory nerve from side to side should be performed to assess symmetry. If there is a clear clinical asymmetry, comparison of more nerves is indicated.

When looking for conduction block and other electrophysiologic evidence of demyelination, it is often worthwhile to study additional nerves. The formal criteria for a demyelinating polyneuropathy are based on finding a number of different abnormalities (Boxes 26-5 and 26-6). If these criteria are only partially met, a more extensive search is warranted to try to secure the electrodiagnosis of a demyelinating neuropathy.

Electromyographic Approach

The EMG strategy in polyneuropathy (Box 26–8) is similar to that of the nerve conduction studies. Distal and proximal muscles of at least one upper and lower extremity must be sampled. In polyneuropathy, there is a characteristic distal-to-proximal gradient of neuropathic changes (lower extremity more affected than upper extremity; legs more affected than thighs; hands more affected than arms). It is very unusual for any polyneuropathy to affect the gluteal muscles or the muscles of the upper arm and shoulder girdle. Important exceptions to this include AIDP, which is a polyradiculoneuropathy, as well as other neuropathies with a proximal predominance, including porphyria and some diabetic neuropathies. As in the nerve conduction studies, it is worthwhile to compare a contralateral muscle in each limb to assess symmetry. In cases in which there is a clinical suggestion of asymmetry, more muscles should be sampled, especially in the distribution of the asymmetry.

Although the intrinsic foot muscles are the most distal muscles, they are best avoided in the EMG evaluation of polyneuropathy. First, examination of these muscles is often painful for most patients to tolerate. Second, activation of these muscles is usually difficult or nearly impossible (especially the tibial-innervated foot muscles), making any assessment of MUAPs difficult. Finally and most importantly, some denervation and reinnervation are commonly found in normal patients, especially in the EDB muscle. Presumably, repetitive trauma over time from shoes, walking, and running injures the distal nerves in the feet. Any EMG abnormality in those muscles must always be interpreted with caution and compared from side to side. In general, the best distal muscles to sample are those in the lower calf, especially the extensor hallucis longus and flexor digitorum longus.

For evaluation of polyneuropathy, the needle EMG is clearly the more sensitive part of the electrophysiologic study. Although the typical polyneuropathy shows distal abnormalities on both nerve conduction studies and EMG, in some mild polyneuropathies the only abnormal findings may be those present on the EMG. The loss of only a few axons may result in fibrillation potentials that are easily seen on the EMG but may cause little appreciable change on the motor and sensory nerve conduction studies. To emphasize this point, take the example of mild neuropathy wherein 10% of the fibers have been lost. A sural sensory amplitude that had been 20 μV drops to 18 μV (normal >6 μV), and a tibial motor amplitude that had been 10 mV drops to 9 mV (normal >4 mV). Thus, the nerve conduction studies still are interpreted as "normal." However, within the extensor hallucis longus muscle, there may be 200 motor units (i.e., 200 axons). Each motor unit may be composed of 50 muscle fibers. Thus, if 10% of the fibers are lost (20 axons), 20 × 50 = 1000 muscle fibers will be fibrillating and easily appreciated on needle EMG.

Box 26–8. Recommended Electromyography Protocol for Polyneuropathy

Lower extremity routine muscles:
1. Extensor hallucis longus
2. Tibialis anterior
3. Soleus/medial gastrocnemius
4. Quadriceps
5. Gluteal muscles or tensor fascia latae

Upper extremity routine muscles:
1. First dorsal interosseous
2. Extensor indicis proprius
3. Forearm muscles (pronator teres or flexor carpi radialis)
4. Biceps brachii
5. Medial deltoid

Special considerations:
- At a minimum, the above muscles should be studied on one side. In addition, in each extremity on the contralateral side, one muscle should be sampled to assess symmetry. If there is a clinical suggestion of asymmetry, additional muscles on the contralateral side should be studied.
- It is best to avoid the intrinsic foot muscles because denervation and reinnervation are commonly present in normal individuals.
- If abnormalities are found in the proximal muscles (e.g., glutei, biceps brachii), the paraspinal muscles should be sampled as well.

EXAMPLE CASES

In the following polyneuropathy example cases, we use the history, physical examination, and EDX study to answer the seven key questions about the polyneuropathy illustrated in the case. By doing so, the differential diagnosis is narrowed to a much smaller number of disorders, and subsequent evaluation and treatment proceeds in a more directed and logical way.

Case 26–1

History and Physical Examination

A 45-year-old woman was referred for numbness and tingling in the legs. She had been well until 6 months previously, when bilateral numbness began in the toes. Over the next several months, the numbness spread to above the ankles and was associated with pins-and-needles paresthesias. She described her feet as feeling like wooden blocks. More recently, numbness spread to the calves, with some tingling in the fingertips. She noted some difficulty opening jars, buttoning buttons, and turning keys.

On examination, there was mild atrophy of the intrinsic foot muscles bilaterally, especially of both extensor digitorum brevis muscles. Muscle strength testing was normal in all extremities. Ankle reflexes were absent bilaterally. Both knee reflexes were present but hypoactive. The upper extremity reflexes were normal and symmetric. Sensory testing demonstrated decreased vibration at both ankles. Sensation to light touch and pinprick was decreased below the knees bilaterally and in the fingers of both hands. There was no Romberg sign. Gait and coordination were normal. She had no family history of polyneuropathy, and no significant medical illnesses.

Summary

The history in this case is quite typical for polyneuropathy: a slow progression over several months and an onset that cannot be clearly dated. Symptoms began distally in the feet and slowly spread up the legs. A length-dependent pattern subsequently developed; the fingertips became involved at the same time as the upper calves (i.e., because the length from the cervical spinal cord to the fingertips is approximately the same length from the lumbosacral spinal cord to the upper calf).

Symptoms in this case are predominantly sensory, including altered sensation and pins-and-needles paresthesias distally. Likewise, the examination shows decreased vibration and pinprick sensation distally in a stocking-glove distribution. Although the symptoms are predominantly sensory, there is evidence of some motor dysfunction on examination. There is atrophy of the EDB muscle bilaterally. The ankle reflexes are absent, whereas knee and upper extremity reflexes are intact, a common finding in a distal polyneuropathy.

Based on the history and physical examination, it appears likely that the patient has a symmetric polyneuropathy involving predominantly large sensory fibers (decreased light touch and vibration). However, there also is some involvement of both motor and small sensory (decreased pinprick) fibers.

Nerve conduction studies are performed in the right lower and upper extremities, and some studies are done on the contralateral side to assess symmetry. Most of the abnormalities are noted in the lower extremity studies. The peroneal motor study shows a low amplitude, but without any prominent drop of amplitude on proximal stimulation, with a normal distal latency and slightly slowed conduction velocities. Similar findings occur in the tibial motor studies: low amplitudes, normal distal

CASE 26–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F Wave latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	6.2	5.8	≥4	3.5	3.2	≤4.4				31	32	≤31
	Antecubital fossa	APB	6.1	5.8		7.3	7.2		52	50	≥49			
Ulnar (m)	Wrist	ADM	7.3		≥6	3.1		≤3.3				32		≤32
	Below elbow	ADM	7.2			6.4			55		≥49			
	Above elbow	ADM	7.2			8.3			53		≥49			
Median (s)	Wrist	Index finger	13	12	≥20	3.4	3.3	≤3.5	50	51	≥50			
Ulnar (s)	Wrist	Little finger	7		≥17	3.1		≤3.1	49		≥50			
Tibial (m)	Ankle	AHB	3.2	2.8	≥4	5.7	5.6	≤5.8				57	56	≤56
	Popliteal fossa	AHB	2.5	2.2		12.1	11.7		39	41	≥41			
Peroneal (m)	Ankle	EDB	1.1		≥2	6.2		≤6.5				NR		≤56
	Below fibula	EDB	0.9			12.6			39		≥44			
	Lateral popliteal fossa	EDB	0.8			15.3			37		≥44			
Sural (s)	Calf	Posterior ankle	NR	NR	≥6			≤4.4			≥40			

m = motor study; s = sensory study; R = right; LT = left; NL = normal; NR = no response; APB = abductor pollicis brevis; ADM = abductor digiti minimi; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 26–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right extensor hallucis longus	↑	+3	0	NL	↓↓	+2	+2	+2
Right tibialis anterior	↑	+2	0	NL	↓↓	+2	+1	+1
Right medial gastrocnemius	↑	+2	0	NL	↓↓	+2	+1	+1
Right vastus lateralis	NL	+1	0	NL	↓	+1	+1	NL
Right gluteus medius	NL	0	0	NL	NL	NL	NL	NL
Right first dorsal interosseous	↑	+2	0	NL	↓↓	+2	+1	+1
Right indicis proprius	↑	+1	0	NL	↓	+1	+1	+1
Right pronator teres	NL	0	0	NL	↓	+1	NL/+1	NL/+1
Right biceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right medial deltoid	NL	0	0	NL	NL	NL	NL	NL
Left tibialis anterior	↑	+2	0	NL	↓↓	+2	+2	+2
Left biceps brachii	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓ = slightly reduced; ↓↓ = moderately reduced; NL = normal.

latencies, and borderline slowed conduction velocities. The tibial F responses are slightly prolonged. Although the peroneal F responses are absent, this finding is of unclear significance because peroneal F responses are absent or difficult to obtain in some normal individuals. The sural sensory responses are absent bilaterally.

The motor studies in the lower extremities are consistent with axonal loss: amplitudes are low; velocities and latencies are normal to slightly slowed. The tibial and sural responses are symmetric from side to side. In the upper extremities, the motor studies are completely normal and symmetric. However, the sensory studies show low-amplitude responses with normal latencies and borderline slowed conduction velocities. These abnormalities again are consistent with axonal loss.

On the nerve conduction studies, there is a clear distal predominance of abnormalities, which are more prominent in the lower extremities than the upper. In addition, the nerve conduction studies are fairly symmetric comparing side to side.

Moving on to the needle EMG, the distal muscles of the right leg show fibrillation potentials and large, long, polyphasic MUAPs with reduced recruitment. As more proximal muscles are sampled, however, the amount of fibrillation potentials decreases and the motor unit potential changes are not as marked. When the gluteus medius, a very proximal muscle, is sampled, no abnormalities are seen.

In the upper extremities, a similar distal-to-proximal pattern is present. The first dorsal interosseous and extensor indicis proprius are fibrillating with large MUAPs and decreased recruitment. However, the pronator teres shows no fibrillation potentials and only borderline enlarged MUAPs. More proximally, at the biceps and deltoid, MUAPs and spontaneous activity are normal. Comparing two contralateral muscles, the tibialis anterior and biceps brachii, the findings are symmetric.

At this point we are ready to form our electrophysiologic impression.

IMPRESSION: *There is electrophysiologic evidence of an active and chronic sensorimotor distal, axonal polyneuropathy.*

We now have all the information needed to answer the seven key questions about the polyneuropathy in this case:

Key Neuropathy Questions	Answers
Temporal course	Subacute/Chronic; slowly progressive
Fiber types involved	Sensory (large and small fiber) > motor
Pattern	Symmetric; stocking glove
Pathology	Axonal, active and chronic
Family history	No
Associated medical illness	No
Toxic/Occupational exposure	No

With this information, the case can be further analyzed and other key questions answered.

Does the Clinical–Electrophysiologic Correlation Make Sense?

The key point in this case is the similar pattern of abnormalities that emerges from the clinical data, nerve conduction studies, and EMG. All reveal a length-dependent, distal predominance of findings. In addition, there is no significant asymmetry on physical examination, nerve conduction studies, or EMG.

The polyneuropathy involves both sensory and motor fibers. The history and examination indicate abnormalities of sensation, which correlate with the abnormal sensory responses found on the nerve conduction studies. Although the patient has very few motor complaints, minor motor signs are found on the physical examination, and there is clear evidence of motor dysfunction on both nerve conduction studies and EMG.

Does the Underlying Nerve Pathology Help Limit the Differential Diagnosis?

The pattern on nerve conduction studies is clearly one of axonal loss, which is symmetric, involving both sensory and motor fibers. Both fibrillation potentials and large, long MUAPs are seen on EMG, which are signs of acute and chronic axonal loss, respectively. On nerve conduction studies, amplitudes are generally reduced with normal or slightly prolonged latencies, conduction velocities, and late responses, the electrophysiologic findings of axonal loss. There is no conduction block or markedly slowed latency or conduction velocity to suggest demyelination.

The overall picture in this case is one of a typical, subacute to chronic, axonal polyneuropathy. Such a picture could be seen in a multitude of different axonal polyneuropathies. Toxic, metabolic, endocrine, and drug-induced causes should be carefully considered. Because there is no electrophysiologic evidence of demyelination to suggest one of the demyelinating polyneuropathies, several possibilities have been eliminated from the differential diagnosis. Likewise, the need for certain laboratory tests has been obviated. For instance, there would be little point in obtaining a skeletal survey looking for an osteosclerotic myeloma or in performing an anti-MAG antibody test, both of which would be indicated in a patient with a chronic demyelinating polyneuropathy, while it would certainly make sense to screen for diabetes, thyroid dysfunction, and B_{12} deficiency.

Case Follow-up

The patient underwent routine blood screening for diabetes, thyroid disease, vitamin deficiencies, connective tissue disease, and a monoclonal protein. No abnormality was discovered. On repeat questioning, she admitted to heavy alcohol intake for many years, which she had been reluctant to admit initially. She was treated symptomatically and advised to discontinue alcohol and improve her nutrition.

Case 26–2

History and Physical Examination

A 68-year-old woman gradually developed numbness of the left fourth and fifth digits over several weeks. A month later, she developed similar numbness on her inner thighs bilaterally, which then spread to her outer thighs and then down her legs. A similar sensation then developed around her lower back and abdomen. This was followed by numbness of the remainder of the left hand and then of the entire right hand. She had no complaints of weakness, bowel or bladder difficulties, or visual changes. However, her gait had become very unsteady. Her past medical history was notable for mild rheumatoid arthritis and a 40-pack per year history of smoking.

Examination showed normal cranial nerve function. Eye movements were full. There was no facial weakness. Corneal response and facial sensation were normal. Motor examination revealed full strength in all limbs. Sensory examination revealed a profound loss of vibration in all four extremities and impaired joint position sense in the lower extremities. Pinprick and temperature sensation were reduced in a patchy distribution over the extremities. Pseudoathetosis was present in the upper extremities. Reflexes were diffusely absent. Gait was grossly ataxic, and a Romberg sign was present.

Summary

The history and examination in this case suggest a polyneuropathy, but one very different from the stocking-glove, length-dependent polyneuropathy described in Case 26–1. In this patient, the history is one of an asymmetric, stepwise progression of symptoms, compatible with a mononeuropathy multiplex pattern. This type of presentation would be distinctly unusual for any toxic, metabolic, endocrine, drug-induced, or inherited polyneuropathy, all of which are typically symmetric and distal.

The examination is notable only for sensory abnormalities, mostly involving large sensory fibers. All reflexes are absent, and there is profound loss of vibration and joint position sense in all four extremities. With patchy loss of pin and temperature sense, there must be an element of small-fiber sensory loss as well.

The combination of findings suggests that the person has severe sensory denervation. Pseudoathetosis is an important sign, usually signifying markedly impaired joint position sense. Normally when a patient places the hands and arms straight out with the eyes closed, there is very little movement. A patient with severe sensory loss, who does not know where his or her limbs are in space, will display athetotic movements of the fingers and sometimes of the hands and wrists. In addition, patients with severe sensory loss will often have a Romberg sign, as is present in this case. Finally, gait may be very unstable and ataxic from sensory loss alone. This underscores that gait ataxia is not always a cerebellar problem but may represent dysfunction of the sensory pathways, either in the spinal cord (i.e., dorsal columns) or in the peripheral

CASE 26–2. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F Wave latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	6.5	7.2	≥4	3.4	3.2	≤4.4				25	27	≤31
	Antecubital fossa	APB	6.4	7.0		6.9	6.6		57	59	≥49			
Ulnar (m)	Wrist	ADM	6.7		≥6	2.7		≤3.3				28		≤32
	Below elbow	ADM	6.2			5.7			60		≥49			
	Above elbow	ADM	6.0			7.5			55		≥49			
Median (s)	Wrist	Index finger	7	9	≥20	3.2	3.0	≤3.5	52	54	≥50			
Ulnar (s)	Wrist	Little finger	3	NR	≥17	2		≤3.1	55		≥50			
Radial (s)	Forearm	Snuffbox	5	7	≥15	2.8	2.8	≤2.9	54	54	≥50			
Tibial (m)	Ankle	AHB	10	11	≥4	4.8	4.5	≤5.8				52	51	≤56
	Popliteal fossa	AHB	8.2	7		9.4	9.0		54	55	≥41			
Peroneal (m)	Ankle	EDB	4.9		≥2	5.2		≤6.5				49		≤56
	Below fibula	EDB	4.4			9.3			44		≥44			
	Lateral popliteal fossa	EDB	4.4			11.3			50		≥44			
Sural (s)	Calf	Posterior ankle	3	10	≥6	4.0	3.6	≤4.4	39	52	≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; APB = abductor pollicis brevis; ADM = abductor digiti minimi; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 26–2. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right extensor hallucis longus	NL	0	0	NL	NL	NL	NL	NL
Right tibialis anterior	NL	0	0	NL	NL	NL	NL	NL
Right medial gastrocnemius	NL	0	0	NL	NL	NL	NL	NL
Right vastus lateralis	NL	0	0	NL	NL	NL	NL	NL
Right gluteus medius	NL	0	0	NL	NL	NL/+1	NL	NL
Right first dorsal interosseous	NL	0	0	NL	NL	NL	NL	NL
Right indicis proprius	NL	0	0	NL	NL	NL	NL	NL
Right pronator teres	NL	0	0	NL	NL	NL	NL	NL
Right biceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right medial deltoid	NL	0	0	NL	NL	NL	NL	NL
Left tibialis anterior	NL	0	0	NL	NL	NL	NL	NL
Left biceps brachii	NL	0	0	NL	NL	NL	NL	NL

NL = normal.

nerves. Notably, the patient's motor system is completely normal. Although this observation will have to be confirmed with nerve conduction studies and EMG, clinically the symptoms and signs suggest predominantly sensory dysfunction with an asymmetric presentation.

This sensory asymmetry is subsequently found on the nerve conduction studies. Nearly all sensory responses are abnormal. The median sensory responses are bilaterally low, with normal latencies and conduction velocities. The right ulnar sensory potential is very low, and on the left it is unobtainable. Both radial sensory potentials are low. In the lower extremity, however, the sural potential is low on the right but normal on the left. Those sensory potentials that are abnormal have normal to slightly slowed latencies and conduction velocities, all within the range of axonal loss. The asymmetry of the sural sensory potential is a key finding that would not be expected in a typical length-dependent distal axonal polyneuropathy.

The motor studies in the upper and lower extremities are completely normal. Thus, at the end of the nerve conduction studies, an unusual situation is found: the abnormalities are asymmetric and appear limited to the sensory system.

Moving on to the EMG, the study is entirely normal and shows no evidence of denervation or reinnervation of the proximal or distal muscles of the upper or lower extremities. The recruitment is normal in all muscles tested. In combination with the nerve conduction studies, the EMG study excludes involvement of the motor fibers. EMG is the most sensitive way to detect subtle motor involvement. If only a few motor axons are lost, denervation can usually be seen on EMG, although no appreciable change is seen on the motor conduction studies.

At this time we are ready to make a diagnosis.

IMPRESSION: *The electrophysiologic findings are consistent with an asymmetric, sensory neuropathy or sensory neuronopathy.*

We now have all the information needed to answer the seven key questions about the polyneuropathy in this case:

Key Neuropathy Questions	Answers
Temporal course	Subacute; stepwise
Fiber types involved	Restricted to sensory (large > small fiber)
Pattern	Asymmetric
Pathology	Axonal, asymmetric, sensory
Family history	No
Associated medical illness	Rheumatoid arthritis
Toxic/Occupational exposure	Smoking

With this information, the case can be further analyzed and other key questions answered.

Does the Pure Sensory Involvement Narrow the Differential Diagnosis?

This case is distinctly unusual. The history, physical examination, nerve conduction studies, and EMG show a disorder restricted to the sensory system; the motor system is completely spared. Both large and small sensory fibers are involved. The large-fiber sensory dysfunction has led to the impaired vibration and joint position sense, loss of reflexes, Romberg sign, pseudoathetosis, and gait ataxia. There is minor, small-fiber sensory involvement, demonstrated by pinprick and temperature sense loss.

Because nearly all polyneuropathies have some motor as well as sensory findings, especially on nerve conduction studies and EMG, this particular case is exceptional. Because of the asymmetry and the fact that the upper extremities are as equally involved as the lower extremities, the pattern suggests a sensory neuronopathy, a disorder of the dorsal root ganglia, the primary sensory neuron. Sensory neuronopathies are quite rare. In some cases, a sensory neuronopathy may be part of a larger neurodegenerative disorder. For instance, Friedreich's ataxia and some other chronic spinocerebellar degenerations can have an associated sensory neuronopathy. In acute or subacute cases such as this one, however, sensory neuronopathies usually are associated with only a few distinct disorders. They may be paraneoplastic neuronopathies, often associated with a small cell carcinoma of the lung. In a subset of these cases, an anti-HU antibody will be present. Sensory neuronopathies may also be seen in patients with Sjögren's syndrome and related connective tissue disorders. In addition, sensory neuronopathy may be seen as a postinfectious process, a sequela of pyridoxine (vitamin B_6) intoxication, or as an isolated autoimmune process.

In this patient, who has rheumatoid arthritis and a long history of smoking, one must investigate both the possibility of Sjögren's syndrome associated with rheumatoid arthritis or a paraneoplastic sensory neuronopathy from an underlying, yet unrecognized carcinoma. The subsequent workup and evaluation should be very different from that indicated in the distal axonal sensorimotor polyneuropathy of Case 26–1.

Case Follow-up

Subsequent evaluation for Sjögren's syndrome was negative, and there was no history of pyridoxine ingestion. A chest X-ray film showed a hilar mass that on biopsy proved to be small cell carcinoma. Anti-HU antibodies were present in the blood.

Case 26–3

History and Physical Examination

A 65-year-old man was referred for evaluation of fever, progressive weight loss, and recent numbness and weakness of several months' duration. Three weeks previously,

abrupt pain developed in the left posterior thigh, followed by a foot drop and numbness over the dorsum of the foot and lateral leg. One week ago, a similar episode occurred in the right leg. The day before the examination, pain developed in the left medial arm, followed by weakness of hand grip and numbness involving the ring and little fingers of the left hand.

Examination showed a cachectic, ill-appearing man. Muscle bulk was diminished in the anterolateral compartment of the left leg. Marked bilateral foot drops were present. The left first dorsal interosseous, abductor digiti minimi (ADM), and flexor digitorum profundus to digits 4 and 5 were markedly weak. However, strength testing of the left extensor indicis proprius, abductor pollicis brevis (APB), and flexor pollicis brevis was normal. Reflexes were absent at the ankles but otherwise were normal. Sensation was diminished in the left hypothenar region and fourth and fifth digits. There was a stocking-pattern loss to all sensory modalities in the legs that was somewhat more prominent on the dorsum of both feet.

Summary

In this case, the history suggests some type of systemic illness, manifested by fever and weight loss followed by a progressive polyneuropathy. The polyneuropathy, however, has an unusual presentation: an asymmetric, stepwise progression of numbness and weakness, heralded by the abrupt onset of pain. The entire neurologic history is acute; the first event occurred only 3 weeks ago. Although exact localization is not possible from the history alone, it appears that left peroneal fibers were affected 3 weeks ago (foot drop and numbness), followed by a similar event on the right side 1 week ago. One day ago, the left ulnar fibers became involved, with numbness of the ring and little fingers and weakness of grip.

On examination, there are bilateral foot drops, correlating with the patient's symptoms 1 and 3 weeks ago. In the left leg, some atrophy has developed as well. In the left hand, there are abnormalities in the ulnar nerve distribution, including weakness of the first dorsal interosseous, ADM, and flexor digitorum profundus muscles. The weakness, along with decreased sensation over the left hypothenar region and fourth and fifth digits, clearly suggests involvement of the left ulnar nerve. Distal muscles that are innervated by different nerves (i.e., the extensor indicis proprius, APB, and flexor pollicis brevis) are all normal. This preferential involvement of only certain distal muscles would not occur in a typical distal axonal polyneuropathy. Rather, the history and examination thus far suggest involvement of isolated named nerves. Sensory examination in the lower extremities shows a stocking loss to all modalities that is somewhat more prominent on the dorsum of the feet. Recall that

CASE 26–3. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F Wave latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	5.2	5.4	≥4	4.2	4.0	≤4.4				30	28	≤31
	Antecubital fossa	APB	5.0	5.1		7.4	7.0		56	59	≥49			
Ulnar (m)	Wrist	ADM	11.2	12	≥6	3.1	3.2	≤3.3				28	28	≤32
	Below elbow	ADM	11.2	11.2		6.1	6.5		60	55	≥49			
	Above elbow	ADM	11.2	11		7.8	8.3		60	57	≥49			
Median (s)	Wrist	Index finger	34	32	≥20	3.3	3.2	≤3.5	55	55	≥50			
Ulnar (s)	Wrist	Little finger	24	22	≥17	2.9	2.9	≤3.1	58	56	≥50			
Tibial (m)	Ankle	AHB	4.2	2.1	≥4	5.7	6.0	≤5.8				56	56	≤56
	Popliteal fossa	AHB	3.8	1.7		11.9	12.4		40	39	≥41			
Peroneal (m)	Ankle	EDB	0.2	0.3	≥2	6.2	6.4	≤6.5				NR	NR	≤56
	Below fibula	EDB	0.2	0.2		11.0	11.5		41	39	≥44			
	Lateral popliteal fossa	EDB	0.2	0.2		13.5	14		40	40	≥44			
Peroneal (s)	Lateral calf	Lateral ankle	NR	NR	≥6			≤4.4			≥40			
Sural (s)	Calf	Posterior ankle	12	3	≥6	4.1	4.2	≤4.4	45	46	≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; APB = abductor pollicis brevis; ADM = abductor digiti minimi; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 26–3. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right extensor hallucis longus	NL	0	0	NL	↓↓↓	NL	NL	NL
Right tibialis anterior	↑	0	0	NL	↓↓↓	NL	NL	NL
Right medial gastrocnemius	NL	0	0	NL	NL	NL	NL	NL
Right tibialis posterior	NL	0	0	NL	NL	NL	NL	NL
Right vastus lateralis	NL	0	0	NL	NL	NL	NL	NL
Right gluteus medius	NL	0	0	NL	NL	NL	NL	NL
Left tibialis anterior	↑	+2	0	NL	↓↓↓	NL	NL	NL
Left medial gastrocnemius	↑	+1	0	NL	↓↓	NL	NL	NL
Left tibialis posterior	↑	+1	0	NL	↓↓	NL	NL	NL
Left vastus lateralis	NL	0	0	NL	NL	NL	NL	NL
Left short head biceps femoris	↑	+2	0	NL	↓↓↓	NL	NL	NL
Right abductor pollicis brevis	NL	0	0	NL	NL	NL	NL	NL
Right first dorsal interosseous	NL	0	0	NL	NL	NL	NL	NL
Right pronator teres	NL	0	0	NL	NL	NL	NL	NL
Right biceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right medial deltoid	NL	0	0	NL	NL	NL	NL	NL
Left abductor pollicis brevis	NL	0	0	NL	NL	NL	NL	NL
Left first dorsal interosseous	NL	0	0	NL	↓↓↓	NL	NL	NL
Left flexor digitorum profundus (V)	NL	0	0	NL	↓↓↓	NL	NL	NL
Left biceps brachii	NL	0	0	NL	NL	NL	NL	NL

↑= increased; ↓↓ = moderately reduced; ↓↓↓ = markedly reduced; NL = normal; V = digit five.

the dorsum of the feet receive their sensory innervation from the peroneal nerves.

The history and physical examination tell us that the patient, who is probably systemically ill, had the asymmetric presentation of what appears to be a left peroneal neuropathy 3 weeks ago, a right peroneal neuropathy 1 week ago, and a left ulnar neuropathy 1 day ago.

Because the clinical findings are asymmetric, the assessment of symmetry will be an important part of the nerve conduction studies and EMG. In the lower extremities, both peroneal motor conduction studies show very low amplitudes, with normal latencies and slightly slowed conduction velocities. This pattern of abnormalities is classic for an axonal loss lesion. When the tibial motor conduction studies are performed, however, a normal result is found on the right side, but a low-amplitude response is present on the left. The distal latencies are normal, but the conduction velocities are borderline slowed. Thus, there is evidence of axonal loss in the left tibial nerve. When the lower extremity sensory studies are performed, both peroneal sensory responses are absent, a finding that correlates well with the loss of feeling over the dorsum of the feet. The sural responses, however, are asymmetric: abnormal on the left but intact on the right. The asymmetric sural sensory and tibial motor responses are important findings. Such would not be expected in a typical distal dying-back axonal polyneuropathy. Furthermore, the abnormal tibial and peroneal

findings on the left side suggest that the foot drop may be secondary to a more proximal lesion. Thus, at the end of the lower extremity nerve conduction studies, there is definite evidence of bilateral peroneal neuropathies as well as a left tibial neuropathy.

Median motor conduction studies are performed bilaterally and are completely normal and symmetric. Next, ulnar motor conduction studies are performed bilaterally and are normal and symmetric. At this point, one may question why the left ulnar motor study is completely normal, yet the patient has weakness in the ulnar distribution. Recall that the left ulnar lesion is only 1 day old, so not enough time has passed for wallerian degeneration to have occurred. In this hyperacute period, nerve conduction studies remain normal. Likewise, when the median and ulnar sensory conduction studies are performed, they also are normal and symmetric bilaterally, with normal latencies and conduction velocities. Once again, there is a paradoxical finding of numbness in the ulnar distribution clinically, yet a normal ulnar sensory potential. This unusual combination of findings (clinical sensory loss with normal sensory potential in the distribution of numbness) can only occur in one of three situations: (1) a hyperacute axonal lesion, (2) proximal demyelination, or (3) any lesion proximal to the dorsal root ganglion. In the present case, it is most likely that the sensory response is normal because of the time course of the lesion (i.e., not enough time has passed for wallerian degeneration to have occurred).

On EMG, the right leg is sampled first. Recall that the right leg was clinically affected 1 week ago and that nerve conduction studies in the right leg showed only low peroneal motor and sensory amplitudes. The right leg shows no evidence of active denervation, and all MUAPs are normal. However, MUAP recruitment is markedly reduced in two peroneal-innervated muscles: the extensor hallucis longus and the tibialis anterior. The tibial-innervated muscles are normal, as are the more proximal muscles: the vastus lateralis and gluteus medius. Putting together the right leg nerve conduction studies and needle EMG, we see the pattern of an acute peroneal neuropathy. Enough time has passed for wallerian degeneration to have occurred, resulting in abnormal nerve conduction studies, but it remains too early to see signs of denervation or reinnervation. This is the classic acute axonal pattern: the only abnormality on EMG is decreased recruitment of normal appearing MUAPs

When the left leg is sampled, there is clear evidence of active denervation, both in peroneal- and tibial-innervated muscles including the short head of the biceps femoris, which is above the popliteal fossa. Involvement of the short head of the biceps femoris, along with the abnormal peroneal and tibial motor and peroneal and sural sensory nerve conduction studies, suggests that the lesion is in the sciatic nerve. Once again, the MUAPs are normal in morphology with a reduced recruitment pattern. This is the classic subacute axonal pattern: enough time has passed for wallerian degeneration to have occurred, resulting in abnormal nerve conduction studies; enough time also has passed for denervation to be seen on the needle examination. However, it remains too early for reinnervation. This particular pattern occurs after several weeks but before several months have passed.

In the clinically unaffected right upper extremity, all muscles are normal. However, in the left upper extremity, where the patient had ulnar motor and sensory loss on physical examination yet normal ulnar nerve conduction studies, we find decreased recruitment in ulnar-innervated muscles. Of note, there are no fibrillation potentials or reinnervated MUAPs. When other non-ulnar C8-innervated muscles are sampled (e.g., APB), they are normal. Putting together the clinical examination, nerve conduction studies, and EMG in the left upper extremity, it is apparent that a hyperacute axonal ulnar neuropathy is present. Not enough time has passed (only 1 day) for wallerian degeneration, denervation, or reinnervation to have occurred. The only abnormality is decreased recruitment in weak muscles.

Therefore, at this time we are ready to make a diagnosis.

IMPRESSION: *The electrophysiologic findings are consistent with a mononeuropathy multiplex pattern, with a hyperacute left ulnar neuropathy, acute right peroneal neuropathy, and subacute left sciatic neuropathy.*

We now have all the information needed to answer the seven key questions about the polyneuropathy in this case:

Key Neuropathy Questions	Answers
Temporal course	Subacute, stepwise progressive
Fiber types involved	Motor and sensory
Pattern	Asymmetric, multiple nerves
Pathology	Axonal, asymmetric, multiple nerves
Family history	No
Associated medical illness	Underlying fever, weight loss
Toxic/Occupational exposure	No

With this information, the case can be further analyzed and other key questions answered. This case demonstrates the major clinical and electrophysiologic findings of a mononeuritis multiplex pattern. The clinical presentation is distinctive: an asymmetric stepwise progression of individual mononeuropathies. Nerve conduction studies and EMG, if performed early in the disease, typically will demonstrate evidence of asymmetry. The

presence of asymmetry excludes the typical toxic, metabolic, endocrine, drug-induced, and genetic polyneuropathies that result in a symmetric, dying-back, stocking-glove pattern of abnormalities.

Does the Time Course of the Polyneuropathy Fit with the Electrophysiologic Data?

Mononeuritis multiplex is one of the few polyneuropathies that may present acutely over a short period of time. Knowing the duration of symptoms and the tempo of the polyneuropathy is essential to interpret the nerve conduction studies and EMG properly. As demonstrated in this case, if a patient is studied within 1 week of an acute event, nerve conduction studies and EMG findings will be completely normal, with the exception of decreased recruitment of MUAPs in weak muscles (hyperacute axonal pattern). If studies are performed after 1 week but before several weeks, nerve conduction studies will be abnormal, but EMG findings will be similar (acute axonal pattern). If the study is performed after several weeks but not before months, abnormal nerve conduction studies will be found along with fibrillation potentials on EMG. MUAPs will remain normal in morphology but will show decreased recruitment (subacute axonal pattern). These patterns are not seen in the typical, slowly progressive polyneuropathy. By the time a patient with a typical polyneuropathy reaches the EMG laboratory, there are usually nerve conduction study abnormalities and evidence of denervation and reinnervation on EMG.

What is the Differential Diagnosis of Mononeuropathy Multiplex?

In this particular case, in which the history suggests a coexistent systemic illness, the possibility of systemic vasculitis, especially polyarteritis nodosa, should be strongly considered. Polyarteritis nodosa is a neurologic emergency, requiring prompt diagnosis and treatment to prevent infarction of other nerves or internal organs (e.g., kidney, bowel, heart). The next logical step in such a patient would be to perform a nerve and muscle biopsy as soon as possible, looking for evidence of vasculitis. In this case, the best nerve to biopsy would be the left sural nerve, the side that was abnormal on nerve conduction studies. Note that a muscle should be chosen for biopsy that was not studied on EMG, because of the possibility of the needle creating an inflammatory reaction, which could confuse the biopsy findings.

As in this case, the typical vasculitic mononeuropathy multiplex pattern is asymmetric and purely axonal in nature, showing no electrophysiologic evidence of demyelination. Although vasculitis is the most common cause of mononeuropathy multiplex, the differential diagnosis of mononeuropathy multiplex includes other conditions (Box 26-3), among them a variant of CIDP, which in this case is excluded by the lack of demyelination on nerve conduction studies, as well as diabetes, multiple entrapments, and infectious and infiltrative lesions.

Case Follow-up

Blood testing showed a markedly elevated ESR of 110 mm/h, and mild elevation of the liver function tests. A left sural nerve and lateral gastrocnemius muscle biopsy were performed. Both showed fibrinoid necrosis surrounding small and medium sized arterial blood vessels with an inflammatory infiltrate within the vessel walls. The diagnosis of polyarteritis nodosa was made. The patient was treated with a combination of high dose oral steroids and cyclophosphamide.

Case 26–4

History and Physical Examination

A 32-year-old woman was admitted for progressive weakness and numbness. She had been well until 3 weeks ago, when she developed diarrhea and fever that persisted for several days, and remitted. Ten days ago, she developed pins-and-needles paresthesias in both feet and both hands. Those symptoms were followed by clumsiness of gait and progressive weakness of both arms and legs.

Examination was notable for bifacial weakness and a mild, diffuse quadriparesis. Reflexes were trace in the arms and absent in the legs. A mild distal sensory loss to pinprick, light touch, and vibration was present in both upper and lower extremities.

Summary

In this case, there is a rapidly progressive, subacute polyneuropathy that developed several days after an infectious illness. The history and physical examination provide clear evidence of both motor and sensory dysfunction. However, the pattern is unusual: pins-and-needles paresthesias in the hands and feet at the same time. That combination does not occur in typical distal, length-dependent polyneuropathies, in which symptoms first develop in the feet and only later in the hands after the polyneuropathy has reached the mid-shins. The examination is notable for the lack of reflexes and the predominant motor findings, with minor sensory findings. These clinical findings, along with development of paresthesias simultaneously in the hands and feet, are suggestive of a demyelinating polyneuropathy.

Nerve conduction studies show completely normal motor studies in the upper and lower extremities. All amplitudes are normal, with intact conduction velocities and distal latencies. There is no evidence on proximal stimulation to suggest conduction block. However, all F responses are notably absent, despite the normal distal amplitudes and conduction velocities. This particular pattern of normal distal motor conduction studies with absent late responses is strongly suggestive of proximal demyelination, either at the plexus or root level.

The results of the sensory conduction studies are quite unusual: both sural potentials are normal bilaterally, but the median and ulnar sensory amplitudes are low. Such a pattern does not occur in the typical distal, length-dependent polyneuropathy. This pattern of "sural sparing"

CASE 26–4. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F Wave latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	5.4	6.0	≥4	4.1	3.8	≤4.4				NR	NR	≤31
	Antecubital fossa	APB	5.0	6.0		7.3	7.0		56	55	≥49			
Ulnar (m)	Wrist	ADM	10.2		≥6	3.1		≤3.3				NR		≤32
	Below elbow	ADM	10.2			6.6			57		≥49			
	Above elbow	ADM	10.2			8.3			59		≥49			
Median (s)	Wrist	Index finger	3	4	≥20	3.5	3.4	≤3.5	54	53	≥50			
Ulnar (s)	Wrist	Little finger	5		≥17	2.9		≤3.1	45		≥50			
Tibial (m)	Ankle	AHB	5.7	4.2	≥4	5.8	5.6	≤5.8				NR	NR	≤56
	Popliteal fossa	AHB	4.8	4.0		11.7	11.6		42	41	≥41			
Peroneal (m)	Ankle	EDB	5.2		≥2	5.6		≤6.5				NR		≤56
	Below fibula	EDB	5.0			11.2			44		≥44			
	Lateral popliteal fossa	EDB	5.0			13.4			45		≥44			
Sural (s)	Calf	Posterior ankle	23	18	≥6	4.2	4.1	≤4.4	45	47	≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; APB = abductor pollicis brevis; ADM = abductor digiti minimi; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 26–4. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right extensor hallucis longus	NL	0	0	NL	↓↓	NL	NL	NL
Right tibialis anterior	NL	0	0	NL	↓↓	+1	+1	NL
Right medial gastrocnemius	NL	0	0	NL	↓↓	+1	+1	NL
Right vastus lateralis	NL	0	0	NL	↓↓	NL	NL	NL
Right gluteus medius	NL	0	0	NL	↓	NL	NL	NL
Right first dorsal interosseous	NL	0	0	NL	↓↓	NL	NL	NL
Right indicis proprius	NL	0	0	NL	↓↓	NL	NL	NL
Right pronator teres	NL	0	0	NL	↓↓	NL	NL	NL
Right biceps brachii	NL	0	0	NL	↓↓	NL	NL	NL
Right medial deltoid	NL	0	0	NL	↓↓	NL	NL	NL
Left tibialis anterior	NL	0	0	NL	↓↓	+1	+1	NL
Left biceps brachii	NL	0	0	NL	↓↓	NL	NL	NL

↓ = slightly reduced; ↓↓ = moderately reduced; NL = normal.

in this clinical setting strongly suggests a diagnosis of Guillain–Barré syndrome.

On needle EMG, there is no evidence of denervation in any muscle, and most muscles show moderately decreased recruitment. In general, MUAP morphology is normal. However, the tibialis anterior and medial gastrocnemius appear to have slightly large, slightly long-duration MUAPs.

At this point we are ready to form our impression.

IMPRESSION: *The electrophysiologic findings are consistent with an acute, demyelinating, sensorimotor polyneuropathy.*

We now have all the information needed to answer the seven key questions about the polyneuropathy in this case:

Key Neuropathy Questions	Answers
Temporal course	Acute
Fiber types involved	Motor and sensory
Pattern	Non-length-dependent, symmetric; bilateral cranial nerve 7
Pathology	Demyelination, with sural sparing
Family history	No
Associated medical illness	Gastrointestinal infection 10 days earlier
Toxic/Occupational exposure	No

With this information, the case can be further analyzed and other key questions answered. This patient demonstrates many of the classic clinical and electrophysiologic findings of Guillain–Barré syndrome, specifically the AIDP variant, which is the most common. AIDP usually presents as a postinfectious disorder, with rapidly progressive weakness and loss of reflexes. Sensory paresthesias are common, but sensory loss is relatively less common on examination.

What is the Significance of Absent F Responses?

On nerve conduction studies, absent or impersistent F responses usually are the earliest finding in AIDP, signifying proximal demyelination. AIDP typically starts as a polyradiculopathy, with demyelination occurring at the root level. Absent or impersistent F responses may be the only abnormality noted during the first few days of the illness. Other evidence of demyelination (i.e., prolonged distal latencies, slowed conduction velocities, conduction block) may take several weeks to develop.

What is the Significance of "Sural Sparing"?

Like the results of the motor conduction studies, all sensory potentials usually are normal during the first few days of the illness. Near the end of the first week or so, however, the unusual pattern of sural sparing may occur in some patients. In this pattern, the sural response is normal, yet the upper extremity median and ulnar sensory responses are abnormal. This pattern occurs because of the preferential involvement of the smaller myelinated fibers early in AIDP. The sural fibers, recorded in the lower calf, are actually larger and more myelinated than the median and ulnar sensory fibers recorded over the digits. The median and ulnar nerves are recorded very distally, where the nerves have tapered in diameter and thus are ensheathed with less myelin.

What is the Significance of Large Motor Unit Action Potentials if the Neuropathy is Acute?

The EMG is quite distinctive in early AIDP. The needle examination usually is completely normal, with the exception of decreased recruitment of MUAPs, which results from proximal conduction block of motor fibers. In pure demyelination, there is no denervation or reinnervation. The only abnormality is decreased recruitment in weak muscles. Of course, in most cases of AIDP, some secondary axonal loss will eventually develop, leading to some denervation and reinnervation later on EMG.

In some cases of AIDP, however, slightly large MUAPs may be seen early on, as noted in the tibialis anterior and medial gastrocnemius in this patient. Although one might first consider the possibility that reinnervation is present from some preexisting condition, such a finding is sometimes seen in early AIDP. The mechanism is similar to that of sural sparing. In every muscle, there is a normal range of MUAP size. When a muscle first contracts, the smaller, type I MUAPs have the lowest threshold and are the first to fire. As more force is generated, these MUAPs fire faster as more MUAPs are brought in. With increasing force, larger MUAPs begin to fire; at maximum contraction, the largest MUAPs fire. These large, type II MUAPs are innervated by the largest axons and hence have the greatest amount of myelin. Usually, these largest MUAPs are not seen individually during the EMG examination. By the time these MUAPs are recruited, a full interference pattern is already present, obscuring the identification of the individual MUAPs. In some cases of AIDP, however, the smaller MUAPs, innervated by the smaller myelinated fibers, are blocked earlier, leaving only the larger, unblocked MUAPs, which are more readily seen. Thus, in such cases the larger, normal MUAPs have been "uncovered" and their presence does not necessarily imply that reinnervation is present.

Case Follow-up

The patient underwent a lumbar puncture that showed an elevated CSF protein of 110 mg/dl but without a pleocytosis. She was treated with 5 days of IVIG at a dose of 400 mg/kg per dose. By the third treatment, she showed improvement in her strength. Upon completion of the full course of IVIG, she was discharged to a rehabilitation facility. She subsequently made a complete recovery over the next 6 weeks.

Case 26–5

History and Physical Examination

A 52-year-old man was referred for progressive numbness and weakness of 6 months' duration. The patient first noted the insidious onset of pins-and-needles paresthesias in his toes bilaterally 6 months ago, followed by slow progression up his feet and calves. Recently, a pins-and-needles sensation developed in the fingertips. More recently, difficulty with dexterity developed, along with a tendency to trip with walking.

Examination was notable for a stocking-glove loss of vibration and pinprick sense. Reflexes were diffusely hypoactive and absent at the ankles. Mild distal weakness and atrophy were present on motor examination. A Romberg sign was present. Gait was moderately ataxic.

Summary

Both the history and physical examination in this case strongly suggest a typical distal stocking-glove polyneuropathy. In many ways, the clinical information is not unlike that seen in Case 26–1, a stocking-glove, axonal polyneuropathy. Like most polyneuropathies, this one is slowly progressive; symptoms began distally in the toes and slowly advanced proximally. Physical examination reveals evidence of motor and sensory involvement, including both large (vibration) and small (pinprick) sensory fibers. The only unusual clinical aspect of the case is the presence of diffusely hypoactive reflexes. In most stocking-glove polyneuropathies, the upper extremity reflexes are preserved.

On nerve conduction studies, an unusual pattern is found. In the lower extremities, the tibial motor conduction studies show a marked drop in amplitude stimulating at the popliteal fossa, much more of a drop than would normally be expected. In addition, the tibial distal latencies are markedly prolonged, more than 200% of the upper limit of normal, with markedly slowed conduction velocities and absent late responses. Similar findings are present in the peroneal motor conduction study. Both sural sensory responses are absent.

In the upper extremities, the median motor studies show normal amplitudes distally. With proximal stimulation on the right, however, there is a marked drop of amplitude, from 6.4 to 1.2 mV. The distal latencies are markedly prolonged, and the conduction velocities are markedly slow. Both median F responses are absent. Thus, the results of the median motor conduction studies are clearly asymmetric; there is evidence of conduction block on the right but not on the left. The ulnar motor conduction study also shows a marked drop in amplitude between the wrist and below-elbow sites, with a markedly prolonged latency and very slow conduction velocity. Again, the F responses are absent. Both the median and ulnar sensory potentials are present, but they are low in amplitude with prolonged peak latencies and markedly slowed conduction velocities.

CASE 26–5. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F Wave latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	6.4	7.2	≥4	8.4	6.5	≤4.4				NR	NR	≤31
	Antecubital fossa	APB	1.2	5.8		15.9	13.4		24	26	≥49			
Ulnar (m)	Wrist	ADM	4.6		≥6	6.7		≤3.3				NR		≤32
	Below elbow	ADM	2.2			14.9			22		≥49			
	Above elbow	ADM	2.2			20.1			19		≥49			
Median (s)	Wrist	Index finger	3	5	≥20	4.5	4.1	≤3.5	32	37	≥50			
Ulnar (s)	Wrist	Little finger	5		≥17	3.7		≤3.1	34		≥50			
Tibial (m)	Ankle	AHB	4.2	3.2	≥4	12.5	10.2	≤5.8				NR	NR	≤56
	Popliteal fossa	AHB	0.5	0.2		24.4	23.3		21	19	≥41			
Peroneal (m)	Ankle	EDB	3.1		≥2	9.5		≤6.5				NR		≤56
	Below fibula	EDB	1.0			20.6			18		≥44			
	Lateral popliteal fossa	EDB	0.5			25.9			19		≥44			
Sural (s)	Calf	Posterior ankle	NR	NR	≥6			≤4.4			≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; APB = abductor pollicis brevis; ADM = abductor digiti minimi; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 26–5. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right extensor hallucis longus	↑	+2	0	NL	↓↓	+2	+2	+1
Right tibialis anterior	↑	+1	0	NL	↓↓	+1	+1	+1
Right medial gastrocnemius	↑	+1	0	NL	↓↓	+1	+1	+1
Right vastus lateralis	NL	0	0	NL	↓↓	+1	+1	+1
Right gluteus medius	NL	0	0	NL	↓	NL	NL	NL
Right first dorsal interosseous	↑	+1	0	NL	↓	+1	+2	+1
Right extensor indicis proprius	↑	0	0	NL	↓	NL/+1	+1	NL/+1
Right pronator teres	NL	0	0	NL	↓	NL/+1	NL/+1	NL
Right biceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right medial deltoid	NL	0	0	NL	NL	NL	NL	NL
Left tibialis anterior	↑	+1	0	NL	↓↓	+2	+2	+1
Left biceps brachii	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓ = slightly reduced; ↓↓ = moderately reduced; NL = normal.

Thus, at the end of the nerve conduction studies, there is clear evidence of a sensorimotor polyneuropathy with demyelinating features. First, the distal motor latencies are markedly prolonged, many of which are more than 130% of the upper limit of normal. Second, conduction velocities are markedly slowed, nearly all less than 75% of the lower limit of normal. Third, all the late responses are absent. Finally, and possibly most importantly, there is clear evidence of conduction block in multiple nerves and asymmetry (comparing the left and right median motor studies). These latter abnormalities are consistent with an acquired demyelinating polyneuropathy.

On needle EMG, there is evidence of distal denervation in the legs and arms, although it is more pronounced in the legs. Likewise, MUAPs are large, long, and polyphasic with decreased recruitment, more prominently in the lower extremities. All of the findings on needle EMG have a clear distal-to-proximal gradient.

At this time, we are ready to formulate our electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are consistent with a chronic sensorimotor, demyelinating polyneuropathy with secondary axonal features. In addition, the presence of asymmetry and conduction block strongly suggests an acquired condition.*

We now have all the information needed to answer the seven key questions about the polyneuropathy in this case:

Key Neuropathy Questions	Answers
Temporal course	Subacute – chronic progressive
Fiber types involved	Motor and sensory
Pattern	Symmetric, stocking glove
Pathology	Demyelination with conduction block and asymmetry
Family history	No
Associated medical illness	No
Toxic/Occupational exposure	No

With this information, the case can be further analyzed and other key questions answered.

How Does One Distinguish between an Inherited and Acquired Demyelinating Neuropathy?

Although the history and physical examination first suggested nothing more than a typical, distal, axonal polyneuropathy, nerve conduction studies demonstrated

unequivocal evidence of primary demyelination. The presence of primary demyelination narrows the differential diagnosis considerably. There are literally hundreds of causes of axonal polyneuropathies but very few causes of primary demyelination. In addition, the presence of asymmetry and conduction block on proximal stimulation strongly suggests an acquired condition. Asymmetry and conduction block are not seen in the various inherited demyelinating polyneuropathies, such as Charcot–Marie–Tooth polyneuropathy. An exception to this rule may occur in hereditary neuropathy with liability to pressure palsies (HNPP), a condition in which conduction blocks or other evidence of demyelination are typically seen at entrapment sites, and the findings can be asymmetric.

Although conduction blocks are found in multiple nerves in the present case, one might question the right ulnar motor conduction study, in which a conduction block was present between the wrist and below-elbow sites. However, such a drop in amplitude between the two sites may be a normal finding when a Martin–Gruber anastomosis is present. Remember, whenever an ulnar motor conduction study shows an apparent conduction block in the forearm, one must exclude the possibility of a Martin–Gruber anastomosis. Of course, in this particular case, many other nerves also showed conduction block on proximal stimulation, so it was not essential to exclude a Martin–Gruber anastomosis in this case.

Do the Electrophysiologic Findings of Acquired Demyelination Help Guide the Subsequent Evaluation?

The results of the nerve conduction studies and EMG have narrowed the differential diagnosis considerably. Although such findings may be seen in Guillain–Barré syndrome, the clinical history in this case is too long. The likely diagnosis is CIDP. With this knowledge one can proceed to a more appropriate workup, including blood studies for serum protein and immunoprotein electrophoresis and anti-MAG antibodies; a bone survey looking for osteosclerotic myeloma; and possible consideration of an HIV-associated neuropathy. Because the electrophysiologic examination shows an acquired demyelinating polyneuropathy, numerous other tests looking for toxic-, metabolic-, or endocrine-related causes of polyneuropathies would not be indicated, although amiodarone and rare toxins can cause a demyelinating neuropathy.

Case Follow-up

The patient underwent a lumbar puncture which showed a markedly elevated CSF protein of 400 mg/dl without a pleocytosis. Blood studies were negative for HIV, monoclonal proteins, and the anti-MAG antibody. A skeletal survey, however, showed a sclerotic lesion in the vertebral body of L3. Biopsy showed osteosclerotic myeloma. The patient was referred to oncology and was subsequently treated with chemotherapy and radiation.

Case 26–6

History and Physical Examination

A 35-year-old man was referred for a 2-year history of slowly progressive foot drops. The patient reported having been extremely healthy and active until 2 years ago, when he noted progressive tripping during walking. Both legs were affected. There were no sensory complaints and no history of pain.

Examination revealed wasting of the distal leg and foot muscles, with a prominent foot drop bilaterally. Pes cavus was present. All reflexes were absent. There was a subtle stocking loss of sensation to vibration and light touch. Nerves were palpable and enlarged.

Summary

This case is one of progressive, bilateral foot drops. Although the history might suggest a pure motor syndrome, subtle evidence of sensory loss is found on examination. There are several other unusual findings as well.

First is the presence of pes cavus. Pes cavus is an orthopedic deformity of the foot, recognized as a foreshortened foot with a high arch and hammer toes. Pes cavus develops during childhood from the combination of intrinsic foot muscle weakness and relative preservation of the long flexors and extensor muscles in the calves. Because most polyneuropathies preferentially affect distal muscles, polyneuropathies that are present during childhood development commonly result in this deformity. Accordingly, pes cavus in a patient with polyneuropathy usually means that the polyneuropathy has been present since childhood and likely is inherited. One might ask why the patient reports only a 2-year history if pes cavus suggests that the polyneuropathy is of long standing. This situation is not uncommon in inherited polyneuropathies. Because these polyneuropathies often are very mild and progress slowly, patients may not notice any symptoms or seek medical attention until middle age or later. Thus, in many cases, a patient with an inherited polyneuropathy that is, in fact, of longstanding duration reports a history of only several months or years of dysfunction. Of course, some inherited polyneuropathies are more debilitating, and patients present with symptoms in infancy or early childhood. Also note that pes cavus does not always signify a polyneuropathy, but can also be seen in longstanding conditions such as familial spastic paraparesis, slow-growing spinal cord tumors, and local orthopedic disorders.

The second unusual finding is the presence of areflexia on examination. In the typical axonal, stocking-glove polyneuropathy, usually only the ankle reflexes are absent. Global areflexia suggests a demyelinating polyneuropathy.

Third is the unusual finding of palpable and enlarged nerves on physical examination. Nerve hypertrophy may occur if the nerve is infiltrated or infected (as in leprosy), but it is most commonly seen as a sequela of chronic demyelination. Enlarged nerves are characteristic of inherited demyelinating CMT polyneuropathies.

CASE 26–6. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F Wave latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	6.5	7.2	≥4	8.9	9.2	≤4.4				47	44	≤31
	Antecubital fossa	APB	6.2	7.0		17.5	18.2		21	20	≥49			
Ulnar (m)	Wrist	ADM	7.2		≥6	7.2		≤3.3				44		≤32
	Below elbow	ADM	7.0			16.2			18		≥49			
	Above elbow	ADM	6.9			21.2			20		≥49			
Median (s)	Wrist	Index finger	2	3	≥20	5.2	5.4	≤3.5	22	21	≥50			
Ulnar (s)	Wrist	Little finger	NR		≥17			≤3.1			≥50			
Tibial (m)	Ankle	AHB	2.0	1.5	≥4	12.2	13.3	≤5.8				95		≤56
	Popliteal fossa	AHB	1.6	1.1		27.8	29.9		16	15	≥41			
Peroneal (m)	Ankle	EDB	0.8		≥2	10.5		≤6.5				NR		≤56
	Below fibula	EDB	0.7			22.3			17		≥44			
	Lateral popliteal fossa	EDB	0.5			28.9			15		≥44			
Sural (s)	Calf	Posterior ankle	NR	NR	≥6			≤4.4			≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; APB = abductor pollicis brevis; ADM = abductor digiti minimi; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 26–6. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right extensor hallucis longus	NL	+1	0	NL	↓↓	+2	+2	+1
Right tibialis anterior	NL	0	0	NL	↓↓	+2	+2	NL
Right medial gastrocnemius	NL	0	0	NL	↓↓	+2	+1	+1
Right vastus lateralis	NL	0	0	NL	↓	+1	+1	NL
Right gluteus medius	NL	0	0	NL	NL	NL/+1	NL	NL
Right first dorsal interosseous	NL	0	0	NL	↓↓	+1	+1	NL
Right extensor indicis proprius	NL	0	0	NL	↓	NL/+1	NL/+1	NL
Right pronator teres	NL	0	0	NL	NL	NL	NL	NL
Right biceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right medial deltoid	NL	0	0	NL	NL	NL	NL	NL
Left tibialis anterior	NL	0	0	NL	↓↓	+2	+1	+1
Left biceps brachii	NL	0	0	NL	NL	NL	NL	NL

↓ = slightly reduced; ↓↓ = moderately reduced; NL = normal.

The nerve conduction studies demonstrate many abnormalities. In the lower extremities, the motor responses have low amplitudes, with markedly prolonged latencies and slowed conduction velocities. The right tibial F response is markedly prolonged. Both sural potentials are absent. Notably, side-to-side comparisons show no significant asymmetry. In addition, there is no abnormal drop in amplitude on proximal stimulation to suggest conduction block. The median and ulnar motor conduction studies show normal amplitudes, but with markedly prolonged distal latencies and markedly slowed conduction velocities. In addition, the late responses are extremely prolonged. The median sensory potentials are quite low in amplitude, with slowed latencies and conduction velocities. The ulnar sensory potential is absent.

On needle EMG, denervation is absent except very distally in the extensor hallucis longus muscle. MUAPs are reinnervated, however, with decreased recruitment that is more prominent distally and worse in the legs than in the arms.

At this point, we are ready to form our electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are consistent with a sensorimotor demyelinating polyneuropathy with secondary axonal loss. The lack of asymmetry or conduction block suggests an inherited disorder.*

We now have all the information needed to answer the seven key questions about the polyneuropathy in this case:

Key Neuropathy Questions	Answers
Temporal course	Chronic (in addition, the pes cavus suggests a problem dating back to childhood)
Fiber types involved	Motor ≫ sensory
Pattern	Distal, symmetric
Pathology	Demyelination without asymmetry or conduction block
Family history	Need to check
Associated medical illness	No
Toxic/Occupational exposure	No

With this information, the case can be further analyzed and other key questions answered. The clinical examination showing pes cavus and palpable nerves suggests an inherited demyelinating polyneuropathy, most likely some form of Charcot–Marie–Tooth. The nerve conduction studies provide unequivocal evidence of primary demyelination: markedly prolonged latencies, markedly slowed conduction velocities, and markedly prolonged or absent late responses.

How Does One Distinguish between an Inherited and Acquired Demyelinating Neuropathy?

In inherited disorders, all myelin is equally affected. Hence, there is uniform slowing of conduction without asymmetry and without the presence of conduction block or temporal dispersion. Although several of the Charcot–Marie–Tooth polyneuropathy types are primarily demyelinating, there are always secondary axonal changes, demonstrated by the low motor and sensory amplitudes on nerve conduction studies and by evidence of denervation and reinnervation on needle EMG.

Charcot–Marie–Tooth polyneuropathy typically presents very slowly, often with more prominent motor than sensory symptoms and signs. With careful testing, however, sensory abnormalities are always found on examination, and they are also present on nerve conduction studies.

What is the Appropriate Laboratory Evaluation in this Patient?

For this patient, it would be appropriate to obtain blood DNA testing to look for the duplication error on chromosome 17 that is associated with the most common type of demyelinating Charcot–Marie–Tooth polyneuropathy, CMT1A. Note that many of the antibody and other studies routinely obtained in cases of CIDP need not be performed in this case, because the combination of clinical and electrophysiologic data point clearly to an inherited, demyelinating polyneuropathy.

Case Follow-up

The patient underwent DNA testing for CMT1A, which showed a duplication error in chromosome 17p11.2. He was fitted for bilateral ankle foot orthoses and referred to physical therapy. Genetic counseling was advised.

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Amyotrophic Lateral Sclerosis and its Variants

27

Electrodiagnostic (EDX) studies play a central role in the evaluation of patients with amyotrophic lateral sclerosis (ALS), the most common of all motor neuron disorders. Although described earlier by others, the French neurologist Jean-Martin Charcot is credited as naming the disorder *amyotrophic lateral sclerosis* in 1869. The name is derived from the Greek *amyotrophic*, which means "no nourishment to the muscle," *lateral*, which refers to the lateral area in the spinal cord where the corticospinal tract is located, and *sclerosis*, which describes the scarring in the spinal cord that occurs when motor neurons deteriorate. In the United States, ALS is commonly referred to as *Lou Gehrig's disease*, after the famous baseball player who died of the condition in 1941.

ALS is most often encountered as a sporadic, progressive, degenerative disorder of unknown etiology that characteristically affects both upper motor neurons (UMNs) and lower motor neurons (LMNs) and spares sensory and autonomic function. A small number of cases of ALS (approximately 10%) are familial and are discussed in Chapter 28. In addition, several variants of ALS are well recognized, including progressive bulbar palsy, progressive muscular atrophy (PMA), and primary lateral sclerosis (PLS). Other less common motor neuron disorders exist, including those with atypical motor neuron manifestations caused by genetic mutations, infections, and immunologic disorders (see Chapter 28). Because the prognosis in ALS is uniformly poor compared with other motor neuron disorders, it is essential that the correct diagnosis be reached.

Electromyography (EMG) and nerve conduction studies are most often used to support the diagnosis of ALS. More importantly, however, they are used to help exclude other conditions, some potentially treatable, which may mimic ALS.

Nowhere else is the clinical–electrophysiologic correlation more important than in ALS. *EDX studies, by themselves, cannot make a diagnosis of ALS*. Rather, ALS remains a clinical diagnosis supported by EDX findings. The electromyographer must appreciate that other disorders may display EDX findings similar to those found in ALS (e.g., coexistent cervical and lumbar radiculopathy) and that it is the combination of clinical and EDX findings that allows a final diagnosis to be reached.

CLINICAL

Classic Amyotrophic Lateral Sclerosis

ALS is a degenerative, progressive disorder that affects both UMNs and LMNs. Although younger patients may be affected, it occurs most frequently in those 55 to 60 years old, with a slight male predominance. Signs and symptoms of LMN dysfunction include muscle atrophy, weakness, fasciculations, and cramps. UMN dysfunction manifests as stiffness, slowness of movement, spasticity, weakness, pathologic hyperreflexia, and Babinski responses. The presence of both UMN and LMN signs in the same myotome is characteristic of ALS. The mean duration of illness from symptom onset to death is approximately 3 years. However, it is important to remember that about 10% of patients follow a more benign course, surviving for many more years.

ALS is remarkably specific for the motor system. Although detailed pathologic studies have shown some minor loss of sensory fibers, it is distinctly unusual to see sensory complaints or findings on examination. Likewise, there is no disturbance of vision, hearing or the autonomic system. Late in the course, spasticity can affect the bladder, creating symptoms of urinary urgency and frequency. Clinically, an association between abnormalities of cognition and ALS has been recognized in some patients, especially between ALS and Frontotemporal Dementia (FTD). This association is seen in both sporadic and familial forms of ALS and FTD. If patients with classic ALS undergo formal neuropsychological testing, some 40–50% will display some mild evidence of executive dysfunction. FTD develops in approximately 5 to 15% of patients with ALS, and conversely, 10–15% of FTD patients show an associated motor neuron syndrome. Most often, ALS is a regional disease that usually starts in one body segment and progresses to adjacent myotomes. Most cases begin with insidious weakness in either a distal upper or lower extremity. In the upper extremity, the initial presentation can mimic an ulnar neuropathy, especially one at the wrist. In the lower extremity, the presentation is often a progressive foot drop, sometimes misdiagnosed as a peroneal palsy or L5 radiculopathy. As time progresses, symptoms develop in

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adjacent myotomes of the same limb and then spread to the contralateral limb. Progression continues to other extremities and ultimately to bulbar and respiratory muscles. Death usually results from respiratory insufficiency or from medical complications of prolonged inactivity (pulmonary embolus, sepsis, pneumonia, etc.).

The El Escorial criteria are most often quoted in reaching a diagnosis of ALS. These criteria were set by the World Federation of Neurology meeting in El Escorial, Spain, and published in 1994. They identify four separate body part regions: craniobulbar, cervical, thoracic and lumbosacral. Definite ALS requires that both UMN and LMN signs be seen together in at least three of these regions. Probable ALS requires UMN and LMN signs in two regions, with some UMN signs rostral to the LMN signs. Possible ALS requires UMN and LMN signs in one region or UMN signs in at least two regions. In addition to these criteria, there must be an absence of EDX, pathologic, or radiologic evidence that would support the diagnosis of another disease that may mimic ALS.

Patients with a typical ALS presentation including diffuse atrophy, weakness, fasciculations, and spasticity, in the appropriate age group and clinical setting, are relatively easy to identify. However, not all cases are straightforward, especially when patients present early in the illness with signs and symptoms that are anatomically restricted. In addition, several variants within the spectrum of classic ALS can present diagnostic problems (discussed in the following sections).

Progressive Bulbar Palsy

Patients with progressive bulbar palsy initially develop symptoms restricted to the bulbar muscles. They usually present with a several month history of progressive dysarthria with gagging, choking, and weight loss. The speech disturbance may lead to complete anarthria. These patients are commonly incorrectly diagnosed, and many undergo exhaustive ear, nose, and throat or gastrointestinal evaluations looking for the cause of dysarthria or dysphagia. Occasionally, patients may present with respiratory distress as the result of aspiration. Speech is most commonly slow and spastic with variable flaccid features, depending on the degree of LMN dysfunction. The tongue may be atrophied with fasciculations, accompanied by brisk jaw, gag, and facial reflexes (Figure 27–1). One of the characteristic signs is the "napkin or handkerchief sign." Because of excessive drooling from bulbofacial weakness, patients often carry a tissue in their hand to frequently clear their mouth and face of saliva. Occasionally the symptoms remain relatively restricted to the bulbar muscles. However, in the vast majority of patients the disorder eventually progresses to involve the limbs, as in typical ALS. Indeed, approximately 25% of patients with ALS will have the bulbar onset form.

Progressive Muscular Atrophy

Approximately 15% of patients with sporadic motor neuron disease present with a pure LMN syndrome referred to as progressive muscular atrophy. These patients have distal limb wasting and weakness, fasciculations, and cramps, with no sensory symptoms or signs. Reflexes may be present but are generally reduced or absent in weak limbs. The clinical course is commonly long, with slow progression to proximal limb muscles. Bulbar involvement is unusual, occurring very late if at all. Unequivocal UMN dysfunction is not present, although some patients have retained or slightly brisk reflexes that appear inappropriate for the level of limb weakness and atrophy. Of all the ALS variants, progressive muscular atrophy is the one that especially warrants thorough evaluation to exclude other disorders, in particular multifocal motor neuropathy with conduction block (MMNCB, discussed in the section on Differential Diagnosis), which is potentially treatable.

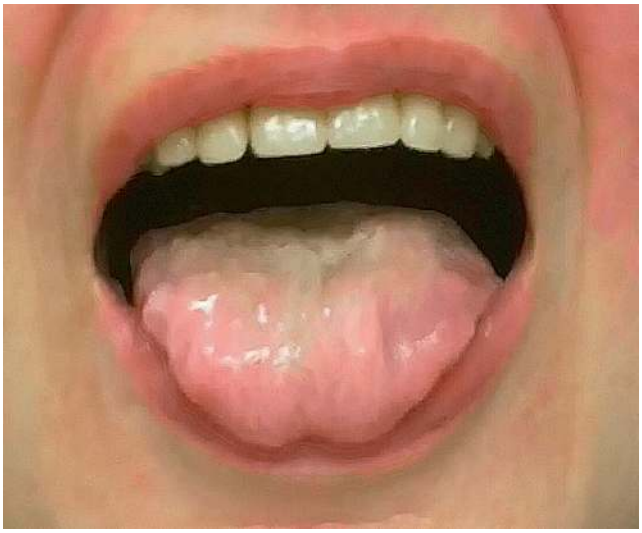

FIGURE 27–1 Tongue atrophy. One of the important findings in ALS is the presence of bulbar muscle weakness. The tongue is commonly affected in ALS. Typical lower motor neuron signs include atrophy, fasciculations and weakness; upper motor neuron dysfunction can also be discerned as difficulty moving the tongue quickly from side to side. In the photo, note the prominent atrophy of the tongue, especially on the left lateral side.

Primary Lateral Sclerosis

Primary lateral sclerosis is a very rare disorder marked by progressive and selective UMN involvement with sparing of the LMNs. It accounts for less than 1% of patients with an acquired motor neuron disorder. The disorder is characterized by spasticity, weakness, pathologically increased reflexes, Babinski signs, and pseudobulbar speech and affect. Atrophy (except due to disuse), fasciculations, or other LMN signs are not seen. The disease commonly presents as a progressive paraplegia or quadriplegia. Occasionally, patients present with progressive bulbar weakness of the spastic type, or hemiplegia. The course tends to be prolonged, with a better prognosis than classic ALS. Some patients may live for decades after the onset of the illness.

Flail Arm and Flail Leg Syndromes

The flail arm (FA) and flail leg (FL) phenotypes have been recognized for over a century, but have recently been studied in more detail. The FA syndrome has gone by many names, including the scapulohumeral variant of progressive muscular atrophy, the hanging arm syndrome, and the man-in-the-barrel syndrome. It presents with progressive weakness and wasting of both upper extremities, is often symmetric, and may affect proximal before distal muscles. However, there is little to no involvement of the lower extremities or bulbar muscles. Males are affected out of proportion to females (ratio 4:1). Many patients remain ambulatory for years. In a similar vein, FL syndrome (also known as the pseudopolyneuritic variant of ALS) presents with wasting and weakness of the lower extremities. UMN signs are either absent, subtle or occur late in the course. Unlike FA syndrome, FL syndrome shows no predilection for males over females. FA and FL syndrome often remain restricted to the upper or lower extremities, respectively, typically for 1 to 3 years.

Both the FA and FL presentations have important prognostic implications. Both progress very slowly and have significantly higher 5-year survival rates than classic limb onset ALS (FA: 52%; FL 64%; classic ALS: 20%). By 10 years out, however, the survival rates for FA and FL are similar to classic ALS.

ETIOLOGY

The etiology of sporadic motor neuron disorders is unknown. Immunologic, infectious, and excitotoxic etiologies have been speculated, but none have been proven. As new gene mutations associated with familial ALS are discovered, genetic screening of patients with sporadic ALS shows a very small percent of those patients have one of the genetic mutations associated with familial ALS.

DIFFERENTIAL DIAGNOSIS

The diagnosis of ALS usually is straightforward in patients who present with prominent UMN and LMN signs in both limb and bulbar muscles. However, most patients initially are seen early in the course of the disease, often when only one extremity is clinically affected. In addition, there are other disorders, some potentially treatable, which can mimic the clinical signs, electrophysiologic findings, or both in ALS and its variants (Box 27–1; also see Chapter 28). These disorders are discussed in detail later. In the case of classic ALS, the most important diagnosis to consider is coexistent cervical and lumbar stenosis. For PMA or predominantly LMN presentations of ALS, including the flail arm and flail leg syndromes, the most important diagnoses to consider are demyelinating motor neuropathy, especially MMNCB, and inclusion body myositis (IBM). In addition, benign fasciculation syndrome (BFS) and the myotonic disorders need to be kept in mind. In PLS, there is a large list of neurologic conditions that can be confused with the disorder and need to be excluded by appropriate imaging and other laboratory testing (see the section on Primary Lateral Sclerosis below).

Box 27–1. Differential Diagnosis of Motor Neuron Disease

- Idiopathic
  - Amyotrophic lateral sclerosis
  - Amyotrophic lateral sclerosis variants
    - Progressive bulbar palsy
    - Primary lateral sclerosis
    - Progressive muscular atrophy
    - Flail arm syndrome
    - Flail leg syndrome
  - Monomelic amyotrophy (benign focal amyotrophy)
- Infectious/postinfectious
  - Poliomyelitis
  - Postpolio syndrome
  - Retroviral-associated syndromes
  - West Nile encephalitis
- Inherited
  - Familial amyotrophic lateral sclerosis
  - Spinal muscular atrophy
    - Proximal adult or juvenile onset (Kugelberg–Welander disease)
    - X-linked bulbospinal muscular atrophy (Kennedy disease)
    - Distal spinal muscular atrophy (spinal form of Charcot–Marie–Tooth disease)
  - Hexosaminidase A deficiency
- Other conditions that may mimic motor neuron disease
  - Cervical/lumbar lesions
  - Toxic syndromes (e.g., lead poisoning)
  - Post-irradiation syndromes
  - Immune-mediated, demyelinating motor neuropathies
    - Multifocal motor neuropathy with conduction block
    - Atypical chronic inflammatory demyelinating polyradiculoneuropathy
  - Motor neuropathies associated with lymphoma and other malignancies

Cervical/Lumbar Stenosis

Degenerative disease of the neck and back is extremely common, especially in older individuals. The combination of cervical and lumbar spondylosis occasionally can mimic ALS, both clinically and in the EMG laboratory. Cervical spondylosis, by itself, is a common cause of gait disturbance in the elderly. Compression in the cervical area can result in a polyradiculopathy involving the cervical nerve roots as well as a myelopathy from direct cord compression. This can create a clinical picture of LMN dysfunction in the upper extremities and UMN dysfunction in the lower extremities (Figure 27–2). If additional compression occurs above the C5 level, UMN signs can be seen in the upper extremities as well. To complicate the situation further, patients with coexistent lumbar stenosis may have additional LMN signs in the lumbosacral myotomes. Taken together, the clinical picture can resemble ALS.

However, several points in the history and on the neurologic examination should raise the question of possible

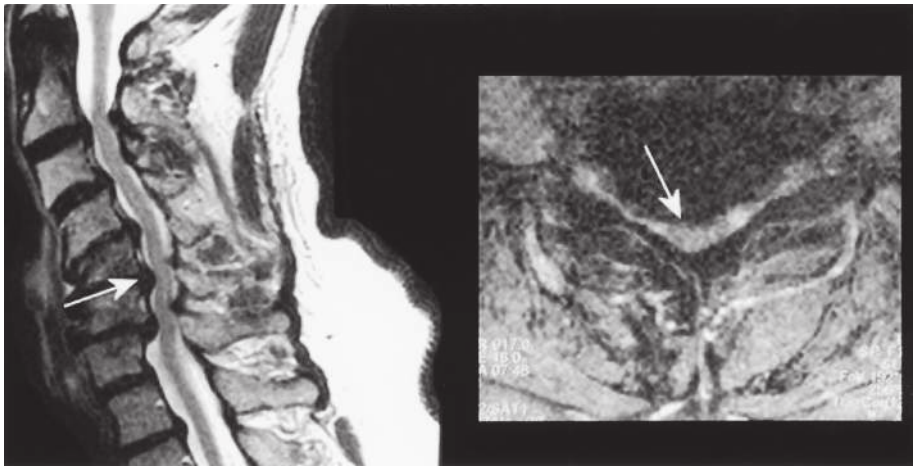

FIGURE 27–2 Cervical spondylosis. In the differential diagnosis of amyotrophic lateral sclerosis, one of the most important diagnoses to exclude is cervical spondylosis. Compression of the cervical nerve roots **(left, arrow)** results in a polyradiculopathy while direct cord compression **(right, arrow)** results in a myelopathy. This can create a clinical picture of lower motor neuron dysfunction in the upper extremities and upper motor neuron dysfunction in the lower extremities. If additional compression occurs above the C5 level, upper motor neuron signs can be seen in the upper extremities as well.

cervical or lumbar (or combined) stenosis. Cervical stenosis often follows a stepwise progression, sometimes associated with periods of improvement. In addition, there is usually some neck or radicular pain, along with limitation of neck motion and sensory symptoms in the arms. Paresthesias and vibratory loss in the lower extremities may occur as a result of posterior column compression. A Romberg sign may be present. Back pain commonly accompanies coexistent lumbar stenosis. Moreover, increased pain or sensory disturbance may develop after walking a distance, which is relieved only by the sitting position.

The signs and symptoms noted above will usually suggest the diagnosis of cervical and lumbar stenosis. However, occasionally a patient with cervical and lumbar stenosis presents with a relatively pure motor syndrome consisting of muscle weakness, atrophy, and spasticity, making the clinical distinction from ALS difficult. It is in these patients that the clinical and EMG evaluation of the bulbar and thoracic paraspinal muscles assumes special significance, because they should never be abnormal in lesions restricted to the cervical or lumbar spine (see Chapter 26).

Multifocal Motor Neuropathy with Conduction Block

An important condition that can mimic the PMA presentation of ALS clinically is demyelinating motor neuropathy. Nearly all peripheral neuropathies have both sensory and motor symptoms and signs; therefore, they are not frequently confused with ALS. Very few neuropathies, however, are purely or predominantly motor. Of those, most are demyelinating and are believed to be immune mediated. Although the exact pathophysiology is not understood, presumably some component of motor nerve or myelin is selectively targeted by the immune system, leading to motor dysfunction. It is in these circumstances that a motor neuropathy may be mistaken for a motor neuronopathy (i.e., motor neuron disease). Although it is quite rare, the motor neuropathy that must be excluded, especially in patients with predominantly LMN dysfunction, is MMNCB (see Chapter 26).

MMNCB usually affects only motor fibers, sparing sensory fibers. It often is slowly progressive and begins distally, like ALS. In addition, fasciculations and cramps are common. Unlike ALS, however, it more commonly affects younger patients (<45 years) and has a strong male predominance (male-to-female ratio of approximately 2:1). Several important clues may suggest MMNCB on examination. Often, individual motor nerves are affected out of proportion to adjacent nerves that have the same myotomal innervation (hence, multifocal motor neuropathy). For instance, severe weakness in distal median-innervated muscles with relative sparing of ulnar-innervated muscles might occur in MMNCB, but would be very unusual in ALS, marking the disorder as a motor nerve rather than a motor neuron disorder. Second, muscle weakness may appear out of proportion to muscle atrophy in MMNCB, especially early in the course of the disease, reflecting that demyelination, not axonal loss, is the major underlying pathology. Finally, MMNCB does not result in any UMN dysfunction. Reflexes usually are depressed or normal. Pathologic hyperreflexia, spasticity, and Babinski signs are not seen.

The diagnosis of MMNCB may be suggested by the clinical presentation as well as by elevated titers of antiganglioside antibodies, which occur in more than half of patients. Most often, MMNCB is diagnosed through nerve conduction studies, which show evidence of conduction block along motor fibers, between distal and proximal segments. It is extremely important not to miss this diagnosis because the prognosis for these patients is far better than for patients with ALS. Most patients with MMNCB respond well to immune-modulating therapy, especially treatment with intravenous immunoglobulin.

Inclusion Body Myositis

IBM is an idiopathic inflammatory disorder of muscle that can be confused clinically and sometimes electrically with the PMA variant of ALS. IBM is now the most common inflammatory myopathy in individuals older than 50 years. Clinically, IBM presents as slowly progressive weakness.

It is more common in men than in women. Along with proximal muscle weakness, distal muscles are commonly involved. In some patients, the distal muscles are weaker than the proximal ones. Although the distribution of weakness most commonly is symmetric, asymmetric presentations often occur. The disease has a predilection for certain muscles, including the iliopsoas, quadriceps, tibialis anterior, biceps, triceps, and long finger flexors. Prominent muscle atrophy, especially of the quadriceps, is common. Facial and ocular weakness does not occur. However, dysphagia is common. The deep tendon reflexes tend to be depressed or absent early in the course, especially the quadriceps reflex. Patients with IBM and severe distal and proximal weakness and wasting, with depressed reflexes, can easily be mistaken for an LMN disease such as PMA.

Unfortunately, the electrophysiology often complicates the diagnosis of IBM. Prominent fibrillation potentials and positive sharp waves are common. Motor unit action potentials (MUAPs) can be small and short, typical of a myopathy; large and long, suggestive of a neuropathic process; or a combination of both. Although large, long duration MUAPs are classically associated with neuropathic disorders, they are also seen in chronic myopathies, especially in those associated with denervation (i.e., usually myopathies with inflammatory or necrotic features).

One of the key differentiating features between LMN disease and IBM is the presence of fasciculations and cramps. Both fasciculations and cramps are neuropathic phenomena; they are not seen in any myopathy, including IBM. In the absence of fasciculations and cramps in a patient with a LMN syndrome, muscle biopsy sometimes is needed to make the differentiation between a motor neuron disorder and IBM.

Benign Fasciculation Syndrome

Fasciculations are noted in nearly all individuals and are a benign phenomenon. However, because of the well-recognized association of fasciculations and ALS, some people, especially medical personnel or those with a family member with ALS, are more likely to be concerned about fasciculations and bring them to medical attention. The vast majority of persons who experience fasciculations have no neurologic disease. BFS is diagnosed in those individuals who have frequent fasciculations beyond what is normally experienced and have normal neurologic and EMG examinations (except for fasciculations). In some patients with BFS, there may be accompanying fatigue, cramps, and exercise intolerance. In extensive follow-up studies, no patient with BFS developed ALS or any other significant neurologic disorder. It is important to reassure patients with BFS that they have no greater risk of developing motor neuron disease than any other individual.

Myotonic Syndromes

Patients with one of the myotonic syndromes (see Chapter 36) typically are not confused clinically with ALS or other motor neuron disorders. However, occasional patients have been given the diagnosis of motor neuron disease erroneously, based on an electromyographer misinterpreting myotonic discharges as denervating potentials (fibrillation potentials and positive sharp waves). A myotonic discharge is the spontaneous discharge of a muscle fiber (similar to fibrillation potentials and positive sharp waves) but is differentiated by its characteristic waxing and waning of both amplitude and frequency. On EMG, myotonic discharges have a characteristic "revving engine" sound due to the waxing and waning of amplitude and frequency. The error in interpretation occurs because both have the same basic morphology as both are generated in muscle fiber, and denervating potentials are common whereas myotonic discharges are uncommon in clinical practice. However, once the waxing and waning sound of myotonic discharges is recognized, the differentiation is easily made.

Primary Lateral Sclerosis Mimics

There are a large number of neurologic conditions that can present with UMN symptoms and signs similar to PLS. Most can be excluded by brain and cervical spine imaging. Occasionally, brain imaging will demonstrate abnormalities consistent with PLS. In these cases, abnormal T2 or fluid-attenuated inversion recovery (FLAIR) signals restricted to the corticospinal tracts will be seen on magnetic resonance imaging (Figure 27–3). However, imaging is usually indicated primarily to help exclude certain disorders such as multiple sclerosis, multiple infarcts, cervical spondylosis, syringomyelia, Chiari malformation, compressive foramen magnum lesions, and spinal cord tumors, all of which may be confused with PLS.

In addition, some cases of familial spastic paraparesis (Strümpell disease) and adrenomyeloneuropathy may be difficult to differentiate from primary lateral sclerosis without an accurate family history and, in the case of adrenomyeloneuropathy, a blood assay for very long chain fatty acids. Many forms of familial spastic paraparesis can be definitively diagnosed through commercially available genetic testing. Tropical spastic paraparesis resulting from human T-lymphotropic virus type 1 (HTLV-1) may be difficult to differentiate from PLS, although these patients often have minor sensory loss in the lower extremities. A blood assay for HTLV-1 antibodies confirms the diagnosis. Lastly, there are rare reports of patients with PLS- or ALS-like syndromes who are positive for the human immunodeficiency virus. When treated with antiviral therapy, their motor neuron syndrome either improved or recovered.

ELECTROPHYSIOLOGIC EVALUATION

Nerve Conduction Studies

It is essential to perform both motor and sensory nerve conduction studies in patients suspected of having ALS (Box 27–2). At a minimum, routine motor and sensory nerve conduction studies along with late responses should

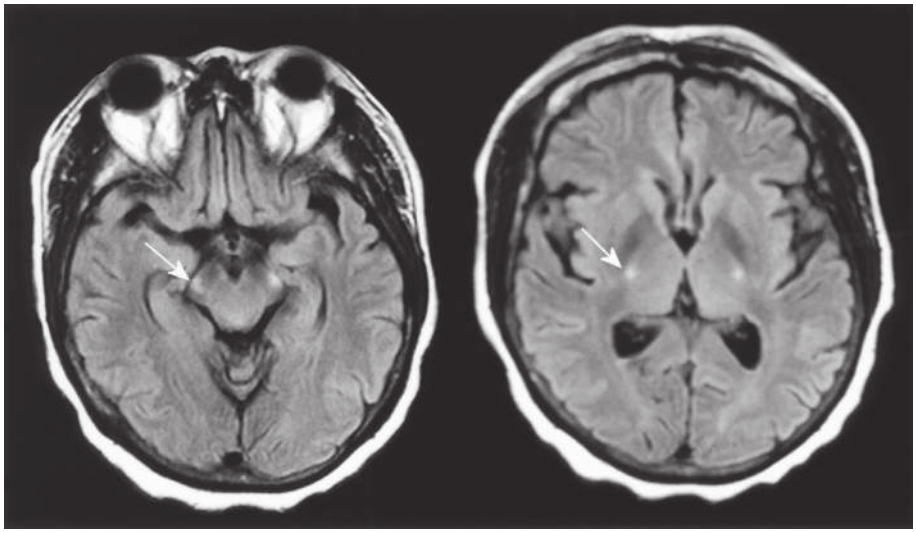

FIGURE 27–3 Magnetic resonance imaging (MRI) and motor neuron disease. Axial fluid-attenuated inversion recovery (FLAIR) MRI at the level of the upper midbrain **(left)** and basal ganglia/internal capsule **(right)** in a patient with primary lateral sclerosis. Note the abnormal signal in the cerebral peduncle and internal capsule bilaterally, corresponding to the location of the corticospinal tracts. Similar findings occasionally are present in patients with amyotrophic lateral sclerosis.

Box 27–2. Recommended Nerve Conduction Study Protocol for Motor Neuron Disease

Routine motor studies (ipsilateral to the most symptomatic side):

1. Median study, recording abductor pollicis brevis and stimulating the wrist and antecubital fossa
2. Ulnar study, recording abductor digiti minimi and stimulating the wrist and below and above the elbow
3. Ulnar study, recording first dorsal interosseous and stimulating the wrist and below and above the elbow
4. Peroneal study, recording extensor digitorum brevis and stimulating the ankle, below the fibular neck, and lateral popliteal fossa
5. Tibial study, recording abductor hallucis brevis and stimulating the ankle and popliteal fossa

Routine sensory studies (ipsilateral to the most symptomatic side):

1. Median SNAP, stimulating the wrist and recording digit 2
2. Ulnar SNAP, stimulating the wrist and recording digit 5
3. Radial SNAP, stimulating the forearm and recording the snuffbox
4. Sural SNAP, stimulating the calf and recording posterior ankle

Late responses (ipsilateral to the most symptomatic side):

1. F responses: median, ulnar, peroneal, and tibial
2. H reflexes

Special considerations:

- The yield of searching for conduction block increases as additional motor nerves or segments are studied. In selected patients, either the contralateral routine motor nerves can be studied or proximal stimulation studies can be performed (or both). The ulnar and median nerves can be stimulated with surface electrodes in the axilla and at Erb's point. Needle stimulation can be performed at the C8 root. Proximal tibial studies can be performed by needle stimulation at the gluteal fold and at the S1 root. Proximal stimulation studies have significant technical limitations.
- Contralateral motor studies should be considered, especially in patients with predominantly lower motor neuron syndromes without definite upper motor neuron signs. Proximal stimulation studies should also be considered in patients with predominantly lower motor neuron syndromes and in patients in whom the routine motor studies are normal but the late responses are abnormal, a pattern suggestive of a proximal lesion.
- Compute the amplitude ratios of the APB/ADM and FDI/ADM. In some cases of ALS, the lateral hand is affected more than the medial hand. This results in an APB/ADM ratio <0.6 and an FDI/ADM ratio of <0.9. If both of these are abnormal, in the appropriate clinical setting, they are supportive of the diagnosis of ALS.

SNAP, sensory nerve action potential.

be performed in an upper and a lower extremity, preferably on the most symptomatic side, before proceeding to the needle EMG study.

Results of motor nerve conduction studies may be normal in ALS, especially in clinically unaffected limbs, but more often show evidence of axonal loss. Axonal loss results in similar changes on motor nerve conduction studies regardless of whether the lesion is at the level of the motor neuron, root, plexus, or peripheral nerve. Compound muscle action potential (CMAP) amplitudes decrease, whereas distal latencies and conduction velocities remain relatively intact. If the larger and faster motor axons are lost, some slowing of conduction velocity and distal latency may occur (Figure 27–4), although the slowing usually never reaches the unequivocal demyelinating range (i.e., conduction velocity <75% of the lower limit of normal; distal latency >130% of the upper limit of normal). It is not unusual to find some mild to moderate slowing of conduction velocity and distal latency, especially when CMAP amplitudes are very low.

Although not completely specific to ALS, one pattern that may be seen is the "split-hand syndrome," a term first coined by Wilbourn. In patients with ALS, muscle wasting may affect the lateral hand (thenar muscles and first dorsal

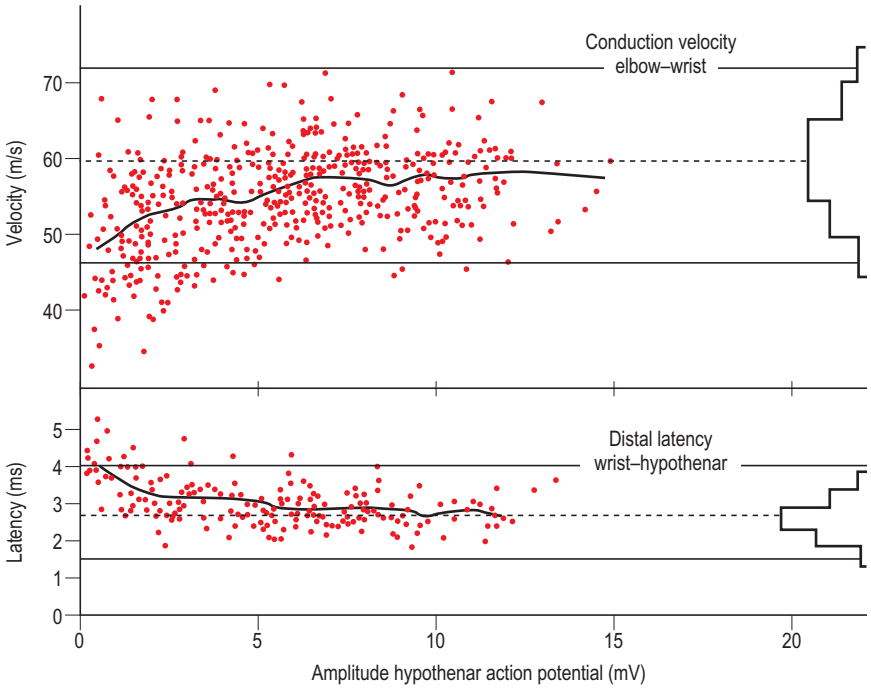

FIGURE 27–4 Conduction velocity and distal latency in amyotrophic lateral sclerosis. Ulnar compound muscle action potential (CMAP) amplitude, recorded over hypothenar muscles and plotted against conduction velocity **(top)** and distal latency **(bottom).** Each dot represents a patient; the dark solid line shows the mean value. Note that both the mean conduction velocity and distal latency remain within the normal range but slow as CMAP amplitude decreases.
(Reprinted from Lambert EH. Electromyography in ALS. In: Norris HF Jr, Kurland LT, eds. Motor neuron diseases. New York: Grune & Stratton, 1969. With permission.)

interosseous) out of proportion to the medial hand (hypothenar) muscles. Similarly on nerve conduction studies, the motor amplitudes from the abductor pollicis brevis (APB) and first dorsal interosseous (FDI) may be decreased more than the amplitude from the abductor digiti minimi (ADM), though all three muscles are C8–T1 innervated. In one study, both the APB/ADM ratio and FDI/ADM ratios were lower in patients with ALS than controls. These ratios are calculated simply by measuring the amplitudes of the CMAPs of the APB, FDI, and ADM, during routine median and ulnar motor conduction studies. An APB/ADM ratio of <0.6 (considered abnormal) was present in 40% of patients with ALS, compared to only 5% of normals. An FDI/ADM ratio of <0.9 (considered abnormal) was seen in 34% of patients with ALS, compared to only 1% of normals. Twenty percent of patients with ALS had *both* an abnormal APB/ADM and FDI/ADM ratio with no normal controls showing both. These results suggest that the split-hand syndrome is supportive of a diagnosis of ALS. The reason behind this pattern in some patients with ALS is not completely understood. However, in the cortex, the number of cortical motor neurons that supply the APB and FDI outnumber those to the ADM. Another possible explanation is the relative contribution of C8 and T1 fibers in the FDI, APB, and ADM. The FDI and APB have a relatively greater amount of T1 innervation compared to the ADM, which has a large contribution from C8. Thus, motor neuron degeneration at T1 would disproportionally affect the FDI and APB compared to the ADM.

The most important reason to perform motor nerve conduction studies is to look for unequivocal evidence of demyelination, especially conduction block along motor nerves. *The presence of conduction block along motor nerves signifies that (1) the underlying disorder is a motor neuropathy and not a motor neuron disease, (2) the major cause of weakness is conduction block and not loss of motor neurons or axons, and (3) the disorder is potentially treatable with immune-modulating therapy*. Conduction block of motor fibers is the major electrophysiologic finding in patients with MMNCB (Figure 27–5). Other electrophysiologic evidence of demyelination (slowed conduction velocities, prolonged distal latencies, and prolonged late responses) may be seen.

Because temporal dispersion without conduction block may cause some decrease in both CMAP amplitude and area between proximal and distal stimulation sites, the electrophysiologic criteria for conduction block are complicated. Computer simulation models have shown that marked temporal dispersion can cause the CMAP amplitude to drop by more than 50% between proximal and distal sites, even in the absence of conduction block. In contrast, these models have shown that any drop of CMAP *area* greater than 50% between proximal and distal stimulation sites always signifies conduction block, and cannot be explained on the basis of temporal dispersion alone. The effects of temporal dispersion are always more pronounced when a nerve is studied over a long distance. In practice, when routine nerve segments (wrist-to-elbow, ankle-to-knee) are studied in normal individuals and in patients with axonal loss, CMAP area and amplitude rarely drop by more than 20%. Therefore, any drop in CMAP area or amplitude of more than 20% over a short segment, especially if associated with focal slowing, usually indicates conduction block.

To increase the yield of nerve conduction studies for detecting conduction block, more proximal stimulation (axilla, Erb's point, cervical nerve roots) often is attempted

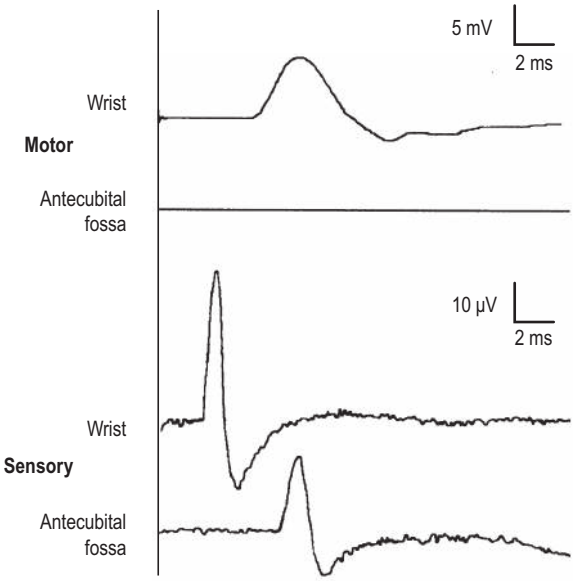

FIGURE 27–5 Conduction block in multifocal motor neuropathy. Median motor and sensory studies, with the abductor pollicis brevis and digit 2 co-recorded and the wrist and elbow stimulated. The hallmark finding in patients with multifocal motor neuropathy with conduction block is the presence of conduction block between proximal and distal stimulation sites in motor but not sensory fibers. Note complete block of motor fibers **(top).** The drop of sensory amplitude is within the normal range, expected for normal phase cancellation **(bottom).** Motor conduction block is not seen in patients with amyotrophic lateral sclerosis or other motor neuron diseases.

in patients with suspected ALS. Although this technique may be of value in selected individuals, several important technical considerations must be kept in mind. First, supramaximal stimulation can be difficult to achieve, even with maximum current output, especially at Erb's point and at the root level. If submaximal stimulation is mistaken for supramaximal, a conduction block may be erroneously identified. Second, proximal stimulation often results in co-stimulation of adjacent nerves. For instance, at Erb's point and the C8 root, it is not possible to stimulate ulnar motor fibers without also stimulating median motor fibers. Unless collision techniques are used to eliminate the contribution from the co-stimulated nerve, the findings may be difficult if not impossible to interpret (see Chapter 30). Finally, with increased distance the effects of temporal dispersion are greater. For example, when studying the ulnar nerve between the elbow and wrist, one allows a drop in CMAP area or amplitude of up to 20% to account for the normal effects of temporal dispersion. However, stimulating the ulnar nerve at Erb's point (hence, doubling the distance), one must allow a drop in CMAP amplitude and area of up to 40% between distal and proximal sites to account for normal temporal dispersion. In proximal stimulation studies performed on patients with well-documented ALS, the drop in CMAP area and amplitude does not exceed 50%.

The presence of conduction block along motor fibers usually signifies a demyelinating neuropathy; in a patient with suspected motor neuron disease, especially PMA, it often signifies MMNCB. Of course, the diagnosis of MMNCB cannot be based on finding conduction blocks only at the usual entrapment sites, such as ulnar neuropathy at the elbow or peroneal neuropathy at the fibular head. Thus, a patient with ALS who develops an ulnar neuropathy at the elbow due to weight loss and immobility still has ALS, not MMNCB.

Like motor studies, sensory nerve conduction studies must be performed in an upper and a lower extremity. Sensory nerve conduction studies are always normal in ALS and its variants. Unless there is a clear reason that a patient should have an underlying polyneuropathy or entrapment neuropathies, the presence of abnormal sensory conduction studies should always cause the clinician to seriously question the diagnosis of ALS. The only notable exception to normal sensory conduction studies in a motor neuron disorder is X-linked bulbospinal muscular atrophy, in which patients may have absent or abnormal sensory nerve action potentials (SNAPs), probably due to involvement of the dorsal root ganglia (see Chapter 28).

It is critical to note that motor and sensory nerve conduction studies can be identical in patients with ALS and in patients with cervical/lumbar stenosis. In patients with either diagnosis, the SNAPs will be normal, but for different reasons. Patients with ALS have no sensory findings, whereas patients with cervical/lumbar stenosis may have sensory loss, but since the lesion is proximal to the dorsal root ganglia, the SNAPs are spared. In both cases, motor studies may be normal or may show evidence of axonal loss. The late responses may help to differentiate the two, but should never be used as the sole differentiating factor. F-wave abnormalities (prolongation, impersistence, dispersion, or absence) are more likely to occur in a polyradiculopathy. Likewise, the H reflexes may be absent or delayed in lumbar stenosis affecting the S1 nerve roots.

In some patients with ALS, especially late in the course, late responses may also show subtle abnormalities. As motor neurons are lost, fewer motor units are available to participate in the F response. Indeed, some muscles may be left with only a few motor units. In this situation, F responses may be impersistent, simply reflecting the reduced number of motor units available to backfire. If the largest and fastest firing motor units have been lost, minimal F-wave latency may be slightly prolonged, reflecting the normal though more slowly conducting motor neurons still present. In addition, "repeater F responses" may occur with some frequency. In general, it is unusual to see the same F-wave morphology twice because there usually are many motor units available to participate in the F response. In ALS, however, if only a few motor units remain, only those few motor units are available to create the F response. Accordingly, the chance of seeing the same F response twice is increased. In summary, although late-response abnormalities are more suggestive of polyradiculopathy than ALS, they cannot definitively differentiate between the two, since similar abnormalities can also be seen in ALS.

Electromyographic Approach

The EMG evaluation of patients with suspected ALS usually is extensive (Box 27–3). It is not unusual to sample all four limbs, the paraspinal muscles, and the bulbar muscles. Even though symptoms are often restricted to one or two limbs when a patient first presents for neurologic evaluation, EMG often reveals widespread denervation and reinnervation, even in the early stages of the disease. Because the diagnosis of ALS portends a grave prognosis, a thorough evaluation must always be conducted before a conclusion is reached. In order for the EMG study to support a diagnosis of ALS, active denervation with reinnervation must be found in three of four body segments (craniobulbar, cervical, thoracic, lumbosacral) and be unexplained by multiple mononeuropathies or radiculopathies.

In each muscle sampled, one looks for evidence of prior axonal loss (reinnervation) as well as evidence of ongoing axonal loss (denervation). Spontaneous activity usually is prominent, in the form of fibrillation potentials, positive sharp waves, and fasciculations. Fasciculations, the spontaneous depolarizations of motor units, often are irregular and quite slow (<1 Hz). The best way to look for fasciculations is to place the needle in the muscle, have the patient relax, and then, most importantly, remove one's hand from the needle. Fasciculations by themselves are insufficient evidence of active denervation. The conclusion that active denervation is present must be based on finding fibrillation potentials or positive sharp waves, because fasciculations occur in many other disorders and are also seen as a benign phenomenon in many normal individuals.

Despite the presence of prominent denervation, it is unusual to find complex repetitive discharges in ALS. Complex repetitive discharges are a chronic phenomenon; when observed in patients with motor neuron disease, they more often imply a very chronic motor neuron disorder, such as old poliomyelitis, or the LMN presentation of adult-onset hexosaminidase A deficiency (see Chapter 28).

Along with abnormal spontaneous activity, there is always evidence of compensatory reinnervation in ALS. With the exception of poliomyelitis, all motor neuron disorders usually are slowly progressive. *The pattern of acute or subacute neuropathic loss (active denervation, with normal MUAP morphology and decreased recruitment of MUAPs) is not seen in ALS.*

In patients with suspected ALS, many muscles should be sampled to demonstrate the underlying widespread nature of the disease. *Neuropathic changes must be demonstrated in muscles innervated both by different nerves that share the same myotome, and by different myotomes.* This point cannot be overemphasized. For example, if a C7 median-innervated muscle is severely abnormal and a C7 radial-innervated muscle is normal, one must seriously question the diagnosis of any type of motor neuron disorder. By its nature, motor neuron disease is a myotomal disease; it does not spare individual nerves in the same myotome, as MMNCB often does.

In addition to documenting denervation and reinnervation, one must pay particular attention to MUAP recruitment. Decreased recruitment signifies loss of motor units, which is the primary problem in motor neuron disease. Judging recruitment of MUAPs allows the electromyographer to assess the number of functioning motor units. Although there are electrophysiologic techniques available to count the number of motor units in a particular muscle, most are time consuming, and each has its own set of potential technical problems.

The evaluation of MUAP recruitment also plays a crucial role in differentiating motor neuron disorders from some cases of chronic myopathy with denervating features. As noted earlier, some patients with IBM and other chronic myopathies may have profuse fibrillation potentials and positive sharp waves associated with long-duration, high-amplitude, polyphasic MUAPs (i.e., the pattern typically associated with acute and chronic axonal loss). Although some patients with chronic myopathy may also have brief-duration, low-amplitude, polyphasic MUAPs (so-called myopathic motor unit potentials), others may not. It is in such cases, wherein myopathic motor unit potentials are not seen, that the assessment of MUAP recruitment usually allows the differentiation of neuropathic from myopathic conditions. In contrast to motor neuron disease, in which recruitment is reduced, in chronic myopathy, recruitment

Box 27–3. Recommended Electromyographic Protocol for Motor Neuron Disease

Limb muscles:
Sample at least three limbs, making sure to sample the following in each limb: distal and proximal muscles, muscles with different nerve innervation, and muscles with different root innervation

Thoracic paraspinal muscles:
Sample at least three segments
Avoid sampling T11–T12 (may rarely be affected by spondylosis)

Bulbar muscles:
Sample at least one muscle (patients with bulbar weakness should have more muscles sampled)
Tongue, masseter, sternocleidomastoid, and facial muscles can be sampled

Special considerations:
- Electrophysiologic evidence consistent with amyotrophic lateral sclerosis usually is defined as active denervation and reinnervation in three of four body segments (craniobulbar, cervical, thoracic, lumbosacral) that cannot be explained by multiple individual mononeuropathies or radiculopathies. Thus, examination of the thoracic paraspinal and craniobulbar musculature assumes special importance in the electrophysiologic differentiation of amyotrophic lateral sclerosis from cervical/lumbar polyradiculopathy.
- Patients with old poliomyelitis often display diffuse chronic reinnervation with reduced recruitment of motor unit action potentials. Prominent active denervation, however, is unusual.

usually remains normal or early. If, in rare situations, it is reduced, the degree to which it is reduced often is less than would be expected for the degree of denervation and reinnervation.

Along with decreased recruitment, decreased activation may be seen in patients with ALS. Activation, the ability to fire available motor units faster, is a central nervous system process. The UMN dysfunction in patients with ALS results in decreased activation. On the whole, the EMG picture of classic ALS is one of denervation, reinnervation, decreased recruitment, and decreased activation of MUAPs in multiple muscles innervated by different nerves and myotomes.

In patients with suspected ALS, the limb muscles often are sampled first. Of course, widespread EMG abnormalities found in the limb muscles cannot differentiate severe cervical/lumbar polyradiculopathy from ALS. It is in these cases that the evaluation of the thoracic paraspinal and craniobulbar muscles assumes diagnostic importance.

Denervation is often found in the thoracic paraspinal muscles in patients with ALS. This finding is important in eliminating the possibility of coexistent cervical and lumbar spinal stenosis mimicking ALS. One prospective study of patients referred with the suspected diagnosis of ALS found that 78% of all patients who eventually were diagnosed with ALS by conventional means had evidence of denervation in the thoracic paraspinal muscles when three or four segments were assessed. In a control group of patients with spondylosis, denervation in the thoracic region was extremely uncommon, occurring in only 1 (5%) of 21 patients. This single patient had severe stenosis of the lumbar and adjacent thoracic spine. The thoracic paraspinal muscles generally constitute a safe and accessible site for needle EMG and are one of the most useful areas to examine to help differentiate patients with spondylosis from those with ALS. The only difficulty often encountered is inadequate muscle relaxation. This is a problem especially in very weak patients, in whom thoracic paraspinals may activate with each breath, making it difficult to determine the presence of spontaneous activity.

The other area in which EMG abnormalities assume great diagnostic significance is in the craniobulbar musculature. Clear-cut evidence of denervation and reinnervation in the bulbar muscles removes the possibility of cervical or lumbar spondylosis as the sole cause of the motor dysfunction. Muscles often chosen for study include the tongue, masseter, and facial muscles. However, several points must be taken into account when evaluating the bulbar muscles. First, it is difficult for patients to relax the tongue, so the assessment of spontaneous activity often is demanding. In addition, the size and firing pattern of MUAPs in the bulbar muscles are different from those in the limb muscles. Bulbar MUAPs are shorter in duration than those found in the limb muscles and may be misinterpreted as fibrillation potentials or myopathic MUAPs. In addition, the onset firing frequency is higher for bulbar than for limb muscles and may suggest a neuropathic recruitment pattern even in normal muscles. Every electromyographer should gain familiarity with normal bulbar MUAPs before examining the bulbar muscles in patients with suspected ALS.

EXAMPLE CASE

Case 27–1

History and Physical Examination

A 54-year-old woman was referred for progressive weakness over the past 8 months. Weakness began as a footdrop in the left lower extremity, and similar symptoms developed in the contralateral leg 2 months later. There was no history of trauma, pain, paresthesias, or sensory loss. The patient had no complaints in the upper extremities.

On neurologic examination, mental status and cranial nerve function were normal. In the upper extremities, there was slight atrophy of the intrinsic hand muscles bilaterally, noted in the thenar eminence. However, strength was normal. In the lower extremities, there was spasticity with prominent wasting and fasciculations in all muscles below the knees. Strength testing showed marked bilateral footdrops. In addition, there was weakness of plantar flexion, ankle inversion, and ankle eversion distally. Proximally in the lower extremities, there was mild weakness of hip flexion, extension, abduction, and adduction. Deep tendon reflexes were present and normal in the upper extremities. In the lower extremities, reflexes were pathologically brisk with clonus at the ankles. Plantar responses were extensor bilaterally. Sensory examination showed normal sensitivity to light touch, temperature, and vibration.

Summary

The history in this case is essentially one of bilateral footdrops. The history alone might suggest the possibility of bilateral peroneal neuropathies, due to either compression or entrapment at the fibular neck. Likewise, there may be bilateral peroneal neuropathies from another cause, such as mononeuritis multiplex. It is not unusual for mononeuritis multiplex to affect the peroneal nerves and to progress in an asymmetric, stepwise manner. However, several points argue against either of these diagnoses. First, the patient describes her problem as slowly progressive. Second and more important is the notable absence of sensory symptoms (i.e., numbness or paresthesias). Accordingly, the clinical sensory examination and the sensory nerve conductions will be of particular importance.

On examination, the cranial nerves and upper extremities are relatively normal, with only the suggestion of slight atrophy in the thenar eminence bilaterally. In the lower extremities, there are marked bilateral footdrops with wasting of the lower legs, as expected from the history. However, the weakness of plantar flexion and ankle inversion (both tibial-innervated functions) clearly places the abnormalities beyond the territory of the

CASE 27–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = μV			Latency (ms)			Conduction Velocity (m/s)			F-Wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	4.2		≥4	4.6		≤4.4				24		≤31
	Antecubital fossa	APB	4.0			8.4			53		≥49			
Ulnar (m)	Wrist	ADM	8.8		≥6	3.9		≤3.3				25		≤32
	Below elbow	ADM	8.4			7.3			59		≥49			
	Above elbow	ADM	8.4			8.4			65					
Ulnar (m)	Wrist	FDI	5.2		≥6	4.2		≤4.5				27		≤32
	Below elbow	FDI	5.1			8.5			57		≥49			
	Above elbow	FDI	5.0			9.7			59		≥49			
Median (s)	Wrist	Index finger	46		≥20	3.3		≤3.5	55		≥50			
Ulnar (s)	Wrist	Little finger	35		≥17	2.9		≤3.1	57		≥50			
Radial (s)	Forearm	Snuffbox	42		≥17	2.5		≤2.9	62		≥50			
Tibial (m)	Ankle	AHB	11.8		≥4	6.4		≤5.8				46		≤56
	Popliteal fossa	AHB	8.9			14.1			43		≥41			
Peroneal (m)	Ankle	EDB	2.4		≥2	4.9		≤6.5				45		≤56
	Below fibula	EDB	2.3			12.8			46		≥44			
	Lateral popliteal fossa	EDB	2.0			13.1			51		≥44			
Sural (s)	Calf	Posterior ankle	9		≥6	4.3		≤4.4	47		≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis; ADM = abductor digiti minimi; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

peroneal nerves. In addition, there is mild weakness of hip flexion, extension, abduction, and adduction. Fasciculations are also noted in the lower extremities. At this point, the clinical abnormalities do not correspond to any one nerve or root distribution. The lesion must involve multiple nerves, the lumbosacral plexus, or multiple nerve roots in both lower extremities. However, the sensory examination is completely normal. The finding of weakness with sparing of sensation indicates that we are dealing with a predominantly motor problem. The normal sensory examination makes multiple mononeuropathies, a lumbosacral plexopathy, or polyradiculopathy seem unlikely. Finally and probably most importantly, the deep tendon reflexes are pathologically brisk with clonus at the ankles. The plantar responses are extensor bilaterally. The hyperreflexia, increased tone (spasticity), and extensor plantar responses denote an additional UMN lesion in this patient. Thus, the neurologic examination reveals evidence of both lower and upper motor neuron dysfunction in the lower extremities and sparing of the sensory system. Furthermore, the lower and upper motor neuron signs are in the same spinal segments. For example, the plantar flexors (L5–S1 segments) are weak, wasted, and fasciculating, but there is also spasticity and clonus at the ankles (S1 segment). This is a very unusual situation that is strongly suggestive of ALS.

The nerve conduction studies are performed first, with the electromyographer keeping in mind the strong

CASE 27–2. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
						Configuration		
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Duration	Amplitude	Polyphasia
Right tibialis anterior	↑	+2	+1	Fair	↓↓	+3	+2	+2
Right medial gastrocnemius	↑	+2	+2	Poor	↓↓	+2	+2	+2
Right vastus lateralis	↑	+1	+1	NL	↓	+1	+2	+2
Right iliacus	↑	+1	0	NL	↓	+1	+1	+1
Right gluteus medius	↑	+2	+1	Fair	↓↓	+2	+2	+2
Right gluteus maximus	↑	+2	0	NL	↓	+1	+1	+1
Left tibialis anterior	↑	+3	0	Poor	↓↓↓	+3	+3	+2
Left medial gastrocnemius	↑	+2	+2	Fair	↓	+2	+2	+2
Left vastus lateralis	↑	+2	+1	Fair	↓	+2	+1	+1
Left iliacus	↑	+2	0	NL	↓	+1	+1	+1
Left gluteus medius	↑	+2	+1	NL	↓↓	+2	+1	+1
Right first dorsal interosseous	↑	+1	0	NL	↓	+1	NL	+1
Right abductor pollicis brevis	↑	+1	0	NL	↓	+1	+1	+1
Right pronator teres	↑	+1	+1	NL	↓	+1	NL	+1
Right biceps brachii	↑	+1	+1	NL	NL	NL/+1	+1	NL
Right pronator teres	↑	+1	0	NL	↓	+1	+1	+2
Right triceps brachii	↑	+2	+1	NL	↓	NL/+1	+1	+1
Right T6 paraspinal	↑	+2	0					
Right T8 paraspinal	↑	+2	0					
R. tongue	NL	0	0	NL	NL	NL	NL	NL

↑ = increased;↓= slightly reduced; ↓↓ = moderately reduced; ↓↓↓ = markedly reduced; NL = normal.

possibility of ALS. As mentioned earlier, the primary role of nerve conduction studies in a patient with suspected ALS is to exclude the possibility of a demyelinating polyneuropathy, especially one associated with conduction block. To this end, nerve conduction studies are performed in one upper and one lower extremity. The median, ulnar, tibial, and peroneal motor nerve conduction studies all show normal motor amplitudes, conduction velocities, and minimal F-wave latencies. The only exception is slightly reduced motor amplitude recording the FDI during ulnar motor studies. The only other abnormalities found on the motor nerve conduction studies are slightly prolonged median, ulnar, and tibial distal motor latencies. None of the nerves studied shows an abnormal drop in CMAP amplitude with proximal stimulation, except for the tibial nerve, where the

amplitude drops from 11.8 to 8.9 mV. However, this amount of drop would be considered normal for the tibial nerve.

Moving next to the sensory nerve conduction studies, the median, ulnar, radial, and sural sensory conduction studies show robust amplitudes throughout, with normal latencies and conduction velocities. Thus, the sensory nerve conduction studies correlate well with the history and examination; the sensory system appears intact.

During the EMG examination, attention is focused first on the weak lower extremities. There is evidence of diffuse spontaneous activity, manifest as fibrillation and fasciculation potentials in most muscles tested in both lower extremities. The amount of fibrillation potentials is marked. In addition, all muscles studied in the lower extremities show very large amplitude, long-duration, polyphasic MUAPs with decreased recruitment. Several distal muscles also show reduced activation.

Although the upper extremities are clinically unaffected, with the exception of mild distal atrophy, there is evidence of diffuse denervation with occasional fasciculations in the right upper extremity. There also is evidence of mild reinnervation in all muscles tested, along with decreased recruitment of MUAPs. A very important finding is that the thoracic paraspinal muscles at the T6 and T8 levels show profuse fibrillation potentials. Finally, one bulbar muscle, the tongue, is sampled and is normal.

At this time we are ready to formulate our electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are consistent with an active, generalized disorder of the motor neurons, their axons, or both.*

This case displays many of the prominent clinical and electromyographic features of ALS, the prototypic motor neuron disorder. Commonly, ALS begins in a distal limb, resulting in hand weakness or a footdrop. Thus, it is often initially mistaken for an ulnar neuropathy or a peroneal palsy. The course is relentlessly progressive; progression to the contralateral side usually occurs within several months. ALS usually starts as a regional disease and then progresses to adjacent myotomes. One of the major clues to the diagnosis is the complete absence of sensory symptoms, confirmed by both the clinical examination and the sensory nerve conduction studies. The only motor neuron disorder that regularly results in sensory disturbances is the rare X-linked bulbospinal muscular atrophy (Kennedy disease), in which SNAPs may be decreased or absent.

Several important questions can be addressed at this point.

How are the Nerve Conduction Studies Helpful in the Evaluation of Motor Neuron Disease?

Nerve conduction studies are essential in the evaluation of patients with motor neuron disease. Beyond confirming that sensory fibers are normal, their primary role is to exclude a demyelinating motor neuropathy with conduction block mimicking motor neuron disease. This differentiation is especially important in patients with predominantly LMN syndromes (i.e., with no clinical evidence of UMN dysfunction such as spasticity or hyperreflexia), in whom it is essential to perform extensive motor studies. Studies can be performed bilaterally as well as proximally to look for conduction blocks in motor nerves. In rare patients with a demyelinating motor neuropathy, proximal studies (e.g., stimulating axilla, Erb's point, cervical nerve roots) occasionally may be abnormal when the distal sites are normal. Proximal studies may be especially helpful in patients with normal distal conduction studies but abnormal late responses, a pattern suggestive of proximal demyelination. However, it is important to remember that proximal stimulation is technically difficult and, if not performed correctly, may lead to confusing and misleading results.

How are the Upper Extremity Nerve Conduction Motor Amplitudes Helpful in the Evaluation of Motor Neuron Disease?

When performing the routine median and ulnar motor studies, all the amplitudes are normal with the exception of the amplitude of the FDI which is borderline low. Looking at the median amplitude, however, it is just slightly above the lower limit of normal. This is in contradistinction to the ADM amplitude which is well above its lower limit of normal. If we compute the APB/ADM and FDI/ADM ratios, both are low are 0.5 and 0.6, respectively. In the appropriate clinical setting of possible ALS, an APB/ADM ratio <0.6 and FDI/ADM ratio < 0.9 together are supportive of the electrical diagnosis of ALS. This "split-hand" pattern, wherein the lateral hand (APB and FDI) is affected more than the medial hand (ADM), is a pattern seen in classic ALS.

Is this Study Consistent with a Diffuse Severe Polyradiculopathy?

EMG cannot differentiate between a severe polyradiculopathy and LMN disease. Indeed, there is no good electromyographic way to distinguish between a disorder of nerve roots and one of motor neurons. In both cases, nerve conduction studies will be essentially normal. In LMN disease, the SNAPs are spared. In polyradiculopathy, the SNAPs also are spared because the lesion is proximal to the dorsal root ganglion. The motor nerve conduction studies are identical in both; they either are normal or show evidence of axonal loss. The EMG findings in both may show evidence of diffuse denervation and reinnervation. Although polyradiculopathy from structural causes rarely involves the thoracic paraspinal muscles, they certainly may be involved with infectious, inflammatory, and infiltrative lesions. Only the late responses (especially the F responses) are more likely to be abnormal in a polyradiculopathy than in motor neuron disease. However, one would hesitate to make a distinction between the two on the basis of F responses alone.

Thus, although there is no difference between polyradiculopathy and LMN disease based on EMG and nerve conduction studies, the clinical difference is clear and unequivocal. Patients with polyradiculopathy have prominent sensory symptoms including pain and paresthesias, whereas in motor neuron disease, sensory symptoms and signs are completely lacking. Accordingly, the same EMG can be interpreted quite differently depending on the history and physical examination. If the EMG results in this case were found in a patient with progressive spinal pain associated with radiating paresthesias into the legs, thorax, and upper extremities and whose clinical examination showed hyporeflexia and sensory loss, the same nerve conduction study and EMG would more properly be interpreted as consistent with a severe ongoing diffuse polyradiculopathy.

Why Sample so Many Muscles on Needle Electromyogram?

The EMG examination in a patient with suspected ALS must be extensive, with the electromyographer looking for both active denervation and reinnervation. Sampling multiple muscles innervated by different nerves and different roots is important to avoid mistakenly interpreting multiple radiculopathies or mononeuropathies as ALS. One must document a diffuse process. Although most patients present with symptoms restricted to one or two limbs, it is not unusual to find evidence of diffuse reinnervation and denervation in clinically unaffected limbs.

There are two areas that assume special significance on EMG studies: the thoracic paraspinal muscles and the craniobulbar musculature. The thoracic paraspinal muscles usually are unaffected by spondylosis, and abnormalities there cannot be explained by coexistent cervical and lumbar spine disease, which can mimic ALS. Profuse denervation in the thoracic paraspinals usually suggests the diagnosis of ALS rather than spondylosis with polyradiculopathy, although, as noted earlier, in the rare case of infectious, inflammatory, and infiltrative lesions, the thoracic paraspinal muscles may be involved. In addition, it is always important to check the craniobulbar muscles because abnormalities there certainly exclude an isolated cervical lesion as the source of a patient's weakness. In the case described here, the symptoms began in the lower extremities, and the bulbar musculature was not yet affected. However, if the patient is tested several months later, abnormalities likely will be found there as well.

Does this Patient also have Superimposed Carpal Tunnel Syndrome?

The distal median motor latency to the abductor pollicis brevis muscle is prolonged. Does this suggest that the patient also has carpal tunnel syndrome (CTS)? One must remember that CTS is a clinical diagnosis; this patient had no clinical symptoms or signs suggesting a diagnosis of CTS. One might then ask whether the patient simply has an asymptomatic median neuropathy at the wrist, given the prolonged distal median motor latency to the abductor pollicis brevis. That possibility might be considered, but note that the ulnar and tibial motor nerves also show slightly prolonged distal motor latencies. It is unlikely that the patient also has an ulnar neuropathy at Guyon's canal and a tibial neuropathy at the tarsal tunnel. In addition, the median sensory latency is normal. Slowing of median motor, but not sensory, fibers is not the typical pattern seen in CTS (sensory fibers are more often abnormal than motor fibers in CTS). The slowing of the distal latencies in this case simply represents axonal loss with dropout of some of the largest and fastest motor neurons/axons. EMG examination of the median, ulnar, and tibial muscles is very helpful in clarifying this situation because it shows clear evidence of ongoing axonal loss in the form of fibrillation potentials and large, reinnervated MUAPs. Thus, the prolonged distal motor latencies, albeit mild, are simply a manifestation of axonal loss from the underlying motor neuron disease.

What is the Electromyographic Correlate of the Patient's Spasticity and Upper Motor Neuron Pathology?

Although EMG and nerve conduction studies are usually thought of as primarily assessing the peripheral nervous system, they often provide some insight into the central nervous system. The central nervous system can be assessed by the MUAP firing pattern on EMG. Activation (the ability to fire available motor units faster) is entirely a central process. Patients with a UMN lesion resulting in weakness will have decreased activation of MUAPs on EMG. Accordingly, in ALS, which is a disorder of both UMNs and LMNs, one often sees the unusual combination of both decreased activation and decreased recruitment of MUAPs. The decreased activation pattern represents the UMN pathology, and the decreased recruitment pattern represents the loss of LMNs.

Suggested Readings

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28 Atypical Motor Neuron Disorders

There are a heterogeneous group of motor neuron disorders that are rare but nonetheless important to recognize, because they often can mimic the presentation of amyotrophic lateral sclerosis (ALS). These often are referred to as *atypical motor neuron disorders*. Although many of the atypical motor neuron disorders share some features with ALS, they often can be distinguished by their clinical and electrophysiologic characteristics (Boxes 28–1 and 28–2).

One of the most important atypical motor neuron disorders that can be confused with motor neuron disease is the immune-mediated motor neuropathy *multifocal motor neuropathy with conduction block* (MMNCB). Strictly speaking, this is a disorder of the motor nerve and as such is discussed in detail in Chapter 26. Patients present with progressive, asymmetric weakness and wasting that often affect the distal upper extremity muscles first. Weakness is in the distribution of named motor nerves, often with sparing of other nerves in the same myotome (clinical multifocal motor neuropathy). This pattern is not seen in ALS or its progressive muscular atrophy variant, in which the entire myotome is characteristically affected at the same time. Occasional patients have weakness without wasting, a finding usually associated with pure demyelination. The disease is slowly progressive, with a male predilection, generally presenting before the fifth decade. Definite upper motor neuron signs are absent, although

Box 28–1. Clinical Clues of An Atypical Motor Neuron Disorder

Acute onset
- Paralytic poliomyelitis
- West Nile encephalitis

Non-myotomal pattern of weakness
- Multifocal motor neuropathy with conduction block

Absence of significant muscle wasting in chronically weak limbs
- Multifocal motor neuropathy with conduction block

Predominantly lower motor neuron signs
- Multifocal motor neuropathy with conduction block
- Kennedy's disease
- Spinal muscular atrophy
- Radiation injury
- Paralytic poliomyelitis
- West Nile encephalitis
- Monomelic amyotrophy

Presence of sensory symptoms and/or signs
- HTLV-1-associated myelopathy
- Adult polyglucosan body disease
- Late-onset Tay–Sachs disease (adult-onset hexosaminidase A deficiency)

Bladder or bowel dysfunction
- HTLV-1-associated myelopathy
- Adult polyglucosan body disease

Cerebellar, extrapyramidal, cognitive, and/or psychiatric dysfunction
- Late-onset Tay–Sachs disease (adult-onset hexosaminidase A deficiency)
- Hereditary spastic paraplegia (complicated)
- Adult polyglucosan body disease

Duration of illness longer than 5 years
- Kennedy's disease
- Radiation injury
- Late-onset Tay–Sachs disease (adult-onset hexosaminidase A deficiency)
- Spinal muscular atrophies
- Hereditary spastic paraplegia
- Adult polyglucosan body disease

Onset of illness before age 40 years
- Late-onset Tay–Sachs disease (adult-onset hexosaminidase A deficiency)
- Familial amyotrophic lateral sclerosis
- Spinal muscular atrophy
- Hereditary spastic paraplegia
- Monomelic amyotrophy

Positive family history
- Kennedy's disease
- Late-onset Tay–Sachs disease (adult-onset hexosaminidase A deficiency)
- Familial amyotrophic lateral sclerosis
- Spinal muscular atrophy
- Hereditary spastic paraplegia
- Adult polyglucosan body disease

History of radiation therapy
- Motor neuron disease associated with radiation injury

History of malignancy
- Paraneoplastic motor neuron disease (especially lymphoma)

History of old poliomyelitis
- Postpoliomyelitis syndrome

History of electrical injury
- Motor neuron disease associated with electrical injury

History of human immunodeficiency virus infection
- Retrovirus-associated motor neuron disorder

HTLV-1, human T cell lymphotropic virus-type 1.

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Box 28–2. Electrodiagnostic Clues of An Atypical Motor Neuron Disorder

- Conduction block on motor nerve conduction studies (not at entrapment sites)
  - Multifocal motor neuropathy with conduction block
- Markedly slowed conduction velocities or prolonged distal latencies (not at entrapment sites)
  - Multifocal motor neuropathy with conduction block
- Sensory nerve conduction abnormalities
  - Kennedy's disease
  - Adult polyglucosan body disease
  - Late-onset Tay–Sachs disease (adult-onset hexosaminidase A deficiency)
  - Multifocal motor neuropathy with conduction block (rare)
  - West Nile encephalitis (rare)
- Myokymic discharges
  - Radiation injury
- Prominent complex repetitive discharges
  - Late-onset Tay–Sachs disease (adult-onset hexosaminidase A deficiency)
- Facial fasciculations/grouped repetitive motor unit discharges with activation
  - Kennedy's disease
- Acute or subacute neuropathic pattern on needle electromyogram
  - Paralytic poliomyelitis, including West Nile encephalitis

retained or inappropriately brisk reflexes for the degree of weakness and wasting may be seen. Bulbar function and sensation are characteristically spared. Mild or transient sensory symptoms may be present. The characteristic finding on motor nerve conduction studies is that of conduction block, temporal dispersion, or both, along the motor nerves. Other signs of demyelination also may be seen, including slowed conduction velocities, absent or impersistent F responses, and prolonged distal motor latencies. Sensory conduction studies are typically normal.

Other than multifocal motor neuropathy with conduction block, atypical motor neuron disorders are seen most often in association with certain viral infections or as the result of specific genetic mutations. Rarely, atypical motor neuron disorders are seen as a remote effect of some neoplasms or as a result of electrical injuries or radiation. Because the prognosis in ALS is uniformly poor compared with these atypical motor neuron disorders, it is essential that the correct diagnosis is reached. In addition, some are potentially treatable; in others, genetic counseling is important.

INFECTIOUS MOTOR NEURON DISORDERS

Paralytic Poliomyelitis and Postpolio Syndrome

Paralytic poliomyelitis was once a common cause of acute lower motor neuron dysfunction. In the United States from 1951 to 1955, an average of more than 15,000 cases occurred per year. Through widespread use of the oral polio vaccine, the incidence of acute poliomyelitis has been drastically reduced. Most cases now are associated with the live attenuated virus in the oral polio vaccine and occur either in vaccine recipients or in individuals who are in contact with vaccine recipients, especially immunocompromised patients. Other cases occur in travelers to areas where poliomyelitis is endemic; in 2011, these countries were Afghanistan, India, Nigeria, and Pakistan. Sporadic outbreaks have also occurred in other underdeveloped countries. In rare, sporadic cases, infection presumably is due to incomplete immunization status. Most sporadic cases are no longer associated with the poliovirus but are the result of coxsackievirus, echovirus, or enterovirus infection.

Patients with acute poliomyelitis present with fever, headache, myalgias, and gastrointestinal disturbance. Weakness, wasting, and depressed reflexes begin to appear during the first or second week of the illness. The distribution of weakness typically is asymmetric, and the lower extremities are most commonly involved. The upper extremities, trunk, diaphragm, and bulbar muscles are occasionally involved. Sensation and autonomic function are spared. Cerebrospinal fluid (CSF) typically shows a lymphocytic pleocytosis, often in the range of 100 to 200 cells per cubic millimeter (rarely, polymorphonuclear leukocytes may be seen early), during the preparalytic phase of the illness. Pleocytosis, while invariably present in the preparalytic phase of the illness, tends to clear with the onset of the weakness. The CSF protein level is commonly elevated within the first several weeks of the illness, whereas CSF glucose is normal. Cultures from CSF usually fail to isolate the virus, although the virus can commonly be isolated from the stool if it is obtained within the first 10 days of the paralysis. In addition, antibody titers from the acute and convalescent phases may allow virus identification.

Weakness associated with poliomyelitis now is seen most often in the electromyography (EMG) laboratory not as an acute process but in patients with postpolio syndrome (PPS). PPS occurs in at least one fourth of previously infected patients, usually 25 to 30 years after the attack of acute poliomyelitis. Patients develop pain, fatigue, and weakness, often most prominent in the muscle groups previously affected by the poliomyelitis. However, muscles that were clinically normal may develop symptoms, reflecting the diffuse underlying nature of the previous poliomyelitis. The etiology of PPS is not completely known, but it is most likely related to the normal aging process (i.e., most individuals lose some motor neurons after age 55 years) superimposed on chronically denervated muscles. Patients with PPS and worsening symptoms often are referred to the EMG laboratory to exclude a new, superimposed process, such as radiculopathy, entrapment neuropathy, myopathy, or motor neuron disease as a source of increased fatigue, pain, and weakness.

West Nile Encephalitis

Over the past several years, there have been an increasing number of reports of a "polio-like" syndrome associated

FIGURE 28–1 West Nile virus. The vector for the West Nile virus is the common mosquito. Although rare, an increasing number of cases of poliomyelitis have been associated with this virus, either alone or in association with encephalitis.
(Courtesy of US Geological Survey.)

with West Nile encephalitis. The responsible virus, which is a member of the flavivirus family and is composed of a single strand of RNA, was first isolated in 1937 in northern Uganda. In nature, the virus is transmitted between birds by mosquitoes (Figure 28–1). Jays, blackbirds, finches, warblers, sparrows, and crows appear to be most important in maintaining the infection. Most infections in humans occur by way of a mosquito bite, although cases have been reported following transplanted organs and infected blood products. Because the disease is primarily spread to humans by mosquitoes, patients typically are affected in the summer and early fall.

Fortunately, most infections with the West Nile virus are asymptomatic, with only one in 150 infections resulting in neurologic involvement. The elderly and the immunocompromised appear to be at highest risk. After an incubation period of several days, a nonspecific flulike illness develops, often with fever, headache, and joint and muscle pain. In some patients there may be additional features suggestive of West Nile infection, including retro-orbital pain, facial congestion, and rash. Definitive diagnosis is made by the presence of immunoglobulin M antibodies in CSF or serum.

In patients with neurologic involvement, a combination of encephalitis, meningitis, and myelitis can occur. Diffuse weakness is common and often thought to be due to the encephalitis. Other patterns of weakness are also seen, among them monoplegia, flaccid quadriplegia, bulbar weakness, and respiratory weakness. In some patients, an acute segmental flaccid paralysis has been described as an initial presentation of West Nile virus, even in the absence of meningitis or encephalitis. Such cases initially were attributed to Guillain–Barré syndrome, although it now is clear that the weakness more likely was due to anterior horn cell disease. In patients in whom electrodiagnostic (EDX) studies have been performed, nerve conduction studies show reduced compound muscle action potential (CMAP) amplitudes with relatively intact sensory conduction studies. No evidence of demyelination is present. Rarely, patients have had abnormal sensory conduction studies, suggesting involvement of the dorsal root ganglia or peripheral sensory nerve as well. Needle EMG shows evidence of axonal loss. The pattern of findings depends on when the study is performed in relationship to the start of the illness.

Thus, in addition to coxsackievirus, echovirus, and enterovirus, West Nile virus can be added to the list of infectious agents that can result in an acute infection of the anterior horn cells. Thus, paralytic poliomyelitis is best regarded as a clinical syndrome that can be caused by a variety of viruses, not simply the poliovirus.

Retrovirus-Associated Motor Neuron Disorders

Human immunodeficiency virus (HIV) is associated with a variety of neuromuscular disorders, including peripheral neuropathies, myopathies, and radiculopathies. Experimental studies in mice have shown that retroviruses can induce a lower motor neuron syndrome in mice and suggest a relationship between retroviruses and the pathogenesis of motor neuron disease. There are rare reports of patients with HIV infection and classic ALS, or a clinical syndrome resembling primary lateral sclerosis, without any other explanation for their symptoms. Other patients have had restricted lower motor neuron signs. Some reports have noted improvement or complete remission of the syndrome in these patients when they are treated with highly active antiretroviral therapy.

Another retrovirus, the human T cell lymphotropic virus-type 1 (HTLV-1), is well known to be associated with spastic paraparesis in endemic areas (i.e., the Caribbean basin, southwest Japan, southeast United States, southern Italy, and sub-Saharan Africa) in a syndrome known as HTLV-1-associated myelopathy or Tropical Spastic Paraparesis (HAM/TSP). Along with spastic paraparesis, patients usually have bladder dysfunction and minor sensory symptoms. A motor neuron syndrome mimicking ALS is also observed in a series of patients with HTLV-1 infection. The presence of spastic paraparesis or even typical ALS symptoms, with minor sensory findings or bladder dysfunction, especially in an endemic area for HTLV-1, should prompt a search for HTLV-1 antibodies.

INHERITED MOTOR NEURON DISORDERS

Familial Amyotrophic Lateral Sclerosis (FALS)

Approximately 10% of cases of ALS are familial. Inheritance is usually autosomal dominant. Over 10 different genes have been identified, with the most common being a mutation in the superoxide dismutase (*SOD-1*) gene on chromosome 21. The *SOD-1* gene mutation accounts for 15–20% of FALS. Other more commonly identified genes include the fused-in-sarcoma (*FUS*) and the TAR (transactive response) DNA-binding protein (*TDP-43*) genes. These two genes account for approximately 3–5% and 1–3% of

FALS, respectively. Most recently, the gene encoding ubiquilin 2 has been found to be a cause of X-linked FALS. In addition, inclusions containing ubiquilin 2 have been found in a large number of ALS patients suggesting a common pathology. Ubiquilin 2 is involved in the protein degradation pathway. Recently, a mutation in the chromosome 9 open reading frame 72 (*C9ORF72*) gene, resulting in an expanded hexanucleotide repeat in a noncoding region of the gene, was found in a large percent of patients with familial ALS (23%) or frontotemporal dementia (12%). The clinical presentation and prognosis of patients with FALS are similar to sporadic cases. One should consider the diagnosis of FALS in patients with ALS and a known family history or in patients with an early clinical presentation. Commercial DNA testing is available for the more common genetic mutations. Very rarely a patient with sporadic ALS (i.e., no family history) is reported with one of these mutations.

Spinal Muscular Atrophy

A large number of inherited spinal muscular atrophies (SMA) result in selective degeneration of the lower motor neurons. The characteristic clinical presentation is that of progressive, symmetric, proximal muscle weakness and atrophy, without upper motor neuron signs. Most are recessively inherited and linked to the survival motor neuron 1 (*SMN1*) gene on chromosome 5q. Among the various types, the most severe form occurs in infancy (Werdnig–Hoffmann disease), usually resulting in death before age 2 years. Others present in early childhood or during adolescence or adulthood (Kugelberg–Welander disease) and have a much better prognosis. Although occasionally confused with ALS, adult-onset SMA is more commonly mistaken clinically for a myopathy. Direct DNA deletion analysis is now commercially available but does not detect all cases.

Although proximal muscles are most frequently involved, other anatomic variants have been described, including scapuloperoneal, facioscapulohumeral, and generalized forms. In addition, there is a rare distal SMA (also known as distal hereditary motor neuropathy or neuronopathy) that presents with a clinical phenotype similar to Charcot–Marie–Tooth polyneuropathy, although with a notable lack of sensory symptoms or findings. This variant often is referred to as the spinal form of Charcot–Marie–Tooth.

X-Linked Bulbospinal Muscular Atrophy (Kennedy's Disease)

The one inherited SMA that deserves special attention, because it can easily be confused with the progressive bulbar palsy variant of ALS, is X-linked bulbospinal muscular atrophy (Kennedy's disease). It affects only men and has its onset between the third and fifth decades of life, followed by a slow progression. Because there frequently is no obvious family history in X-linked disorders, many of these cases at first appear to be sporadic.

Some patients complain of exercise-induced muscle cramps and hand tremors several years before weakness develops. Proximal muscles are affected first, followed by bulbar involvement, which may become marked. Dysarthria and dysphagia are associated with atrophy and weakness of facial, jaw, and glossal muscles. Because of the prominent bulbar involvement, Kennedy's disease can be difficult to differentiate from the bulbar variant of ALS. A classic and striking clinical feature is the presence of facial fasciculations, most prominent around the mouth and chin. Fasciculations are present at rest, but they are more prominent with contraction and are best elicited by having the patient whistle or blow out the cheeks. Facial fasciculations are reported in more than 90% of case reports. Distal muscles are affected later in the course. Reflexes typically are hypoactive or absent. There are no long-tract signs. Sensory loss or sensory symptoms are rare. *Although not universal, most patients have gynecomastia, and some have other endocrine abnormalities, including diabetes and infertility*.

Laboratory test results are normal except for a modestly elevated creatine kinase (CK) level (often 500–1500 IU), which is higher than the mild elevation typically seen in SMA or other motor neuron disorders. Nerve conduction studies often show normal motor studies. However, the CMAP amplitudes may be low if they are recorded from weak and wasted muscles. *Most patients have low-amplitude or absent sensory nerve action potentials (SNAPs), which reflect the association of Kennedy's disease with degeneration of the dorsal root ganglia. This finding is very important because it is not seen in ALS and is an important clue in the recognition of Kennedy's disease*. Needle EMG shows neurogenic changes, including increased insertional activity and reduced recruitment of large, prolonged duration, polyphasic motor unit action potentials (MUAPs) in affected muscles. Needle EMG examination of the facial muscles may show grouped repetitive motor unit discharges, which occur with mild activation of the facial muscles. Because these discharges occur with mild voluntary contraction rather than spontaneously, they are distinguished from myokymic or neuromyotonic discharges and are quite characteristic of Kennedy's disease.

Despite prominent bulbar weakness and the corresponding risk of aspiration, longevity usually is not affected. Consequently, the correct diagnosis is important both for prognosis and for its value in genetic counseling. The diagnosis should be suspected in any male patient with motor neuron disease who presents with proximal and bulbar weakness, a positive family history, facial fasciculations, or gynecomastia and whose EDX studies show abnormal sensory studies in addition to the typical widespread neuronopathic pattern on needle EMG. An unusually elevated CK level is often an important clue as well. DNA testing is commercially available. The gene is an androgen receptor gene with an expansion of a trinucleotide repeat (CAG).

Hereditary Spastic Paraplegia

Hereditary spastic paraplegia, also known as *familial spastic paraparesis*, consists of a diverse group of genetic disorders characterized by progressive spasticity and sometimes

weakness of the lower extremities. They are classified by their type of inheritance (autosomal dominant, autosomal recessive, or X-linked) and whether the spasticity is the sole manifestation of the disorder, termed *uncomplicated* or *pure* spastic paraplegia, or whether there are other accompanying abnormalities (termed *complicated* spastic paraplegia). These other manifestations may include ataxia, dementia, mental retardation, optic neuropathy, retinopathy, peripheral neuropathy, amyotrophy, extrapyramidal dysfunction, deafness, or ichthyosis. The clinical presentation, which includes age of onset, degree of deficit, and associated symptoms, varies both within and between families.

The diagnosis usually is straightforward if there is a known family history of pure progressive spastic paraparesis. If there is no known family history, other diagnoses are considered, including HTLV-1-associated myelopathy (see earlier), and most often the primary lateral sclerosis variant of ALS.

Adult-Onset Hexosaminidase A Deficiency (Late-Onset Tay–Sachs Disease)

Hexosaminidase A is a lysosomal enzyme important in the metabolism of gangliosides. Deficiency of this enzyme results in an abnormal accumulation of GM2 ganglioside, leading to nerve cell degeneration. The adult-onset form of hexosaminidase A deficiency (also known as *late-onset Tay–Sachs disease*) is a rare recessively inherited disorder, only recognized in the late 1970s. In some affected individuals, the disorder can be mistaken for ALS or one of its variants, although most patients have coexistent cerebellar disturbances, about half have psychiatric disturbance (especially psychosis and depression), and approximately 25% have an axon loss sensorimotor polyneuropathy. The adult-onset form is quite different from the well-known rapidly progressive infantile form of hexosaminidase A deficiency, known as infantile Tay–Sachs disease. An absolute deficiency of hexosaminidase A causes *infantile Tay–Sachs disease*, whereas a partial deficiency results in the late-onset form.

Although the disorder affects multiple systems, nearly every affected patient has lower motor neuron involvement. Weakness and atrophy initially involve the lower extremities and are more prominent in the proximal muscles. In the upper extremities, there is a predilection for involvement of certain muscles, especially the triceps. It is not uncommon for patients to initially be misdiagnosed as adult-onset SMA. In one case series, nine of 14 patients also had upper motor neuron signs, but severe spasticity is rare. Cerebellar signs are common, including dysarthria, truncal ataxia, and dysmetria. If cerebellar signs are not prominent, however, the neurologic picture can mimic SMA or the progressive muscular atrophy variant of ALS, or classic ALS when upper and lower motor neuron signs predominate.

EDX studies usually show normal motor conduction studies, unless they are recorded from weak muscles, in which case the CMAP amplitudes are low, with normal or slightly slowed conduction velocities. Sensory nerve conduction studies are also usually normal, but may be abnormal in approximately 25% of patients, consistent with an axonal loss polyneuropathy. The needle EMG examination shows abnormal spontaneous activity including fasciculation and fibrillation potentials. C*omplex repetitive discharges (CRDs) may be especially prominent*. Large, polyphasic MUAPs with reduced recruitment are seen in affected muscles.

Adult-onset hexosaminidase A deficiency should be considered in the differential diagnosis of any patient presenting with lower motor neuron disease, especially if there are coexistent cerebellar and/or psychiatric signs, or a family history of similarly affected siblings. A definitive diagnosis is made by measuring hexosaminidase A activity in serum, leukocytes, or fibroblasts.

Adult Polyglucosan Body Disease

Adult polyglucosan body disease (APGBD) is an exceedingly rare neurologic disorder; fewer than 30 cases have been reported. The clinical presentation includes progressive upper and lower motor neuron dysfunction, sensorimotor peripheral neuropathy, gait disturbance, urinary incontinence, and dementia. All components of the disorder may not be present initially, and motor symptoms may predominate. The pathologic hallmark of the disease is the presence of a large number of polyglucosan bodies, which structurally resemble Lafora bodies or corpora amylacea, in central and peripheral neuronal processes and astrocytes. Some cases appear to be sporadic and some familial (usually autosomal recessive), with a high proportion occurring in families of Ashkenazi Jewish descent. The presumed cause of adult polyglucosan body disease is genetic, especially in patients of Ashkenazi Jewish descent. A mutation in the glycogen branching enzyme gene, causing a deficiency of the glycogen branching enzyme, has been described in Ashkenazi Jewish patients with adult polyglucosan body disease.

The diagnosis should be suspected in patients with progressive upper and lower motor neuron dysfunction that resembles typical ALS, but which is accompanied by urinary incontinence, sensorimotor polyneuropathy, and dementia. If dementia and the motor neuron dysfunction are prominent, one should also consider frontotemporal dementia (see above) in addition to APGBD in the differential diagnosis. However, unlike frontotemporal dementia, in APGBD some distal sensory loss may be found on clinical exam. EDX studies reveal mild to moderate slowing of motor nerve conduction velocity and low-amplitude or absent SNAPs. Extensive white matter abnormalities often are seen on brain magnetic resonance imaging. A definitive diagnosis is based on pathologic findings of widespread deposition of polyglucosan bodies in the central and peripheral nervous systems (Figure 28–2). Sural nerve biopsy shows multiple intra-axonal polyglucosan bodies, which together with the appropriate clinical

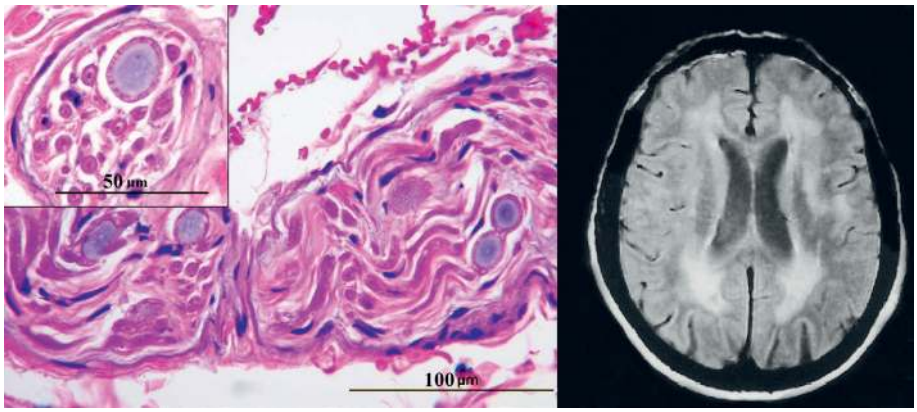

FIGURE 28–2 Adult polyglucosan body disease. **Left:** Longitudinal section of a nerve biopsy from a patient with adult polyglucosan body disease. Transverse section is in the upper left. Note the intra-axonal location of the polyglucosan bodies. **Right:** Fluid attenuated inversion recovery axial magnetic resonance imaging of the brain in the same patient shows bilateral white matter signal abnormalities in periventricular and subcortical white matter, which are characteristic of adult polyglucosan body disease.

manifestations can confirm the diagnosis of adult polyglucosan body disease.

OTHER ATYPICAL MOTOR NEURON DISORDERS

Monomelic Amyotrophy

Monomelic amyotrophy is a rare restricted form of motor neuron disease. Most cases are sporadic, although a familial form has been reported. The male-to-female ratio is 5:1, with the majority of patients presenting between 18 and 22 years old. Although first reported in Japan and India, the disease has been described in young adults from all parts of the world. Many different names have been used for this condition, including monomelic atrophy, juvenile muscular atrophy of a unilateral upper extremity, benign focal amyotrophy, Sobue disease, Hirayama's disease and juvenile segmental muscular atrophy.

Patients typically present with the insidious onset of unilateral weakness and atrophy of the hand muscles that often progresses to the forearm. In some cases, the syndrome is bilateral but often asymmetrical. *Of note, the brachioradialis muscle is usually spared. The syndrome affects C7–C8–T1 muscles with sparing of the C5–6 muscles. In most cases, no particular precipitating infection or trauma is identified.* The weakness tends to progress slowly over 1 to 3 years and then stabilizes. In some patients, there is an aggravation of weakness when exposed to cold, a phenomenon known as cold paresis. Deep tendon reflexes are usually normal, and upper motor neuron signs are absent. Sensation in the affected extremity is preserved, except for a rare and mild sensory abnormality over the dorsum of the hand.

The etiology of monomelic amyotrophy is unknown. Postulated mechanisms include low-grade venous ischemia of the spinal cord, especially the anterior horn cells, which lie in the watershed area, possibly precipitated by trauma to the arm or neck, or by recurrent neck flexion and extension.

The diagnosis is often made with the classic clinical presentation of distal hand weakness and atrophy, usually in a young male. Laboratory investigations including blood chemistries and CSF analysis are normal, with the exception of the serum CK, which may be slightly elevated. On EDX testing, motor nerve conduction studies may be normal or may reveal asymmetrically low median or ulnar CMAP amplitudes in the affected hand. Slightly prolonged distal motor latencies or slightly slowed conduction velocities may occur, depending on the degree of axonal loss. The SNAPs are always preserved.

Recall that one of the patterns that may occur in typical sporadic ALS is the "split-hand syndrome," wherein the first dorsal interosseous (FDI) and abductor pollicis brevis (APB) are more affected than the abductor digiti minimi (ADM) (see Chapter 27). In monomelic amyotrophy, the reverse pattern is more often noted: the ADM is much weaker and more wasted than the APB. The correlate of this clinical observation is a distinctive pattern on routine ulnar and median motor nerve conductions: an ADM/APB CMAP amplitude ratio of <0.6, which strongly suggests the diagnosis of monomelic atrophy rather than ALS. First described by Lyu et al., this ratio is calculated simply by measuring the amplitudes of the CMAPs of the ADM and the APB, during routine ulnar and median motor conduction studies. An ADM/APB CMAP amplitude ratio of <0.6 is considered abnormal. Conversely, in cases wherein the ADM/APB CMAP amplitude ratio was >4.5 or when the median motor response was absent and the ulnar motor response recording the ADM was present, this pattern only occurred in ALS. Of course, these conclusions are predicated on the understanding that there is no additional lesion affecting the median and/or ulnar nerves, especially median neuropathy at the wrist or ulnar neuropathy at the elbow. In cases in which the diagnoses of monomelic amyotrophy and ALS are being considered in a patient, paying attention to this ratio may be helpful.

On needle EMG, fibrillation potentials are not prominent; they are found in slightly less than half of patients.

MUAPs are large and prolonged in duration, and recruitment is invariably reduced. Low-amplitude, short-duration MUAPs, which represent early reinnervated motor unit potentials, occur in approximately 20% of patients. Often, similar EDX abnormalities are detected, to a much lesser degree, in the clinically unaffected contralateral limb. Radiologic findings on computed tomographic myelogram or magnetic resonance imaging may show segmental atrophy of the spinal cord at the level of the involved myotomes, especially in the lower cervical and upper thoracic spinal cord. The course in monomelic amyotrophy is generally benign.

Motor Neuron Disease Associated with Electrical Injury

There are rare case reports of adults and children who develop a delayed upper and lower motor neuron syndrome after exposure to an electrical injury or lightning. Electrical injuries usually occur from high-voltage lines, household circuits, or lightning. Transient neurologic deficits immediately after an electrical shock are well described and usually recover after hours to several days. In more severe electrical injuries, spinal cord damage may occur, resulting in a non-progressive syndrome that includes either lower or upper motor neuron damage, which often correlates with the level of the entrance and exit sites of the electrical current. Patients with non-progressive syndromes may recover partially or completely.

In contrast, a progressive motor neuron syndrome may develop at variable time periods after the electrical injury. Weakness begins near the site of the trauma and progresses in an ALS-like fashion to the contralateral limb. Bulbar weakness and upper motor neuron signs develop later on. Sensory symptoms can occur in the region of the electrical injury. The clinical course in the progressive motor neuron syndrome associated with electrical injury is similar to the progression seen in typical ALS, with death typically occurring within 3 years after the initial presentation. Whether there is truly a causal relationship between the electrical injury and the progressive motor neuron syndrome remains unknown.

The underlying mechanism of the electrical injury and its relationship to spinal cord damage, particularly to the anterior horn cells, are unclear. Autopsy findings in one patient with motor neuron disease after an electrical injury revealed the classic changes found in ALS, including loss of anterior horn cells and motor neurons in the hypoglossal nuclei, and degeneration of the corticospinal tract. There was no evidence of vascular cord injury or mechanical distortion of the spinal cord. Thus, the relationship between electrical injuries and ALS remains tenuous at best.

Delayed Radiation-Induced Motor Neuron Syndrome

Progressive pure lower motor neuron syndromes have been described in patients as a delayed response of radiation therapy, with typical total doses in the range from 5000 to 6000 rads. The clinical syndrome is characterized by progressive weakness, usually of the lower extremities, with marked atrophy and fasciculations, which develops months to years after radiation therapy. Deep tendon reflexes are depressed or absent in the affected limbs. Sphincter function and sensation are spared, and upper motor neuron signs are absent. Interestingly, the lower extremities are preferentially involved, although radiation may involve the entire neuraxis. The weakness generally stabilizes after several months, although weakness continues to progress over years in some patients. A delayed lower motor neuron bulbar palsy, consisting of dysarthria, dysphagia, and in some cases neck weakness, has been reported following radiation to the head and neck for various cancers (Figure 28–3).

The diagnosis is based on a history of lower motor neuron weakness primarily in the lower extremities, months to years following radiation exposure. CSF usually is normal, although there may be a mild elevation of CSF protein. On EDX studies, nerve conduction studies show low CMAPs in the lower extremities, with intact SNAPs. On EMG, prominent fibrillation potentials are often present in the lower extremities. Of course, if the weakness and wasting involves bulbofacial and neck muscles, these findings are seen in the bulbofacial and neck muscles. Myokymic discharges may be seen in affected muscles and are an important marker suggesting radiation-induced injury (Figure 28–4). EDX testing of the upper extremities is normal in most cases, depending on the site of radiation. The clinical course is slowly progressive and usually confined to the region of the spinal cord exposed to the original radiation. Most patients stabilize after several months and usually survive for 15 to 20 years after the initial presentation, although the weakness can be severe and debilitating.

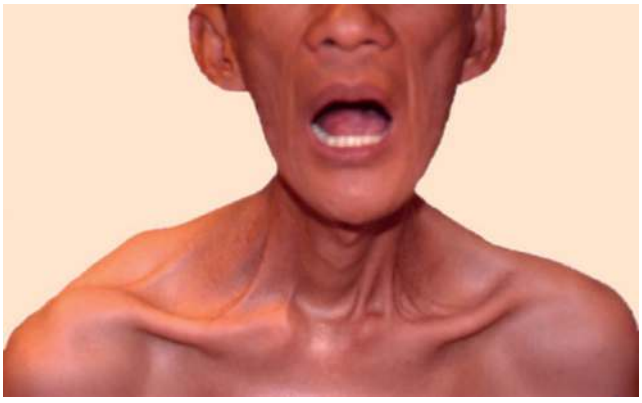

FIGURE 28–3 Delayed lower motor neuron bulbar palsy. A 41-year-old man developed progressive swallowing and speech disturbance 14 years after receiving radiation to the neck for nasopharyngeal carcinoma. Speech was nasal and dysarthric; the palate did not elevate. Note the diffuse atrophy of the anterior cervical musculature, more prominent on the left.

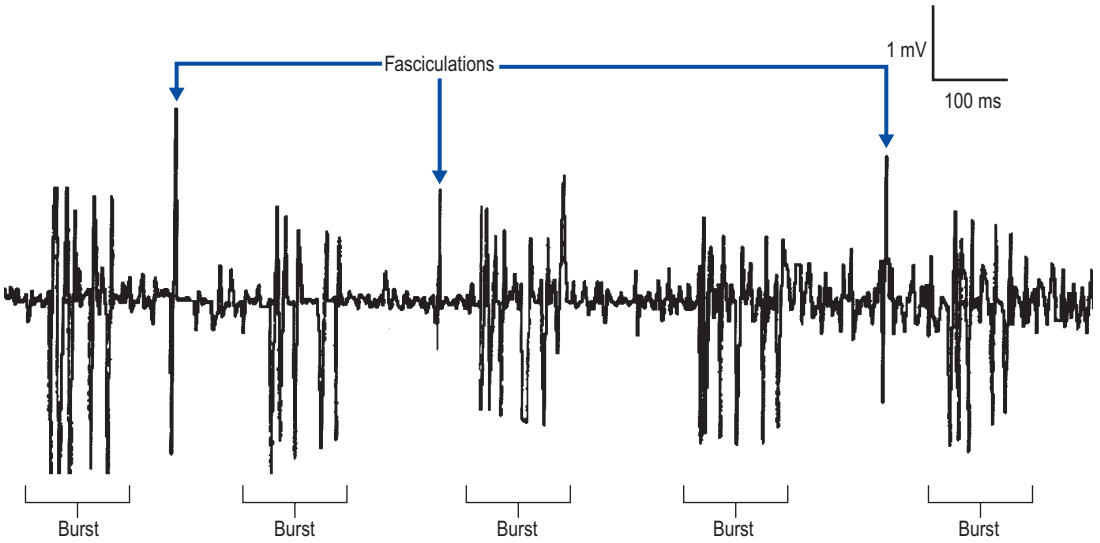

FIGURE 28–4 Myokymic discharges and delayed radiation-induced motor neuron disorder. Tracing made from electromyogram of the tongue from the same patient shown in Figure 28–3. Clinically, continuous undulating movements were present. Tracing shows grouped repetitive bursts of motor unit action potentials (myokymic discharges) and fasciculations. Myokymic discharges, although seen in other conditions, are characteristic of radiation-induced injury.

The pathogenesis of delayed radiation-induced injury is not well defined. Some evidence suggests that the disease process in the lower extremities involves damage to the lumbosacral anterior nerve roots, whereas other evidence suggests that the pathology is in the anterior horn cells. Based on purported mechanisms involved in delayed radiation-induced encephalopathy, it is likely that a combination of factors is involved in postradiation-induced motor neuron syndrome. These include direct radiation-induced damage to neurons and ischemic changes secondary to radiation-induced damage to vascular endothelial cells.

Paraneoplastic Motor Neuron Disease

Paraneoplastic disorders occur as a remote effect of cancer. Whether motor neuron disease occurs as a paraneoplastic syndrome is controversial. Since several initial reports of a paraneoplastic motor neuron syndrome, many have questioned whether the association of cancer and motor neuron disease is simply a coincidence of two relatively common diseases, or if there is a true etiologic relationship between the two conditions. Several epidemiologic studies have failed to find an increased incidence of cancer in patients with ALS compared with the general population, although several small studies have reported a co-occurrence of cancer and motor neuron disease that appears to be higher than the incidence expected in the general population.

One of the strongest cases for a paraneoplastic motor neuron disease occurs in association with lymphoma, wherein a clinical syndrome characterized by subacute progressive, painless lower motor neuron weakness with minimal or absent sensory symptoms has been reported. The progression of neurologic symptoms varies. In some patients the progression is slow; some even show clinical improvement or normalization of neurologic deficits, which appear to be independent of the course of the cancer. In other patients, the disease is progressive, with accompanying upper motor neuron signs and a clinical course similar to typical ALS.

ELECTROPHYSIOLOGIC EVALUATION

Nerve Conduction Studies

The nerve conduction study protocol for a suspected atypical motor neuron disorder is the same as that for ALS (see Chapter 27). At a minimum, routine motor and sensory conduction studies along with late responses should be performed in a symptomatic upper and lower extremity before proceeding to the needle EMG study. The most important reason to perform motor nerve conduction studies is to look for the following:

- Unequivocal evidence of demyelination along motor nerves, especially conduction block, at non-entrapment sites. Demyelination is not present in ALS, and its presence strongly supports an alternative, treatable diagnosis, usually multifocal motor neuropathy with conduction block (Figure 28–5).
- Abnormalities on sensory nerve conduction studies. Sensory nerve conduction studies are always normal in ALS unless the patient has a superimposed disorder (e.g., polyneuropathy or entrapment neuropathies). The presence of abnormal sensory conduction studies should always seriously question the diagnosis of ALS. Abnormal sensory conduction studies are often seen in Kennedy's disease and adult polyglucosan body

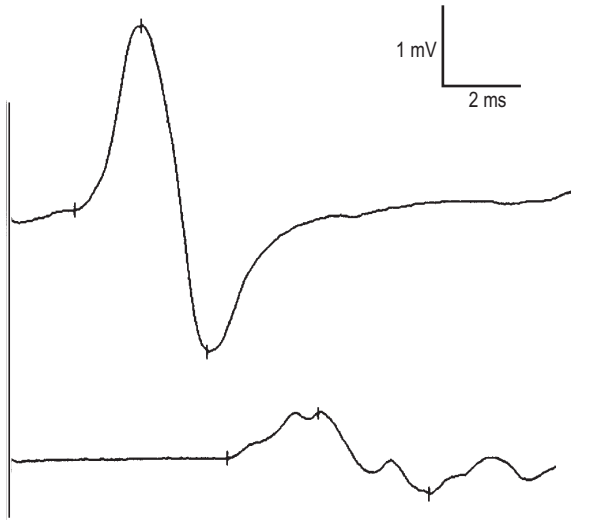

FIGURE 28–5 Conduction block in a patient with multifocal motor neuropathy. Motor nerve conduction of the median nerve recording abductor pollicis brevis muscle, stimulating wrist (top tracing) and antecubital fossa (bottom tracing). Note the drop in area and amplitude of the compound muscle action potential from the wrist to the antecubital fossa. In a patient with a suspected motor neuron disorder, conduction block is not consistent with amyotrophic lateral sclerosis; it indicates a demyelinating motor neuropathy, usually multifocal motor neuropathy with conduction block.

disease. In addition, some cases of West Nile encephalitis and demyelinating motor neuropathy with conduction block may rarely display sensory conduction abnormalities.

Electromyographic Approach

Akin to the nerve conduction studies, the EMG evaluation of patients with suspected atypical motor neuron disorders is similar to that of ALS. An extensive study is indicated, often of all four limbs, the paraspinal muscles, and the bulbar muscles. Certain types of spontaneous discharges take on additional meaning in patients with suspected atypical motor neuron disorders. CRDs are unusual in ALS and imply a much more chronic condition. Prominent CRDs are reported most often in very chronic motor neuron disorders, especially late-onset Tay–Sachs disease, adult-onset spinal muscular atrophy, and some cases of old poliomyelitis. The presence of myokymic discharges should always raise the possibility of prior radiation-induced injury. In addition, myokymic discharges are sometimes seen in acquired demyelinating neuropathies. Lastly, prominent facial fasciculation potentials or grouped discharges with activation should raise the possibility of Kennedy's disease.

Almost all motor neuron disorders are slowly progressive. Thus, MUAPs should be large, long, and polyphasic with decreased recruitment. The pattern of acute or subacute neuropathic loss (active denervation, with decreased recruitment of normal configuration MUAPs) is not seen in ALS. This pattern implies either an acute/subacute motor neuron disease, such as acute poliomyelitis or West Nile encephalitis/myelitis, or demyelination with conduction block and some secondary axonal loss.

EXAMPLE CASES

Case 28–1

History and Physical Examination

A 49-year-old man was referred for progressive weakness and fatigue. Over the past 6 months, he had complained of more difficulty walking and noted increased weakness in the left leg. He had a history of paralytic poliomyelitis at age 5 years. He recalled being hospitalized for 2 weeks at that time and developing weakness of both legs, left more than right. The upper extremities and bulbofacial and respiratory muscles were not affected. Within 1 year following the poliomyelitis, he had regained full function of his legs. During high school and college, he had participated regularly in athletics without difficulty.

On examination, the left leg was slightly shorter and smaller than the right. Neurologic examination revealed normal mental status and cranial nerves. In the upper extremities, muscle bulk, tone, and strength were normal. In the lower extremities, there was slight weakness of all movements around the ankle, especially on the left. In addition, there was mild weakness of hip extension and abduction bilaterally. Reflexes were absent in the lower extremities and hypoactive in the upper extremities. Sensory examination was normal to all modalities.

Summary

The history is that of a 49-year-old man with mild progressive weakness and fatigue in the lower extremities, left greater than right. There is no pain or clear sensory loss. From the history alone, the underlying etiology is not clear. The symptoms could represent some type of orthopedic problem of the hip or leg, or a subtle neurologic problem such as an entrapment neuropathy or, more likely, a lumbosacral radiculopathy. The examination shows only mild distal and proximal weakness in both legs, somewhat in the distribution of the L5–S1 myotomes. However, there is no corresponding sensory abnormality in that distribution, making the diagnosis of radiculopathy less likely. The absent reflexes in both lower extremities and the depressed reflexes in the upper extremities suggest a more widespread disorder.

The left leg is shorter and smaller than the right, likely reflecting the patient's prior poliomyelitis. When weakness is present during childhood development, secondary orthopedic problems often result. When the patient recalled his prior history of poliomyelitis at age 5 years, he remembered that the left leg was more affected than the right. Despite weakness at the time, he made a fairly good recovery and was not subsequently disabled by the poliomyelitis in any meaningful way. He was able to participate regularly in athletics as a teenager and young adult. Furthermore, we know that he was hospitalized for

CASE 28–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = μV RT	Amplitude Motor = mV; Sensory = μV LT	Amplitude Motor = mV; Sensory = μV NL	Latency (ms) RT	Latency (ms) LT	Latency (ms) NL	Conduction Velocity (m/s) RT	Conduction Velocity (m/s) LT	Conduction Velocity (m/s) NL	F-Wave Latency (ms) RT	F-Wave Latency (ms) LT	F-Wave Latency (ms) NL
Median (m)	Wrist	APB		6.2	≥4		3.9	≤4.4					25	≤31
	Antecubital fossa	APB		6.0			6.7			54	≥49			
Ulnar (m)	Wrist	ADM		8.2	≥6		3.1	≤3.3						≤32
	Below elbow	ADM		8.0			5.8			53	≥49		26	
	Above elbow	ADM		7.8			7.2			55	≥49			
Median (s)	Wrist	Index finger		29	≥20		3.3	≤3.5		57	≥50			
Ulnar (s)	Wrist	Little finger		22	≥17		2.8	≤3.1		58	≥50			
Tibial (m)	Ankle	AHB	5.3	4.2	≥4	5.3	5.5	≤5.8				44	45	≤56
	Popliteal fossa	AHB	4.2	3.8		13.0	13.2		46	45	≥41			
Peroneal (m)	Ankle	EDB	2.8	2.3	≥2	5.4	5.8	≤6.5				43	44	≤56
	Below fibula	EDB	2.6	2.2		9.9	10.3		46	45	≥44			
	Lateral popliteal fossa	EDB	2.5	2.2		11.9	12.3		48	44	≥44			
Sural (s)	Calf	Posterior ankle	15	14	≥6	4.2	4.2	≤4.4	48	48	≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis; ADM = abductor digiti minimi; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 28–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity: Fibrillation Potentials	Spontaneous Activity: Fasciculations	Voluntary Motor Unit Action Potentials: Activation	Voluntary Motor Unit Action Potentials: Recruitment	Configuration: Duration	Configuration: Amplitude	Configuration: Polyphasia
Left tibialis anterior	↑	0	0	NL	↓↓↓	+3	+2	+2
Left medial gastrocnemius	NL	0	0	NL	↓↓↓	+2	+2	+2
Left peroneus longus	CRD	+1	0	NL	↓↓↓	+2	+3	+2
Left vastus lateralis	NL	0	0	NL	↓↓	+2	+2	+2
Left iliacus	NL	0	0	NL	↓↓	+2	+2	+2
Left gluteus medius	NL	0	0	NL	↓↓	+3	+2	+2
Right tibialis anterior	↑	±	0	NL	↓↓↓	+3	+2	+1
Right peroneus longus	↑	±	0	NL	↓↓↓	+2	+1	+2
Right medial gastrocnemius	NL	0	0	NL	↓↓↓	+2	+2	+2
Right vastus lateralis	NL	0	0	NL	↓↓	+2	+2	+3
Right iliacus	NL	0	0	NL	↓↓	+2	+2	+2
Left first dorsal interosseous	NL	0	0	NL	↓↓	+2	+2	+1
Left abductor pollicis brevis	NL	0	0	NL	↓↓	+1	+2	+1
Left pronator teres	NL	0	0	NL	↓↓	+2	+2	+1
Left biceps brachii	NL	0	0	NL	↓↓	+2	+1	+2
Left medial deltoid	NL	0	0	NL	↓↓	+2	+2	+2

↑ = increased; ↓↓ = moderately reduced; ↓↓↓ = markedly reduced; NL = normal; CRD = complex repetitive discharge.

only 2 weeks at the time of the early illness, again suggesting that the severity of his poliomyelitis was not great (many more severely affected patients spent months in the hospital or in rehabilitation facilities). Therefore, when the history and physical examination are completed, the diagnosis remains unclear, except that the orthopedic changes in the left leg are likely due to the prior poliomyelitis.

Nerve conduction studies are performed in both legs and in one upper extremity. The CMAP amplitudes are within normal limits, and there is no evidence of focal slowing, conduction block, or prolonged distal latencies. All the minimum F-wave latencies are normal. Likewise, the SNAPs show normal amplitudes and latencies throughout, including the sural potential. In general, these nerve conduction studies are not very informative, except to rule out certain conditions. The normal conduction studies essentially exclude a polyneuropathy or plexopathy to account for the decreased reflexes and weakness. Note that both lower extremities are tested because the examination was asymmetric and showed only lower motor neuron signs, raising the possibility of MMNCB or another demyelinating neuropathy. The absence of conduction blocks or other signs of demyelination essentially excludes these diagnoses.

Moving next to the EMG findings, muscles in both legs are sampled. In both legs, nearly all muscles studied reveal very large, long-duration, polyphasic MUAPs with moderately to markedly decreased recruitment. Similar changes are found on both sides, and there is no clear asymmetry between the two legs. A few muscles have increased insertional activity, but only the left peroneus longus has any sustained fibrillation potentials. Clearly, the degree of reinnervation is much greater than the degree of ongoing denervation. CRDs are also seen in the left peroneus longus. Muscles in the clinically unaffected left upper extremity are sampled next. Somewhat surprisingly, very large, long-duration polyphasic MUAPs are found, with moderately reduced recruitment. Although the changes are not as dramatic as in the lower extremities, they are still quite marked.

At this time, we are ready to formulate our electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are consistent with a chronic disorder of motor neurons, their axons, or both, affecting the lower more than the upper extremities.*

Several important questions can be addressed.

Does the Clinical–Electromyographic Correlation Make Sense?

The clinical diagnosis in this case is PPS. The clinical history and subsequent EMG study display many of the important findings in PPS. Poliomyelitis is a viral infection of the anterior horn cells that subsequently leads to death of the infected anterior horn cells. It presents as fever, headache, myalgias, and gastrointestinal disturbance. The paralysis commonly is asymmetric and develops over the first 1 to 2 weeks. Acute denervation is then followed by reinnervation. If reinnervation is fairly successful, most of the denervated muscle fibers are reinnervated. Accordingly, strength often returns to normal, despite the fact that the number of underlying motor neurons has been greatly reduced. Indeed, many patients who have had poliomyelitis return to a normal level of functioning. Deep tendon reflexes commonly are depressed or lost early in the course and in some cases never return.

As individuals age, there is always some normal loss of motor neurons, beginning at about age 50 to 60 years. At that time, most individuals do not note any appreciable loss of strength from this normal aging process. However, patients with old poliomyelitis, whose number of remaining motor neurons is dramatically reduced, may develop clinical symptoms with loss of further motor neurons. When this occurs, the first symptom often is fatigue, followed by weakness and often pain. The extremities most affected by the original polio usually are the ones most affected by PPS. The limbs apparently spared during the original infection also can be affected by PPS. During the original poliomyelitis infection, subclinical involvement of other body segments is the rule rather than the exception. In the case described here, the clinically unaffected left upper extremity also shows reinnervated MUAPs, but the findings are not as marked as in the lower extremities, which bore the brunt of the original infection.

The SNAPs are always normal in PPS unless there is a superimposed process. Motor nerve conduction studies tend to be normal but may show evidence of axonal loss. In this case, the most important findings are on the needle EMG portion of the examination. Diffusely large, prolonged, polyphasic MUAPs associated with decreased recruitment are found throughout, even in clinically unaffected muscles. Although some active denervation can be seen in PPS, it is generally quite mild, especially in relationship to the amount of reinnervation. CRDs, a marker of chronic denervation, are seen occasionally, which is unusual in ALS.

What is the Differential Diagnosis?

Patients with old poliomyelitis effectively have a decreased reserve of motor neurons and motor nerves. They are more susceptible to the effects of any superimposed neurologic or orthopedic condition, which may disproportionately increase their disability. EMG is often used to evaluate patients with old poliomyelitis to help exclude other superimposed processes such as radiculopathy or myopathy. However, most patients with prior poliomyelitis will have diffuse, chronic, underlying abnormalities on EMG. Thus, it may be difficult to find evidence of a new superimposed neurogenic process. This situation often complicates the evaluation of a possible superimposed radiculopathy in a patient with PPS. In the

case discussed here, it would be difficult to exclude a superimposed mild L5–S1 radiculopathy as a cause of exacerbated symptoms.

Case 28–2

History and Physical Examination

A 60-year-old man was referred for a 5-year history of gradually progressive lower extremity weakness. He noted difficulty getting out of low chairs and going up or down stairs. He reported no pain except for occasional cramps in his hands. He also reported mild difficulty with the shoulder girdle muscles, for instance, when changing the oil in his car. When asked directly, he reported some muscle twitches, especially around the chin and face. There was no similar family history. Routine blood testing was normal other than a CK level elevated at 1425 IU.

On examination, there were obvious fasciculations around the chin and the left face. The tongue looked somewhat scalloped but not definitely atrophic. There was no dysarthria. Motor examination showed mild atrophy, both distally and proximally in the lower extremities. Strength testing was essentially normal in the upper extremities. In the lower extremities, confrontational testing appeared normal. However, on functional testing, he could not arise from a low chair without using his arms. Deep tendon reflexes all were present but hypoactive. Toes were downgoing. Sensory examination showed a mild distal loss to temperature. He walked with a combination of a steppage and waddling gait. Coordination testing was normal.

Summary

The history is that of a 60-year-old man who presents with proximal weakness and an elevated CK level. He has the typical symptoms of proximal muscle weakness (i.e., difficulty getting out of low chairs and going up and down stairs). Initially, one would have thought that this is a clear case of a myopathy. However, there is one important finding on physical examination that is not consistent with a myopathy: the fasciculations around the chin and face. Fasciculations are always a neuropathic phenomenon and are never seen in myopathy. In addition, on examination, there is some mild loss of sensation distally. This is also atypical for a myopathy or motor neuron disorder but could easily be seen in a peripheral neuropathy. Thus, before starting the nerve conduction and EMG studies, we would still likely consider the possibility of a myopathy, but the fasciculations raise the issue of an anterior horn cell or peripheral nerve disorder, and certainly the sensory loss raises the possibility of a peripheral neuropathy.

Proceeding to the nerve conduction studies, the median and ulnar motor conduction studies are completely normal, along with their respective F responses. However, all of the sensory responses in the upper extremities have a low amplitude, consistent with an axonal loss pattern. In the lower extremities, the peroneal motor amplitude is basically normal, with a borderline conduction velocity and F response latency. The sural sensory response, however, is reduced. Thus, from the nerve conduction studies, we know that there is clearly a mild sensory neuropathy.

CASE 28–2. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = μV			Latency (ms)			Conduction Velocity (m/s)			F-wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	8.1		≥4	3.2		≤4.4				29.5		≤31
	Antecubital fossa	APB	7.3			8.2			54		≥49			
Ulnar (m)	Wrist	ADM	8.4		≥6	2.5		≤3.3				32.8		≤32
	Below elbow	ADM	7.2			7.1			57		≥49			
	Above elbow	ADM	7.0			9.5			63		≥49			
Median (s)	Wrist	Index finger	3		≥20	3.5		≤3.5	46		≥50			
Ulnar (s)	Wrist	Little finger	3		≥17	3.0		≤3.1	52		≥50			
Radial	Forearm	Snuffbox	12		≥15	2.3			58		≥50			
Peroneal (m)	Ankle	EDB	4.3		≥2	5.1		≤6.5				58.5		≤56
	Below fibula	EDB	3.7			12.2			40		≥44			
	Lateral popliteal fossa	EDB	3.7			15.0			40		≥44			
Sural (s)	Calf	Posterior ankle	5		≥6	4.3		≤4.4	37		≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis; ADM = abductor digiti minimi; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 28–2. Electromyography

Muscle	Insertional Activity	Spontaneous Activity: Fibrillation Potentials	Spontaneous Activity: Fasciculations	Voluntary Motor Unit Action Potentials: Activation	Voluntary Motor Unit Action Potentials: Recruitment	Configuration: Duration	Configuration: Amplitude	Configuration: Polyphasia
Right tibialis anterior	↑	+1	0	NL	↓	+1	+1	+1
Right extensor hallucis longus	↑	+2	0	NL	↓↓	+2	+1	+2
Right medial gastrocnemius	↑	+1	0	NL	NL	+1	NL/+1	NL
Right vastus lateralis	↑	+1	0	NL	↓↓	+2	+2	+2
Right vastus medialis	↑	+1	0	NL	↓↓	+2	+2	+2
Right iliacus	NL	0	0	NL	↓	+1	+1	+1
Right first dorsal interosseous	↑	+1	0	NL	↓	+1	+1	+1
Right extensor indicis proprius	NL	0	0	NL	↓	+1	+1	+1
Right pronator teres	CRD	0	0	NL	NL	NL/+1	NL/+1	NL/+1
Right biceps brachii	NL	0	0	NL	↓↓	+2	+2	+2
Right triceps	NL	0	0	NL	↓↓	+2	+2	+2
Right medial deltoid	NL	0	0	NL	↓↓	+2	+2	+2
Right infraspinatus	↑	+1	0	NL	↓	+2	+1	+1
Right rhomboid	NL	0	0	NL	NL	NL	NL	NL
Right cervical paraspinals	NL	0	0	NL	NL	NL	NL	NL
Right T6 paraspinal	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓ = slightly reduced; ↓↓ = moderately reduced; NL = normal; CRD = complex repetitive discharge.

Moving on to the needle EMG, nearly every single muscle is abnormal, showing increased insertional activity, and most muscles, especially in the lower extremity, showing fibrillation potentials. In addition, the motor unit potentials are large, long, and polyphasic, with decreased recruitment in nearly all muscles. This widespread pattern is consistent with a diffuse disorder of the motor neurons. Thus, at this point, we are ready to formulate our electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are consistent with an active and chronic generalized disorder of the motor neurons and/or the axons, with a superimposed mild peripheral sensory neuropathy.*

This case raises several important questions.

Putting the Clinical, Laboratory, and EDX Information Together, What is the Most Likely Diagnosis?

This patient presented with proximal muscle weakness, face and chin fasciculations, and an elevated CK level. EDX studies found a diffuse motor neuron disease and accompanying mild sensory neuropathy. Putting all the information together, this is consistent with the diagnosis of X-linked bulbospinal atrophy, also known as Kennedy's disease. Many times, Kennedy's disease is mistaken for a myopathy based on the proximal weakness and the elevated CK level. Because Kennedy's disease presents with proximal muscle weakness, the elevated CK often is inappropriately attributed to a myopathy. In this case, the elevated CK is one more important piece of information that helps make the diagnosis of Kennedy's disease.

After the EDX studies, blood was sent for DNA analysis, which demonstrated the expansion of the trinucleotide (CAG) repeat in the androgen receptor gene, which confirmed the diagnosis of Kennedy's disease.

What Genetic Counseling Should be Advised?

In Kennedy's disease, the genetics are X-linked. Only males are affected. Because the disorder is X-linked, all sons of an affected father will be free of the disease and have no possibility of transferring the disease to their children. However, all daughters of a patient with Kennedy's disease will be carriers. Although none will have the disease, they may transfer the abnormal X chromosome to their children. Half of their daughters will be carriers, while half of their sons will have the disease and half will be free of the disease. Although Kennedy's disease is not generally associated with a change in longevity, patients can become severely disabled; hence, genetic counseling is very important.

Case 28–3

History and Physical Examination

A 25-year-old previously healthy woman was admitted to the hospital with a 3-day history of headache, neck pain, fever, and chills. With the exception of mild nuchal rigidity, her neurologic examination was completely normal. CSF analysis showed an elevated protein (152 mg/dL), normal glucose, and lymphocytic pleocytosis of 60 cells/mm^3. Bacterial cultures were negative.

One day after admission, she developed weakness of the left arm. On examination, there was severe weakness of the left biceps and triceps, and milder weakness in the distal hand muscles. All reflexes were absent in the left upper extremity. Sensory examination was normal. Her weakness remained unchanged several weeks later, when electrodiagnostic studies were done.

Summary

The patient is a previously healthy young woman who was admitted to the hospital with a clinical picture highly suggestive of meningitis. She had several days of fevers, chills, headache, and neck pain, along with a CSF pleocytosis. The cells were predominantly lymphocytes, which is most consistent with a nonbacterial infection. In this setting, she developed acute flaccid weakness of her left arm, with loss of reflexes and completely normal sensation. This case is clearly unusual. The infection and weakness are likely related, either directly or with the weakness occurring as a postinfectious immunologic event.

Moving on to the nerve conduction studies, detailed studies of the left upper extremity are performed with limited comparison studies on the right side. Note that the median, ulnar, and radial motor responses all show low amplitudes with relatively intact distal latencies, conduction velocities, and F responses. There is a clear asymmetry compared with the contralateral side. In contrast, all of the sensory potentials, including the median, ulnar, radial, lateral antebrachial cutaneous, and medial

CASE 28–3. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F-Wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	6.5	1.7	≥4	2.9	3.6	≤4.4					26.3	≤31
	Antecubital fossa	APB		1.4			7.9			48	≥49			
Ulnar (m)	Wrist	ADM	5.7	3.3	≥6	2.9	3.1	≤3.3					27.9	≤32
	Below elbow	ADM		3.0			6.2			53	≥49			
	Above elbow	ADM		2.8			8.1			56	≥49			
Radial (m)	Below spiral groove	EIP	1.8	0.3	≥2	4.2	4.3							
	Above spiral groove	EIP		0.3			7.0			56	≥49			
Median (s)	Wrist	Index finger		41	≥20		2.5	≤3.5		57	≥50			
Ulnar (s)	Wrist	Little finger	38	41	≥17	2.8	2.5	≤3.1	54	58	≥50			
Radial (s)	Forearm	Snuffbox		54	≥15		1.8	≤2.9		62	≥50			
Lateral antebrachial (s)	Elbow	Lateral forearm		17	≥10		2.5	≤3.0		59	≥55			
Medial antebrachial (s)	Elbow	Medial forearm	8	11	≥5	2.4	2.4	≤3.2	52	52	≥50			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; APB = abductor pollicis brevis; ADM = abductor digiti minimi; EIP = extensor indicis proprius.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 28–3. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Left first dorsal interosseous	↑	0	0	NL	↓↓	NL	NL	NL
Left flexor pollicis longus	↑	+1	0	NL	↓↓	NL	NL	NL
Left biceps brachii	↑	+2	0	NL	↓↓↓	NL	NL	NL
Left triceps brachii	↑	+3	0	NL	↓↓↓	NL	NL	NL
Left medial deltoid	↑	+2	0	NL	None	NL	NL	NL
Left rhomboid	↑	+2	0	NL	↓↓↓	NL	NL	NL
Left C5 paraspinal	↑	0	0	NL	None	NL	NL	NL
Left C8 paraspinal	↑	+1	0	NL	None	NL	NL	NL
Let upper trapezius	NL	0	0	NL	NL	NL	NL	NL

↓↓ = moderately reduced; ↓↓↓ = markedly reduced; NL = normal.

antebrachial cutaneous responses are completely normal. Comparison with the contralateral ulnar and medial antebrachial cutaneous sensory responses shows no significant asymmetry. Thus, at the completion of the nerve conduction studies, the findings point to a predominantly motor axonal loss lesion, based on the low motor amplitudes with relatively intact conduction velocities and distal latencies and the absence of any sensory conduction abnormalities. Although a cervical polyradiculopathy might be considered, given the low motor amplitudes and preserved sensory potentials, remember that there is no sensory loss on examination. Thus, this pattern of nerve conduction findings, in the current clinical setting, is highly suggestive of a motor neuron disorder. Note that the findings of low motor amplitudes in the left upper extremity might suggest a presynaptic neuromuscular junction disorder, but the significant asymmetry makes this unlikely.

Moving on to the needle EMG, nearly every muscle in the left upper extremity shows increased insertional activity and prominent fibrillation potentials. Of note, all the MUAPs are normal in morphology, but there is moderately to markedly reduced recruitment in nearly all muscles. Thus, at this time, we are ready to formulate our electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are consistent with a severe subacute process affecting the cervical motor neurons, their axons, or both on the left. These findings are consistent with acute poliomyelitis.*

This case raises several important questions.

Are the EDX Studies Consistent with a Diagnosis of Guillain–Barré Syndrome?

Given the acute weakness after an infection, one might have considered the possibility of a variant of Guillain–Barré syndrome. However, there is no evidence of demyelination on the nerve conduction studies (i.e., no conduction block, conduction velocity slowing, prolonged latencies, or impersistent or absent late responses). In addition, the study is very asymmetric, as is the clinical examination, which would be distinctly uncommon for Guillain–Barré syndrome.

Is the EDX Study Consistent with a Cervical Polyradiculopathy?

If one examines the nerve conduction studies and EMG data in isolation, the study is consistent with a cervical polyradiculopathy. All of the sensory potentials are normal, as would be expected in a radiculopathy (i.e., in a lesion proximal to the dorsal ganglion), with low distal motor amplitudes and widespread denervation on the needle EMG study. This case emphasizes that nerve conduction studies and needle EMG are best interpreted in light of the clinical context. There is no difference on EDX studies between disorders of the nerve roots (e.g., radiculopathy/polyradiculopathy) versus disorders of the anterior horn cells (focal motor neuron disease/diffuse motor neuron disease). However, the distinction is made quite easily clinically. Patients with radiculopathy have prominent pain and sensory symptoms or signs, neither of which is seen in patients with motor neuron disease. In this case, the complete absence of sensory symptoms and signs strongly suggests that this disorder is not at the root level but rather at the anterior horn cell level.

What is the Most Likely Diagnosis?

The study is clearly consistent with a segmental disorder of the anterior horn cells in the cervical area. This is the picture of paralytic poliomyelitis. Poliomyelitis occurs as a febrile illness, with patients usually developing weakness or paralysis during the infection, as opposed to Guillain–Barré syndrome, where there is typically a latency of several days and weeks between the infection and the onset of the weakness. Because of the successful vaccination efforts against the poliovirus, paralytic poliomyelitis is very infrequently caused by the actual poliovirus. Most often, the offending agent is an enterovirus, echovirus, or coxsackievirus. In addition, nowadays West Nile virus has been associated with poliomyelitis-like syndromes in many patients. In this patient, subsequent serology was positive for West Nile immunoglobulin M, confirming that West Nile was the cause of her poliomyelitis.

What is the Time Course of the Lesion?

We know from the nerve conduction studies that the motor amplitudes are abnormal, so at least 3 to 5 days must have transpired, which is the time required for motor nerves to undergo wallerian degeneration. On the needle EMG study, there is active denervation. Thus, at least several weeks must have transpired. However, the MUAP morphology is completely normal, indicating that not enough time has passed for reinnervation to have occurred. This is the classic subacute pattern, typically seen several weeks after the onset of an illness. This particular pattern of a subacute motor neuron disorder is seen only in poliomyelitis-like syndromes. Patients with ALS and other motor neuron disorders typically have a slowly progressive disorder, and, by the time they present, they show signs of active denervation as well as reinnervation. Thus, in most motor neuron disorders, there is a chronic and an acute component. This pattern of a subacute anterior horn cell disease seen in this case is a very unusual and important feature and marks this case as an atypical motor neuron disease. In this patient, serologic studies proved that the paralytic poliomyelitis syndrome was caused by West Nile virus.

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29 Radiculopathy

Radiculopathy is one of the most common diagnoses referred to any electromyography (EMG) laboratory. Even with the widespread use of magnetic resonance imaging, EMG continues to play an important role in the evaluation of radiculopathy. Although imaging studies usually are diagnostic in the more common radiculopathies caused by structural lesions, they often are unrevealing in radiculopathy caused by infection, infiltration, demyelination, or infarction. Whereas imaging studies do well in visualizing the spinal cord and nerve roots and their relationship to the vertebrae and intervertebral discs, they yield no information about how the nerve is functioning. In this regard, EMG complements magnetic resonance imaging with its ability not only to localize the lesion but also to functionally assess the nerve. However, every electromyographer should be aware that EMG has several significant limitations in assessing radiculopathy that can result in false-negative studies.

CLINICAL

The clinical hallmark of radiculopathy includes pain and paresthesias radiating in the distribution of a nerve root, often associated with sensory loss and paraspinal muscle spasm. Motor dysfunction may also be present. Radiculopathy caused by degenerative bone and disc disease most often affects the cervical (C3–C8) and lower lumbosacral (L3–S1) segments, resulting in well-recognized clinical syndromes (Tables 29–1 and 29–2). Associated paraspinal muscle spasm commonly limits the range of motion, and movement of the neck or back may exacerbate symptoms.

The particular sensory and motor symptoms associated with a radiculopathy depend on which nerve root or roots are involved. Each nerve root supplies cutaneous sensation to a specific area of skin, known as a *dermatome* (Figures 29–1 and 29–2), and motor innervation to certain muscles, known as a *myotome* (Tables 29–3 and 29–4). Each dermatome overlaps widely with adjacent dermatomes. *Consequently, it is very unusual for a patient with an isolated radiculopathy to develop a severe or dense sensory disturbance*. Dense numbness usually is more indicative of a peripheral nerve lesion than a radiculopathy. *In a patient with radiculopathy, sensory loss more often is vague, poorly defined, or absent, despite the presence of paresthesias*.

Just as with dermatomes, there is a wide overlap of myotomes. Indeed, nearly every muscle is innervated by at least two if not three myotomes (i.e., nerve roots). For instance, the triceps brachii muscle, predominantly a C7-innervated muscle, also receives some innervation from the C6 and C8 nerve roots. C*onsequently, paralysis of a muscle is very unusual in an isolated radiculopathy*. Even in the case of a severe or complete C7 radiculopathy, the triceps brachii will become weak but not paralyzed, retaining some strength from its partial C6 and C8 innervation.

The deep tendon reflexes may be abnormal in a radiculopathy, depending on the root innervation to the muscle tendon being tested. The biceps and brachioradialis reflexes may be depressed in a lesion of the C5 or C6 nerve roots. The triceps reflex typically is most depressed with a lesion of the C7 nerve root but, because of its significant partial C6 innervation, may be abnormal with a lesion of that root as well. There is no routine reflex to check for a lesion of C8 or T1. In the lower extremities, the knee and ankle reflexes are commonly checked. The knee jerk may be reduced with a lesion of the L3 or L4 (rarely L2) nerve roots and the ankle jerk with a lesion of the S1 nerve root. Again, there is no useful routine reflex to assess the L5 root. Occasionally, a tibialis posterior or medial hamstring reflex can be elicited and, if asymmetric, suggests an L5 radiculopathy. However, both reflexes often are unobtainable in normal individuals.

ETIOLOGY

There are a vast number of causes of radiculopathy. The most common are structural lesions, including herniated discs, bony impingement from spondylosis, and mass lesions such as epidural abscesses and metastatic tumors to the spine.

Less well appreciated is that radiculopathy can occur on a microscopic level without evidence of a mass lesion. The cause can be infiltration by tumor (carcinomatous or lymphomatous meningitis), infiltration by granulomatous tissue (e.g., sarcoid), or infection (e.g., Lyme disease, herpes zoster, cytomegalovirus, herpes simplex). Rarely, cases of pure radiculopathy or polyradiculopathy may be due to acquired demyelinating neuropathy (e.g., early Guillain–Barré syndrome). In addition, radiculopathy can be seen as a result of infarction of the nerve root, which may occur in

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Table 29–1. Common Cervical Root Syndromes

Root	Pain Location	Sensory Disturbance	Weakness	Reflex Change
C3–4	Paraspinal muscles, superior shoulder	Neck	Diaphragm, nuchal muscles, strap muscles	None
C5	Neck, shoulder, anterior arm	Shoulder	Deltoid, supraspinatus, infraspinatus, rhomboids, biceps, brachioradialis	Biceps, brachioradialis
C6	Neck, shoulder, anterior upper arm extending to antecubital fossa	Thumb, index finger, radial forearm	Deltoid, supraspinatus, infraspinatus, rhomboids, biceps, brachioradialis, pronator teres, flexor carpi radialis, extensor carpi radialis	Biceps, brachioradialis
C7	Neck, shoulder, dorsum of forearm	Middle finger	Triceps, latissimus dorsi, pronator teres, flexor carpi radialis, extensor carpi radialis	Triceps
C8	Neck, shoulder, ulnar forearm	Ring, little fingers, hypothenar eminence	Intrinsic hand muscles, finger extensors, finger flexors	None
T1	Neck, shoulder, ulnar arm	Ulnar forearm	Intrinsic hand muscles (Horner's syndrome)	None

Adapted from Geckle, D.S., Hlavin, M.L., 1995. Spondylosis and disc disease. In: Samuels, M.A., Feske, S. (Eds.), Office practice of neurology. Churchill Livingstone, New York, NY.

Table 29–2. Common Lumbar Root Syndromes

Root	Pain Location	Sensory Disturbance	Weakness	Reflex Change
L3	Anterior thigh, groin	Anterior thigh	Iliopsoas, adductors, quadriceps	(Knee)
L4	Anterior thigh	Medial calf, medial foot	Quadriceps, adductors, (iliopsoas)	Knee
L5	Posterolateral thigh and calf, extending into great toe and dorsum of foot	Dorsum of foot, great toe, lateral calf	Tibialis anterior, tibialis posterior, extensor hallucis longus, peronei, gluteus medius, tensor fascia latae	None
S1	Posterolateral thigh and calf, extending into lateral toes and heel	Lateral foot, posterior calf, sole of foot	Gastroc-soleus, hamstrings, gluteus maximus	Ankle

Adapted from Geckle, D.S., Hlavin, M.L., 1995. Spondylosis and disc disease. In: Samuels, M.A., Feske, S., (Eds.), Office practice of neurology. Churchill Livingstone, New York, NY.

vasculitic neuropathy and presumably occurs commonly in diabetic polyradiculopathy. These nonstructural etiologies illustrate how a patient may have a clinical radiculopathy with completely normal imaging studies. It is in such cases that EMG is especially useful in demonstrating a physiologic radiculopathy.

DIFFERENTIAL DIAGNOSIS

The differential diagnosis of pain and radiating paresthesias includes not only radiculopathy but also proximal neuropathy, plexopathy and entrapment neuropathy. Although plexopathies are much less common than radiculopathies, separating plexopathy from radiculopathy on clinical grounds can be quite difficult. In addition, some entrapment neuropathies may be mistaken for radiculopathy, especially when the symptoms are mild. Because an entrapped nerve can cause referred pain and paresthesias, it is possible for distal entrapment to cause symptoms in more proximal segments. For instance, in ulnar neuropathy at the elbow, pain radiating into the upper arm or shoulder is not unusual. Some cases of carpal tunnel syndrome (CTS) are associated with pain in the forearm, the arm, and rarely the shoulder. The presence of referred pain along with distal paresthesias from entrapment neuropathies may suggest radiculopathy. However, pain in the neck or back and exacerbation of symptoms with neck or back movement do not occur in the common entrapment neuropathies and thus provide an important clinical clue pointing to radiculopathy.

Besides plexopathy, proximal neuropathy, and entrapment neuropathy, the major differential diagnosis of radiculopathy includes local orthopedic problems that result in pain and secondary muscle spasm. Often the key task in the EMG laboratory is to try to separate pain due to muscle spasm alone from pain due to true nerve root dysfunction.

ELECTROPHYSIOLOGIC EVALUATION

Nerve Conduction Studies

In patients with radiculopathy, nerve conduction studies typically are normal, and the electrodiagnosis is established

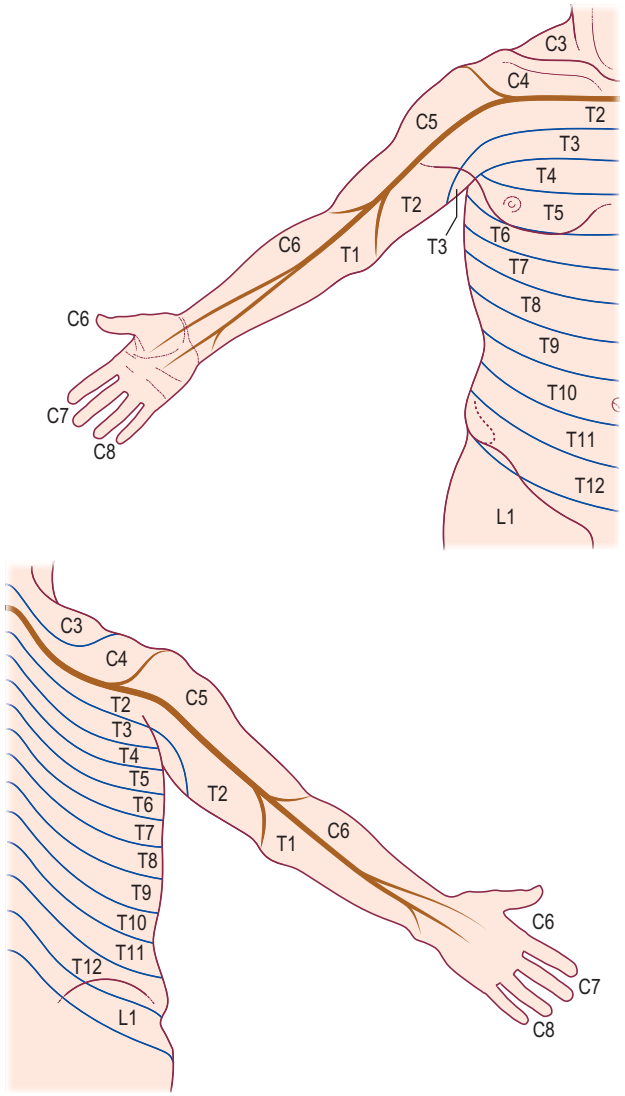

FIGURE 29–1 Cervical and thoracic dermatomes.
(From Aids to the examination of the peripheral nervous system. London: Baillière Tindall. With permission, 1986.)

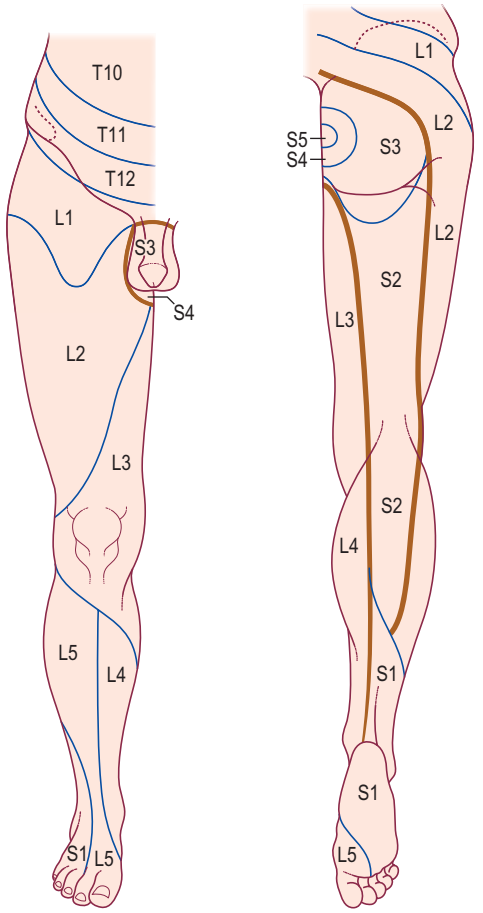

FIGURE 29–2 Lower thoracic and lumbosacral dermatomes.
(From Aids to the examination of the peripheral nervous system. London: Baillière Tindall. With permission, 1986.)

with needle EMG (Box 29–1). Although some motor abnormalities are occasionally seen in radiculopathy, the more important reason to perform nerve conduction studies is to exclude other conditions that may mimic radiculopathy, especially entrapment neuropathy and plexopathy. In cases of upper extremity lesions, ulnar neuropathy at the elbow and CTS must be excluded. Ulnar neuropathy and C8 radiculopathy both can present with pain in the arm associated with numbness of the little and ring fingers. Likewise, pain in the arm with paresthesias involving the thumb, index, and middle fingers may be seen in C6–C7 radiculopathy and CTS. In the case of lower extremity symptoms, one must exclude peroneal neuropathy at the fibular neck. Both peroneal palsy and L5 radiculopathy may present with pain in the leg, accompanied by footdrop and paresthesias over the dorsum of the foot and lateral calf. In more severe cases, the clinical differentiation between a radiculopathy and a common entrapment usually is straightforward. In mild or early cases, however, the distinction often is more difficult, and nerve conduction studies are useful to either demonstrate or exclude an entrapment neuropathy.

Depending on the underlying pathophysiology and the level of the lesion, abnormalities occasionally may be seen on routine motor conduction and F response studies in radiculopathy. If the pathophysiology is predominantly demyelinating, the underlying axons remain intact. In that case, any motor study, stimulating and recording distally, will show a normal latency, conduction velocity, and compound muscle action potential (CMAP) amplitude. The only possible abnormality will be in the F responses. Because the F responses assess conduction both distally and proximally, abnormal F responses with normal distal conduction studies suggest a proximal lesion, either in the proximal nerve, plexus or roots. Of course, F waves will be abnormal only if the recorded muscle is innervated by the affected nerve roots.

Table 29–3. Root Innervation of Major Upper Extremity Muscles

Root	Muscle	Nerve
C4 5	Rhomboids	Dorsal scapular
C5 6	Supraspinatus	Suprascapular
C5 6	Infraspinatus	Suprascapular
C5 6	Deltoid	Axillary
C5 6	Biceps brachii	Musculocutaneous
C5 6	Brachioradialis	Radial
C5 6 7	Serratus anterior	Long thoracic
C5 6 7	Pectoralis major: Clavicular	Lateral pectoral
C6 7 8 T1	Pectoralis major: Sternal	Medial pectoral
C6 7	Flexor carpi radialis	Median
C6 7	Pronator teres	Median
C6 7	Extensor carpi radialis longus	Radial
C6 7 8	Latissimus dorsi	Thoracodorsal
C6 7 8	Triceps brachii	Radial
C6 7 8	Anconeus	Radial
C7 8	Extensor digitorum communis	Radial
C7 8	Flexor digitorum sublimis	Median
C7 8	Extensor indicis proprius	Radial
C7 8	Extensor carpi ulnaris	Radial
C7 8 T1	Flexor pollicis longus	Median
C7 8 T1	Flexor digitorum profundus	Median/Ulnar
C8 T1	Flexor carpi ulnaris*	Ulnar
C8 T1	First dorsal interosseus	Ulnar
C8 T1	Abductor digiti minimi	Ulnar
C8 T1	Abductor pollicis brevis	Median

*In some individuals, the flexor carpi ulnaris may have a C7 contribution.
Note: Underlining indicates predominant root innervation.

Table 29–4. Root Innervation of Major Lower Extremity Muscles

Root	Muscle	Nerve
L2 3 4	Iliacus	Femoral
L2 3 4	Rectus femoris	Femoral
L2 3 4	Vastus lateralis and medialis	Femoral
L2 3 4	Adductors	Obturator
L4 5	Tibialis anterior	Deep peroneal
L4 5	Extensor digitorum longus	Deep peroneal
L4 5 S1	Extensor hallucis longus	Deep peroneal
L4 5 S1	Extensor digitorum brevis	Deep peroneal
L4 5 S1	Medial hamstrings	Sciatic
L4 5 S1	Gluteus medius	Superior gluteal
L4 5 S1	Tensor fascia latae	Superior gluteal
L5 S1	Tibialis posterior	Tibial
L5 S1	Flexor digitorum longus	Tibial
L5 S1	Peronei	Superficial peroneal
L5 S1	Lateral hamstrings (biceps femoris)	Sciatic
L5 S1 2	Gastrocnemius – lateral	Tibial
L5 S1 2	Gluteus maximus	Inferior gluteal
L5 S1 2	Abductor hallucis brevis	Tibial–medial plantar
S1 2	Abductor digiti quinti pedis	Tibial–lateral plantar
S1 2	Gastrocnemius – medial	Tibial
S1 2	Soleus	Tibial

Note: Underlining indicates predominant root innervation.

In the upper extremity, F waves are routinely recorded only for the median and ulnar nerves, which are C8–T1 innervated. Thus, median and ulnar F-wave abnormalities may be seen in C8–T1 radiculopathy; however, these roots are infrequently affected by disc or bone impingement, the most common causes of radiculopathy. A radiculopathy at C5, C6, or C7, which are more common sites of root impingement, will not be reflected in the median or ulnar F responses. The situation is different in the lower extremities. The distally recorded peroneal and tibial muscles (extensor digitorum brevis, abductor hallucis brevis) are innervated predominantly by the L5 and S1 nerve roots, respectively. These levels are often affected by radiculopathy. Thus, in L5–S1 radiculopathies, peroneal and tibial F responses may be prolonged, especially in comparison with the contralateral side.

The H reflex occasionally is helpful in evaluating lower extremity radiculopathy. However, the H reflex, recorded from the soleus, can be used to evaluate only a possible S1 radiculopathy and is most useful when the symptomatic side is compared with the asymptomatic side. The H reflex is the electrical correlate of the ankle reflex; accordingly, it may be delayed or absent in any lesion that depresses the ankle jerk, including polyneuropathy, sciatic neuropathy, lumbosacral plexopathy, and S1 radiculopathy. Unfortunately, the combination of normal distal motor nerve conduction studies and an abnormal H reflex cannot help differentiate between plexopathy and radiculopathy, but can only suggest a proximal lesion.

Box 29–1. Recommended Nerve Conduction Study Protocol for Radiculopathy

Upper Extremity

Motor studies:

- Perform median and ulnar motor conduction studies, recording abductor pollicis brevis and abductor digiti minimi, respectively. Be sure to exclude carpal tunnel syndrome in suspected C6–C7 radiculopathy and ulnar neuropathy at the elbow in suspected C8 radiculopathy. Ideally, studies should be performed bilaterally if CMAP distal latency, amplitude, or conduction velocity is abnormal or borderline.

Sensory/mixed studies:

- Perform at least one sensory study, ideally in the distribution of the suspected radiculopathy (see Table 29–6). It is best to perform the sensory studies bilaterally if the amplitude on the symptomatic side is low or borderline.
- In suspected C6–C7 radiculopathy (paresthesias into thumb, index, and middle fingers), perform at least one median versus ulnar internal comparison study (e.g., median versus ulnar palm-to-wrist mixed studies), as a sensitive internal control, to definitely exclude electrophysiologic evidence of median neuropathy across the wrist.

Late responses:

- Perform median and ulnar F responses. In suspected C8 radiculopathy, these should be performed bilaterally if the results are abnormal or borderline on the symptomatic side.

Lower extremity

Motor studies:

- Perform peroneal and tibial motor conduction studies, recording extensor digitorum brevis and abductor hallucis brevis, respectively. Be sure to exclude peroneal palsy at the fibular neck, especially in suspected L5 radiculopathy. Ideally, studies should be performed bilaterally if CMAP distal latency, amplitude or conduction velocity is abnormal or borderline.

Sensory studies:

- Perform at least one sensory study, ideally in the distribution of the suspected radiculopathy (see Table 29–6). It is best to perform these studies bilaterally if the amplitude on the symptomatic side is low or borderline.

Late responses:

- Perform tibial and peroneal F responses. It is best to perform these studies bilaterally if the results are abnormal or borderline on the symptomatic side.
- Perform H reflexes to soleus bilaterally, especially when considering S1 radiculopathy.

CMAP, compound muscle action potential.

If the pathophysiology also involves axonal loss, nerve conduction abnormalities may be seen in the motor conduction studies. Here again, abnormalities are seen only if the recorded muscle is innervated by the affected nerve root. Axonal loss may result in a decreased CMAP amplitude, with some slowing of conduction velocity and distal latency, especially if the largest fibers are involved. For instance, in an L5–S1 radiculopathy associated with axonal loss, the ipsilateral peroneal and tibial motor responses may have slightly slowed conduction velocities, slightly prolonged distal latencies, and reduced CMAP amplitudes, especially in comparison with the contralateral side. The distal latency prolongation and conduction velocity slowing, however, should never drop into the demyelinating range.

Sensory studies are the most important part of the nerve conduction studies in the assessment of radiculopathy. The sensory nerve action potential (SNAP) remains normal in lesions proximal to the dorsal root ganglion (Figure 29–3). Nearly all radiculopathies, including those caused by compression from herniated discs and spondylosis, damage the root proximal to the dorsal root ganglion (Figure 29–4). Conversely, lesions at or distal to the dorsal root ganglion result in decreased SNAP amplitudes if they are associated with axonal loss. Thus, lesions of the plexus and peripheral nerve (proximal and distal nerve) are associated with abnormal SNAPs, whereas lesions of the nerve root result in normal SNAPs.

It is always imperative to check the SNAP that is in the distribution of the sensory symptoms (Table 29–5). For instance, if a patient has pain down the arm with tingling and paresthesias of the middle finger, the median sensory response to the middle finger should be checked. In such a case, if the lesion is at or distal to the dorsal root ganglion (e.g., in the brachial plexus or median nerve) and there is axonal loss, the SNAP amplitude will be abnormal, if enough time has passed that wallerian degeneration has taken place. On the other hand, if the lesion is proximal to the dorsal root ganglion (e.g., C7 radiculopathy), the SNAP amplitude will be normal. The presence of a normal SNAP yields important diagnostic information. A normal SNAP in the same distribution as sensory symptoms and signs should always suggest a lesion proximal to the dorsal root ganglion (although a proximal demyelinating or acute peripheral nerve lesion also can result in a normal SNAP). One important rare exception to his rule is discussed below.

Superficial Peroneal SNAP and L5 Radiculopathy: the Rare Exception

If one follows the important tenet of EDX testing that SNAPs are normal in radiculopathy (or any lesion proximal to the dorsal root ganglia), and abnormal in disorders of the peripheral nerve associated with axonal loss (at or distal to the dorsal root ganglia), one will be correct over 99% of the time. However, there is one important exception that deserves comment: *in some rare cases of L5 radiculopathy, the superficial peroneal SNAP may be abnormal (abnormal defined as absent, or reduced in amplitude either in an absolute sense or being 50% or less of the contralateral*

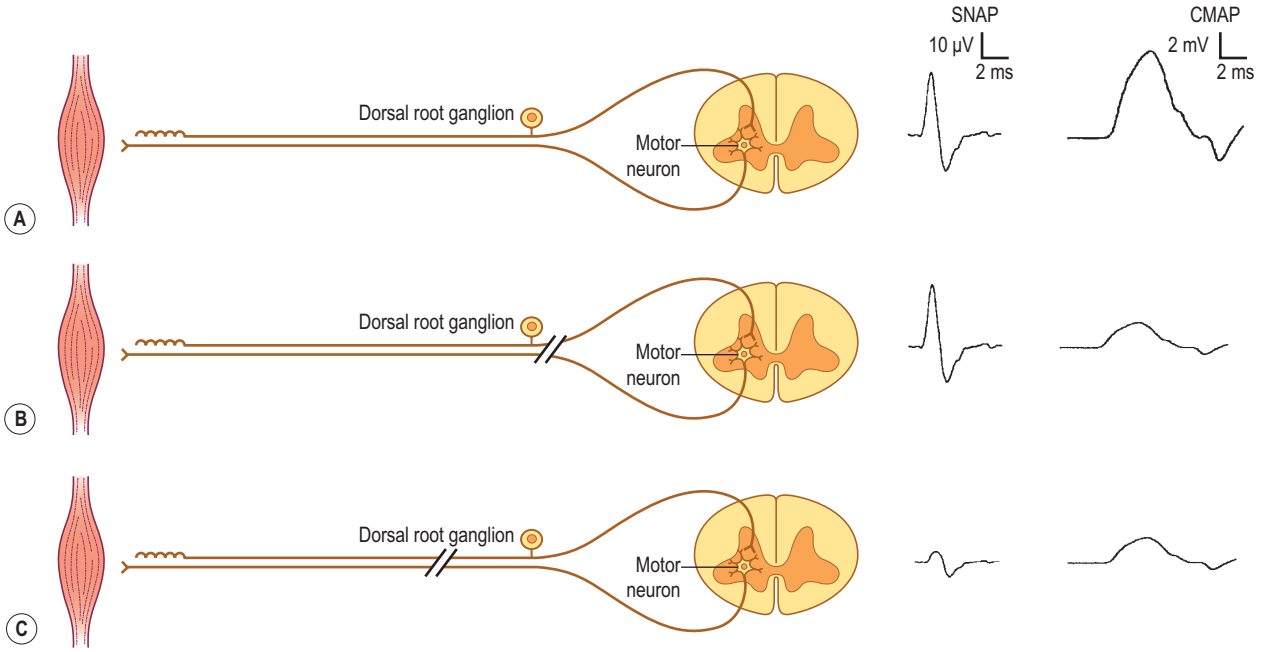

FIGURE 29–3 Sensory and motor potentials in axonal loss lesions distal and proximal to the dorsal root ganglion. **A:** Normal. **B:** Lesion proximal to the dorsal root ganglion. **C:** Lesion at or distal to the dorsal root ganglion. In axonal loss lesions, both proximal and distal to the dorsal root ganglion, degeneration of motor fibers results in decreased compound motor action potential amplitudes. If larger motor fibers are lost, conduction velocities and distal latencies also may slow slightly. The situation is different for sensory fibers. Lesions proximal to the dorsal root ganglion result only in degeneration of sensory fibers proximally into the spinal cord. Because the dorsal root ganglion is a bipolar cell, it remains in continuity with the distal sensory fibers. Therefore, sensory nerve action potentials (SNAPs), when stimulated and recorded distally, remain normal. In axonal loss lesions at or distal to the dorsal root ganglion, distal sensory fibers degenerate, as do the motor fibers. Accordingly, SNAPs are reduced in lesions of the plexus and peripheral nerve but are normal in radiculopathies and other lesions proximal to the dorsal root ganglion.

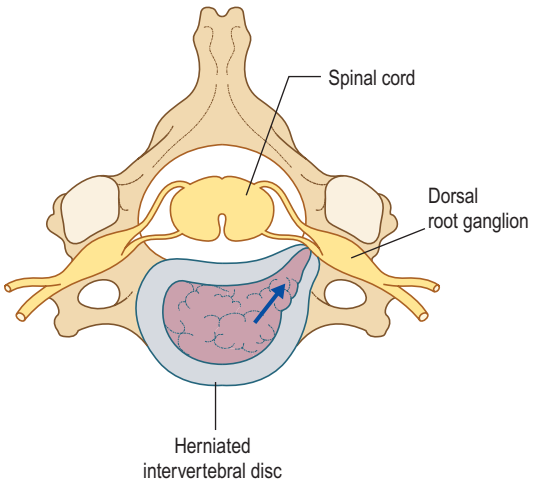

FIGURE 29–4 Radiculopathy and sparing of the dorsal root ganglion. Herniated intervertebral discs are a common cause of cervical and lumbosacral radiculopathy. Herniated discs are most often lateral and posterior, with the dorsal root ganglion located distal to the herniation. In disc herniations, this anatomic relationship results in injury to the roots but sparing of the dorsal root ganglion and the peripheral sensory nerves. Consequently, sensory conduction studies remain normal in radiculopathy.
(From Wilbourn, A.J., 1993 Radiculopathies. In: Brown, W.F., Bolton, C.F. (Eds.), Clinical electromyography, 2nd ed. Butterworth, Boston. With permission.)

superficial peroneal SNAP). The reason behind this finding is not completely understood. In cadaver and other anatomic studies, the L5 dorsal root ganglion is actually located proximal to the intervertebral foramen in 10–40% of individuals, where it is theoretically susceptible to external intraspinal compression (e.g., from a disc). However, some S1 dorsal root ganglia are similarly located, but abnormalities of the sural sensory nerve are never seen in S1 radiculopathies. This discrepancy may be explained by the fact that in cadaver studies, some L5 dorsal root ganglia are found indented by the superior facet. The superior facet frames part of the intervertebral foramen. In contrast, there is no facet joint that frames the intervertebral foramen for the S1 root.

Regardless of the underlying etiology, this finding of an abnormal superficial peroneal SNAP can be seen, although very rarely, in L5 radiculopathy. *The take-home message is the following: in an EDX study wherein all the clinical and electrophysiologic findings are consistent with an L5 radiculopathy, with the exception of an abnormal superficial peroneal SNAP, one can form an EDX impression of an L5 radiculopathy, with the important proviso in the report that these findings could also represent a lumbosacral plexus lesion.* Conversely, if the EDX impression is that of a lumbosacral plexopathy, and the only abnormal sensory response

Table 29–5. Sensory Potentials to Check in Radiculopathy

SNAP	Root
Lateral antebrachial cutaneous	C5–C6
Radial to the thumb	C6
Median to the thumb	C6
Radial to the snuffbox	C6–C7
Median to the index finger	C6–C7
Median to the middle finger	C7
Median to the ring finger	C7–C8
Ulnar to the ring finger	C7–C8
Ulnar to the little finger	C8
Dorsal ulnar cutaneous	C8
Medial antebrachial cutaneous	T1
Saphenous	L4
Superficial peroneal sensory	L5
Sural	S1

SNAP, sensory nerve action potential.

Note: SNAPs are normal in lesions proximal to the dorsal root ganglion, including lesions resulting in radiculopathies. When evaluating a possible radiculopathy, one should examine at least one SNAP in the distribution of the suspected radiculopathy. For example, the ulnar SNAP to the little finger should be normal in a C8 radiculopathy. If it is abnormal, the lesion likely is not at the root, unless there is another reason for the SNAP to be abnormal, such as a superimposed ulnar neuropathy at the elbow.

Box 29–2. Recommended Electromyographic Protocol for Radiculopathy

1. Examine the relevant myotome first. If possible, sample at least two muscles in each of the following areas: paraspinal, proximal and distal limb. In each limb area, try to use muscles with similar root innervation but different peripheral nerve innervation.
2. If abnormalities are found, examine muscles in adjacent myotomes, above and below the suspected lesion level, to exclude a more widespread or diffuse lesion.
3. If findings are mild or equivocal, compare with a contralateral asymptomatic muscle.
4. In the post-spinal surgery setting, fibrillation potentials in the paraspinal muscles do not necessarily have diagnostic significance; thus, they are not helpful to sample.

is the superficial peroneal SNAP, it is likewise essential to put a proviso in the report that the findings could also represent an L5 radiculopathy with the very unusual variant that the superficial peroneal sensory fibers are involved.

Electromyographic Approach

The needle EMG strategy in radiculopathy is straightforward. Distal, proximal, and paraspinal muscles in the symptomatic extremity are sampled, looking for abnormalities in a myotomal pattern that are beyond the distribution of any one nerve (Box 29–2). It is important to exclude a mononeuropathy, polyneuropathy, or more diffuse process that might account for the signs and symptoms.

1. *Muscles innervated by the same myotome but by different nerves must be sampled to exclude a mononeuropathy*. For example, the finding of fibrillation potentials and decreased recruitment of motor unit action potentials (MUAPs) in the triceps brachii (C6–**C7**–C8), extensor carpi radialis (**C6–C7**), and extensor carpi ulnaris (**C7–C8**) could indicate an acute, predominantly C7 radiculopathy, since they all share this nerve root. However, because each of these muscles is also innervated by the radial nerve, one could not differentiate between a radial neuropathy and a C7 radiculopathy by sampling only these muscles. If, however, the flexor carpi radialis (**C6–C7**) or pronator teres (**C6–C7**) were also sampled and showed fibrillation potentials with reduced recruitment of MUAPs, the pattern of abnormalities could no longer be explained by a single nerve lesion (radial neuropathy) because the last two muscles are both innervated by the median nerve. Since all of these muscles have C7 innervation in common, despite different peripheral nerve innervation, this pattern of abnormalities points toward a radiculopathy as the lesion. Note that while nearly all muscles are innervated by multiple myotomes, certain muscles are predominantly innervated by one myotome, and these muscles are the most useful in the electrodiagnosis of radiculopathy (Tables 29–6 and 29–7).
2. *Proximal and distal muscles that are innervated by the same myotome should be sampled to exclude a distal-to-proximal pattern of abnormalities such as occurs in polyneuropathy*. For example, the finding of fibrillation potentials with reduced recruitment of MUAPs in the extensor hallucis longus (**L5**–S1), medial gastrocnemius (**S1**–S2), and peroneus longus (**L5–S1**) muscles would be consistent with an L5–S1 radiculopathy. However, because these are all distal muscles, one could not exclude a typical distal polyneuropathy, especially if the sural sensory potential is borderline low. On the other hand, if more proximal S1 muscles, such as the gluteus maximus (L5–**S1**–S2), also show similar abnormalities, a distal-to-proximal gradient would be excluded, making radiculopathy the more likely diagnosis.
3. *Muscles innervated by myotomes above and below the suspected lesion level must be sampled to exclude a more widespread or diffuse process*. For example, if a C7 radiculopathy is suspected, muscles predominantly innervated by the C5–C6 and C8–T1 nerve roots also should be sampled.
4. *The paraspinal muscles should always be examined*. Examination of the paraspinal muscles is crucial in the evaluation of radiculopathy. The paraspinal muscles are innervated by the dorsal rami, which arise directly from the spinal nerves. Neuropathic abnormalities in these muscles nearly always imply a lesion at or

Table 29–6. Electromyography in Upper Extremity Radiculopathy: Most Useful Muscles to Sample

	C5	C6	C7	C8	T1
Dorsal scapular nerve					
Rhomboid major/minor	■				
Suprascapular nerve					
Supraspinatus	■	■			
Infraspinatus	■	■			
Axillary nerve					
Deltoid	■	■			
Musculocutaneous nerve					
Biceps brachii	■	■			
Median nerve					
Pronator teres		■	■		
Flexor carpi radialis		■	■		
Flexor pollicis longus				■	■
Abductor pollicis brevis				■	■
Ulnar nerve					
Flexor carpi ulnaris			■	■	■
Flexor digitorum profundus (V)				■	■
Abductor digiti minimi				■	■
First dorsal interosseous				■	■
Radial nerve					
Triceps		■	■	■	
Brachioradialis	■	■			
Extensor carpi radialis		■	■		
Extensor digitorum communis			■	■	
Extensor carpi ulnaris			■	■	
Extensor indicis proprius				■	

Note: Green squares indicate "marker" muscles that are most often abnormal for that root in an isolated radiculopathy. Blue squares indicate muscles that may be involved, but are abnormal less frequently. This chart shows those muscles that are most helpful in making the electrodiagnosis of radiculopathy but does not indicate the entire myotomal representation of the individual muscle (see Table 29–3).

From Wilbourn, A.J., 1993. Radiculopathies. In: Brown, W.F., Bolton, C.F. (Eds.), Clinical electromyography, 2nd ed. Butterworth, Boston, with permission.

proximal to the nerve roots. Other than the presence of normal sensory nerve conduction studies, abnormalities in the paraspinal muscles are the only other finding that can conclusively differentiate radiculopathy from plexopathy. Unfortunately, the paraspinal muscles are affected in only about 50% of cases of radiculopathy. *Thus, the absence of paraspinal abnormalities cannot exclude a radiculopathy; however, the presence of paraspinal abnormalities clearly localizes the lesion to the root or anterior horn cell level.* Note that if the patient has had previous neck or back surgery, the paraspinal muscles in the area of previous surgery may remain abnormal for years after the surgery, and any abnormal findings in these muscles would not help differentiate a new lesion from a remote effect of previous surgery. Thus, paraspinal muscles in the area of previous surgery are generally not sampled (see below).

TIME COURSE IN RADICULOPATHY

To interpret an electrodiagnostic study properly, the electromyographer must fully understand the time-related

Table 29–7. Electromyography in Lower Extremity Radiculopathy: Most Useful Muscles to Sample

	L2	L3	L4	L5	S1	S2
Inferior gluteal nerve						
Gluteus maximus						
Superior gluteal nerve						
Gluteus medius						
Tensor fascia latae						
Obturator nerve						
Adductor longus						
Femoral nerve						
Iliopsoas						
Rectus femoris						
Vastus lateralis/medialis						
Sciatic nerve						
Medial hamstrings						
Lateral hamstrings						
Deep peroneal nerve						
Tibialis anterior						
Extensor hallucis longus						
Superficial peroneal nerve						
Peroneus longus						
Tibial nerve						
Medial gastrocnemius						
Soleus						
Flexor digitorum longus						
Tibialis posterior						
Abductor hallucis brevis						
Abductor digiti minimi pedis						

Note: Green squares indicate "marker" muscles that are most often abnormal for that root in an isolated radiculopathy. Blue squares indicate muscles that may be involved, but are abnormal less frequently. This chart shows those muscles that are most helpful in making the electrodiagnosis of radiculopathy but does not indicate the entire myotomal representation of the individual muscle (see Table 29–4).

From Wilbourn, A.J., 1993. Radiculopathies. In: Brown, W.F., Bolton, C.F. (Eds.), Clinical electromyography, 2nd ed. Butterworth, Boston, with permission.

changes that occur in radiculopathy. In all neuropathic lesions resulting in axonal loss, the time that elapses before a muscle begins to show fibrillation potentials (i.e., denervation) is dependent on the intervening distance between the lesion and the muscle. As the normal process of reinnervation then follows, it usually is quite slow and prolonged. Consider the following example. A patient who is otherwise well lifts a heavy box today, herniating the L4–L5 disc, resulting in severe compression of the L5 nerve root. He develops immediate pain in the back that radiates down the buttock and into the leg, along with numbness over the dorsum of the foot and weakness of hip abduction and ankle dorsiflexion.

In the EMG laboratory, the only abnormality that is seen in the acute phase is decreased recruitment of MUAPs in clinically weak muscles – in this case, the weak L5-innervated muscles. Decreased recruitment occurs because some of the L5 motor units have been blocked or lost. MUAP morphology remains normal during the acute phase. The next change occurs at approximately day 10 to 14, when fibrillation potentials and positive waves (i.e., denervating potentials) may develop in the paraspinal muscles (i.e., those

muscles most proximal to the lesion). This is followed at 2 to 3 weeks by similar changes in the proximal L5-innervated muscles (e.g., tensor fascia latae, gluteus medius, etc.). It is not until week 3 or 4 that fibrillation potentials develop in the lower leg L5-innervated muscles (e.g., tibialis anterior), and it can take until week 5 or 6 for the most distally innervated L5 muscles to develop denervating potentials. Throughout this time, the MUAPs remain normal in morphology, with decreased recruitment, just as they were on day 1. After denervation, reinnervation then begins to occur, with the development first of polyphasic MUAPs and later of long-duration, large-amplitude, polyphasic MUAPs. Like denervation, reinnervation occurs first in the most proximal muscles. As months pass, reinnervation is more successful, and the fibrillation potentials diminish, leaving large reinnervated MUAPs with decreased recruitment.

Thus, by examining the combination of spontaneous activity, MUAP morphology, and recruitment pattern, one can approximate the time course of any neuropathic lesion, including radiculopathy.

LIMITATIONS OF THE NEEDLE ELECTROMYOGRAPHIC STUDY IN RADICULOPATHY

Although the EMG study is very sensitive to the presence and approximate localization of a radiculopathy, equivocal or false-negative studies are not uncommon in patients with true radiculopathy. The limitations of nerve conduction studies and needle EMG must be appreciated by both the electromyographer performing the study and the physician ordering and using the results of the study to treat a patient with suspected radiculopathy. The following points should be kept in mind.

It may be Difficult to Localize a Radiculopathy to a Single Root Level

Although the EMG study is a sensitive test for identifying radiculopathy, it may still be difficult to identify the specific segmental level because most muscles are innervated by more than one myotome. For instance, the finding of fibrillation potentials with decreased recruitment of MUAPs in the biceps, deltoid, infraspinatus, and mid-cervical paraspinal muscles is consistent with a C5–C6 myotomal pattern. In such a case, one can be certain that the lesion is not due to a single peripheral nerve injury because abnormalities are present in muscles innervated by the dorsal rami as well as by the musculocutaneous, axillary, and suprascapular nerves. However, in such a case, it is more challenging and sometimes impossible to differentiate between a C5 and C6 radiculopathy.

In such a case, one would next sample muscles that belong to one but not the other myotome. For example, it would be helpful to sample muscles with partial C5 but without C6 innervation, as well as muscles with partial C6 but without C5 innervation. For instance, if the rhomboids (C4–C5) were sampled and found to be normal while the pronator teres (C6–C7) showed fibrillation potentials, then a C6 lesion would be more likely than a C5 lesion. The same approach is used to identify radiculopathies at other levels. One can see that it is just as important to identify which muscles are normal as which are abnormal to try to identify the specific root level involved. Often multiple muscles must be sampled to try to define the level of the involved myotome.

In studies of patients who had a surgically defined single-level radiculopathy, the correct level often could be deduced from extensive needle EMG studies (Figures 29–5 and 29–6). However, not infrequently there was significant overlap between adjacent segments, making a single root localization difficult. The most difficult levels to differentiate were C6 from C7.

If the Lesion is Acute, the Electromyographic Study may be Normal

As noted earlier, during the first 10 to 14 days after the onset of an acute radiculopathy, there are no needle EMG abnormalities except for decreased recruitment of MUAPs in weak muscles. Because it is unusual to find significant weakness in radiculopathy, the EMG study often is completely normal in the acute setting. Fibrillation potentials take several weeks to develop in the more distal limb muscles; therefore, it often is best to wait several weeks before sending a patient for an EMG study, unless one is willing to repeat a normal study after several weeks to look for new changes.

If the Radiculopathy is Purely Demyelinating, the Electromyographic Study will be Normal

If the nerve root is compressed, resulting in demyelination without axonal loss, the needle EMG study may be completely normal. Diagnosing radiculopathy with EMG usually rests on the identification of denervation and reinnervation, signs of axonal loss. If there is no axonal loss, the study usually is normal. Only if demyelination results in significant conduction block, with accompanying weakness, will MUAP recruitment be diminished. This situation, however, is rarely seen in radiculopathy.

If the Sensory Nerve Root is Predominantly Affected, the Electromyographic Study will be Normal

Most patients with radiculopathy have prominent sensory symptoms, including pain and paresthesias, indicating dysfunction of the sensory nerve root. If the sensory nerve root is preferentially affected and the motor nerve root is spared, the EMG study will be normal. Unfortunately, there is no good way to assess the proximal sensory segments using routine nerve conduction studies. Somatosensory evoked potentials are often used to assess the proximal segments,

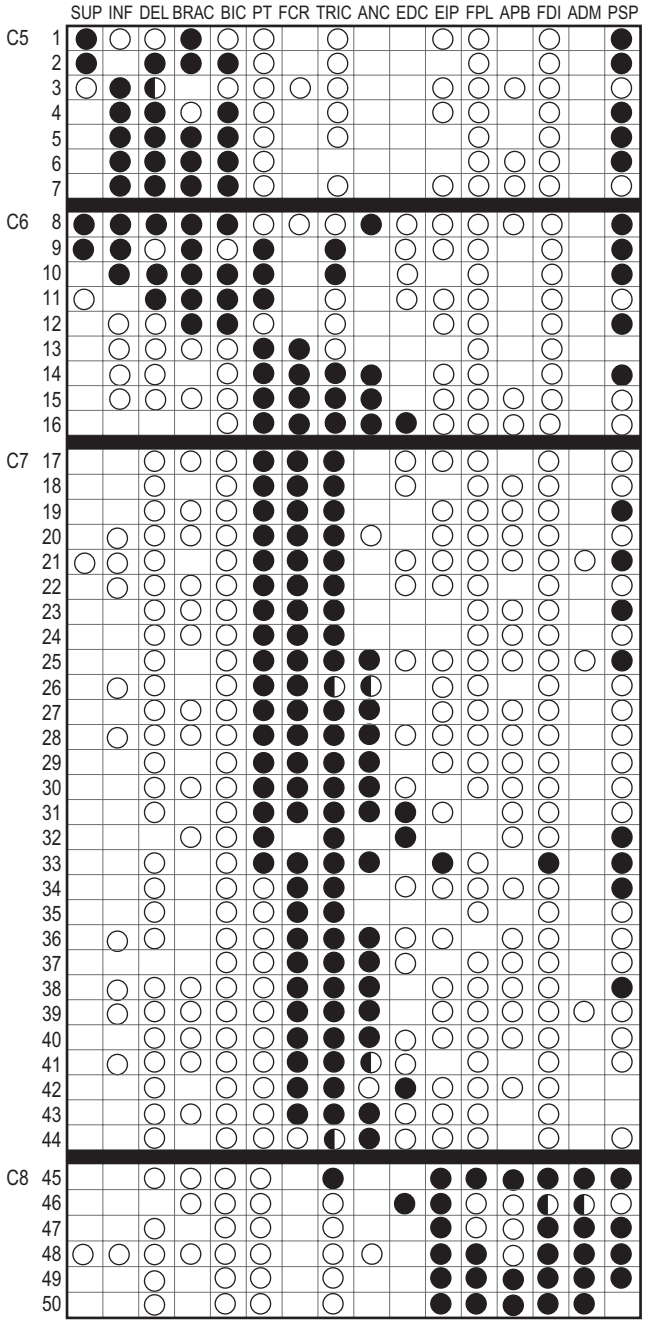

FIGURE 29–5 Cervical radiculopathy: needle electromyographic results in 50 patients grouped by surgically defined root level of involvement. Closed circles represent positive waves or fibrillation potentials, with or without neurogenic recruitment and motor unit action potential changes. Half-closed circles represent neurogenic recruitment changes only. Open circles represent normal examination. ADM, abductor digiti minimi; ANC, anconeus; APB, abductor pollicis brevis; BIC, biceps; BRAC, brachioradialis; DEL, deltoid; EDC, extensor digitorum communis; EIP, extensor indicis proprius; FCR, flexor carpi radialis; FDI, first dorsal interosseous; FPL, flexor pollicis longus; INF, infraspinatus; PSP, paraspinal muscle; PT, pronator teres; SUP, supraspinatus; TRIC, triceps.
(From Levin, K.H., Maggiano, H.J., Wilbourn, A.J., 1996. Cervical radiculopathies: comparison of surgical and EMG localization of single-root lesions. Neurology 46, 1022–1025. With permission.)

but they share many of the limitations of the F response. Most areas of skin are innervated by multiple dermatomes. Accordingly, although a single spinal nerve root may be severely damaged with resultant slowing, the somatosensory evoked latencies may be normal because the adjacent nerve roots (and the overlapping dermatomes they innervate) are not affected.

Different Fascicles may be Preferentially Affected or Spared

Just as in other entrapment syndromes, it is not unusual for some fascicles within a myotome to be affected while others are spared. In fact, some muscles of a particular myotome may be markedly involved, whereas others are affected only minimally or not at all. For example, in some C7 radiculopathies, the triceps may show fibrillation potentials and reduced recruitment of MUAPs, whereas the flexor carpi radialis is essentially normal, although both receive substantial C7 innervation. Thus, the yield of abnormal EMG findings in a radiculopathy clearly increases as more muscles are sampled. As always, however, the electromyographer must balance patient comfort, the length of the test, and the goal of obtaining as much useful information as possible.

The Paraspinal Muscles may be Normal

One expects the paraspinal muscles to be abnormal in radiculopathy, and they often are (Figures 29–5 and 29–6). In some cases, however, they are normal. This may be due to fascicular sparing of fibers to the dorsal rami or may simply be due to sampling error. In addition, some patients have difficulty tolerating the paraspinal examination and consequently may not be able to relax those muscles. The paraspinal needle examination is best done with the patient lying on his or her side in the fetal position, with the side to be studied facing up. This position often will relax the paraspinal muscles. If relaxation is incomplete, however, it may be difficult or impossible to exclude denervation. This situation is encountered most often when studying the thoracic paraspinal muscles.

In addition, reinnervation, like denervation, occurs first in the most proximal muscles. Accordingly, the paraspinal muscles are the first to be reinnervated, often resulting in a pattern of denervation in the limb muscles with sparing of the paraspinals, a pattern equally consistent with plexopathy. In such a case, the finding of normal SNAPs in the distribution of sensory complaints can help to differentiate plexopathy from radiculopathy. One also can look for reinnervated MUAPs in the paraspinal muscles, although it is sometimes difficult for patients to activate these muscles.

Abnormal Paraspinal Muscles are Useful in Identifying a Radiculopathy but Not the Segmental Level of the Lesion

The paraspinal muscles (also known as the erector spinae muscles) run along the spine from the occipital bone in the

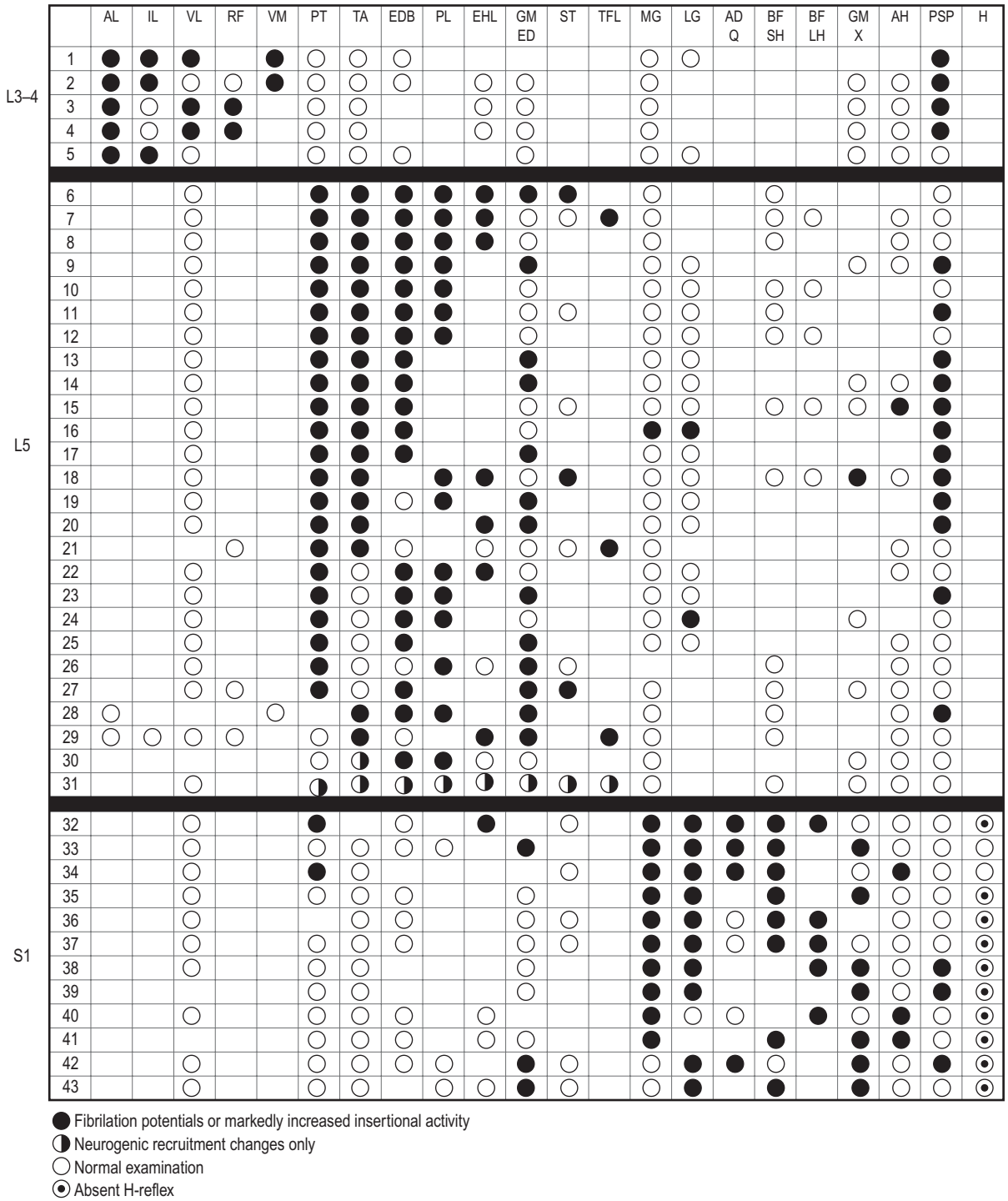

FIGURE 29–6 Lumbosacral radiculopathy: needle electromyographic results in 43 patients grouped by surgically defined root level of involvement. Closed circles represent positive waves or fibrillation potentials, with or without neurogenic recruitment and motor unit changes. Half-closed circles represent neurogenic recruitment changes only. Open circles represent normal examination. ADQ, abductor digiti quinti; AH, abductor hallucis; AL, adductor longus; BFLH, biceps femoris, long head; BFSH, biceps femoris, short head; EDB, extensor digitorum brevis; EHL, extensor hallucis longus; GMED, gluteus medius; GMX, gluteus maximus; H, H-reflex; IL, iliopsoas; LG, lateral gastrocnemius; MG, medial gastrocnemius; PL, peroneus longus; PSP, paraspinal muscles; PT, posterior tibialis; RF, rectus femoris; ST, semitendinous; TA, tibialis anterior; TFL, tensor fascia latae; VL, vastus lateralis.

(From Levin, K.H., 2002. Electrodiagnostic approach to the patient with suspected radiculopathy. Neurol Clin 20, 397–421. With permission.)

skull down to the sacrum. Functionally, they are divided into three groups: (1) the iliocostalis (superficial, lateral); (2) the longissimus (superificial, medial); and (3) the multifidus (deep, adjacent to the spinous process and lamina). In the superficial layers of the iliocostalis and longissimus, which are most often sampled during needle EMG, there is marked overlap in the innervation. Thus, a radiculopathy at one level, determined by examination of the limb muscles, may show denervation in the paraspinal muscles not only at the involved level but also at one or more levels above and below. *Therefore, EMG abnormalities in these paraspinal muscles can be used only to mark the lesion as at or proximal to the nerve root level, but cannot be used to identify which specific nerve root level is involved.*

In contrast, the deep layer of paraspinal muscles, the multifidus, are invariably innervated by only a single nerve root – the one below the spinous process from which they originate. Thus, if these muscles are sampled and are abnormal, the abnormalities are specific to the root (and level) supplying that muscle. The multifidus muscles laterally flex and rotate the spine to the opposite side. The following technique to identify and sample the multifidus has been described:

- The spinous process is first identified and marked.
- The needle insertion point is located 2.5 cm lateral and 1.0 cm rostral to the spinous process (Figure 29–7).
- The needle is directed medially at a 45 degree angle and inserted no more than 3.5 cm.
- When bone is reached, the needle is slightly withdrawn.
- If no bone is encountered, the needle is pulled back and redirected at 60 degrees but no deeper than 5 cm.

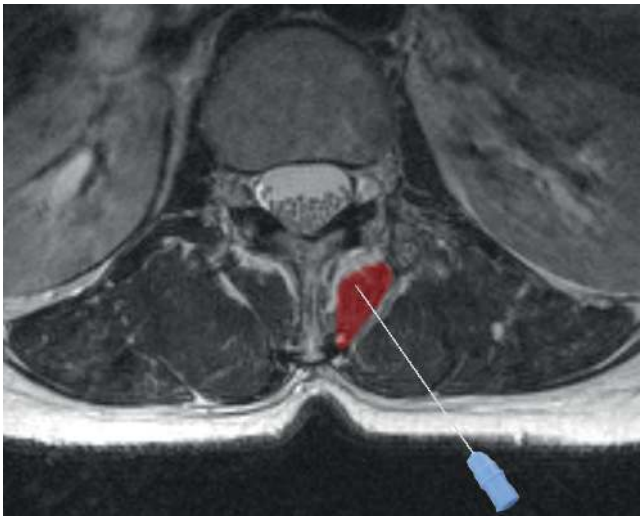

FIGURE 29–7 Needle EMG sampling of the multifidus muscle. The paraspinal muscles consist of three groups: the iliocostalis which is superficial and lateral, the longissimus which is superficial and medial, and the multifidus which is deep. Multiple root levels innervate the superficial iliocostalis and longissimus muscles. However, the multifidus is only supplied by a single nerve root. Techniques to sample the multifidus have been described (see text). In this MRI illustration of the lumbar spine, the EMG needle is in the multifidus muscle (red). Note that the multifidus is deep and adjacent to the spinous process and lamina.

Using this technique, one samples the multifidus muscle above the spinous process that was originally marked. For example, if one identifies the L4 spinous process, this technique would then sample the L3 multifidus muscle, innervated by the L3 root.

Although this technique is appealing because it tries to determine the level of the radiculopathy based on the paraspinal exam, in practice it has several limitations. In cadaver studies, the accuracy of sampling the correct multifidus was approximately 80% (i.e., 20% false-positive rate). Second, it relies on identifying the spinous processes and their correct corresponding levels on the basis of anatomic landmarks – either counting up from the lowest spinous process (L5), and/or identifying the L4 spinous process as being at the highest level of the iliac crests. In many individuals, these landmarks can be difficult to determine; in overweight patients, it is nearly impossible. *Thus, with these limitations in mind, it is prudent to use abnormalities in the paraspinal muscles as a marker that the lesion is at or proximal to the root level, but leave the determination of the actual root level to the pattern of abnormalities seen in the limb muscles.*

There is no Difference between a Radiculopathy/Polyradiculopathy and Focal/Diffuse Motor Neuron Disease on the Electromyographic Study

This is a very important concept often overlooked by electromyographers. Based on EMG results alone, an abnormality of the nerve root cannot be distinguished from an abnormality of the motor neurons supplying that root. The EMG and nerve conduction studies are identical in both conditions. First, all sensory nerve conduction studies are normal in both conditions. In radiculopathy, the sensory roots may be involved, but the SNAPs remain normal because the lesion is proximal to the dorsal root ganglion. In motor neuron disease, the sensory nerves are not involved. Second, motor conduction studies are normal in both radiculopathy and motor neuron disease, unless the muscles being recorded are innervated by the involved roots or anterior horn cells. If there is axonal loss from nerve root or anterior horn cell damage, the CMAP amplitudes may be decreased, with slight prolongation of distal latency and slight slowing of conduction velocity in both situations. Third, in both conditions the EMG shows denervation, reinnervation, or both in the involved myotomes and paraspinal muscles. Consequently, there is no electrophysiologic difference between a polyradiculopathy and diffuse motor neuron disease, or between an isolated radiculopathy and motor neuron disease affecting a single segment.

Although EMG cannot differentiate between a disorder of the nerve roots and a disorder of the motor neurons, there are clear and unequivocal *clinical* differences that allow the distinction to be made. For example, there likely would be no difference between the EMG of a patient with motor neuron disease, such as amyotrophic lateral sclerosis (ALS), and that of a patient with malignant lymphoma diffusely infiltrating multiple nerve roots and cranial nerves. The F responses might be abnormal in polyradiculopathy, in contrast to motor neuron disease, but otherwise the studies could be identical (normal SNAPs, diffuse denervation and reinnervation). However, the clinical presentation and neurologic examination certainly would be markedly different. In motor neuron disease, there are no sensory signs or symptoms. In contrast, pain and paresthesias are prominent in polyradiculopathy. Deep tendon reflexes usually are depressed or absent in polyradiculopathy, whereas they are increased or present in ALS (although they may be depressed in the progressive muscular atrophy variant of ALS). These points once again underscore that EMG and nerve conduction studies can be properly interpreted only in the context of the clinical history and physical examination.

Fibrillation Potentials may Persist in the Paraspinal Muscles after Spinal Surgery

Patients with recurrent or persistent pain after disc surgery often are referred to the EMG laboratory. However, the interpretation of fibrillation potentials in the paraspinal muscles of such patients is not straightforward. Patients who have undergone successful disc surgery and no longer have symptoms or signs of radiculopathy have been demonstrated to have persistent fibrillation potentials in the paraspinal muscles, often for several years. It is not clear why this occurs, but it may be related to the surgical scar through the paraspinal muscles. For this reason, the paraspinal EMG examination no longer assumes the same diagnostic importance in postsurgical patients, and it is questionable whether sampling the paraspinals is worthwhile in such patients (i.e., the absence of denervation cannot exclude a radiculopathy, and the presence of denervation may be a "normal" finding many years after spinal surgery and is of no clinical significance).

Only the Distal Muscles may be Abnormal in Radiculopathy

The diagnosis of radiculopathy is based on demonstrating neuropathic changes in distal, proximal, and paraspinal muscles in a myotomal pattern. Reinnervation, like denervation, occurs in proximal before distal muscles. In addition, the more proximal the denervation, the more successful the reinnervation. Thus, if the proximal limb and paraspinal muscles have been successfully reinnervated, chronic radiculopathies may show denervation only in the distal muscles. Once this reinnervation has occurred in proximal muscles, it may not be possible to differentiate a radiculopathy from a plexopathy or distal neuropathy by the needle EMG examination alone.

There may be Few or no Electromyographic Abnormalities in Spinal Stenosis

Lumbosacral spinal stenosis is a common condition, especially in the elderly. Patients often develop neurogenic claudication (pain and paresthesias in the legs with standing and walking, relieved by sitting). This condition results from *intermittent* compression of the lumbosacral nerve roots. Because the symptoms are intermittent and occur only when the nerve roots are compromised in the upright posture, fixed EMG changes seldom occur. More often, the EMG findings in spinal stenosis, especially in mild to moderate cases, are normal or, at most, equivocal.

Fibrillation Potentials in the Paraspinal Muscles do not Necessarily Imply Radiculopathy

Too often, the presence of fibrillation potentials in the paraspinal muscles is automatically interpreted as evidence of radiculopathy. Although fibrillation potentials in the paraspinal muscles are an important finding in radiculopathy, they are frequently seen in other conditions as well. Most important among those conditions are (1) proximal myopathies with inflammatory or necrotic features (e.g., polymyositis), (2) disorders of the motor neurons (e.g., ALS, intrinsic spinal cord disease), (3) botulism, and (4) neuropathies affecting the dorsal rami (e.g., diabetic polyneuropathy). As in any electrophysiologic study, the final impression should never be based on a single finding but rather on a combination of all nerve conduction and EMG data in conjunction with the clinical information.

In addition, sparse fibrillation potentials and especially positive sharp waves are occasionally seen in the paraspinal muscles in normal individuals. Although this is rare in patients younger than 40 years of age, in one study of normal individuals, approximately 40% of older individuals had brief runs of fibrillation potentials or positive sharp waves in the lower lumbosacral paraspinal muscles. In this study, the denervating potentials were counted if they lasted longer than 0.5 seconds. Remember, traditionally a muscle is graded as +1 fibrillation potentials if you see fibrillation potentials and/or positive waves that last more than 3 seconds, at two or more locations. *The take home message is the following: increased insertional activity or a few brief runs of fibrillation potentials or positive sharp waves limited to the paraspinal muscles, especially in an older individual, may not have any clinical significance, and needs to be interpreted with caution.* Again, remember one of the cardinal rules of EMG: when in doubt, do not overcall a diagnosis. You do not want to make a type I error (i.e., make a diagnosis of an abnormality when one is not really present).

In the Elderly, it may not be Possible to Differentiate a Mild Chronic Distal Polyneuropathy from Mild Chronic Bilateral L5–S1 Radiculopathies

Normally, conduction velocities decrease slightly and sensory amplitudes fall with advancing age. In addition, both polyneuropathy and degenerative disc disease of the lumbosacral spine are common conditions in the elderly. Consider the following pattern in an elderly patient:

- Sural and superficial peroneal SNAPs are just at the lower limits of normal in amplitude
- Peroneal and tibial CMAP amplitudes are slightly reduced, with mildly slowed conduction velocities although still in the range of axonal loss
- Peroneal and tibial F responses and H reflexes are slightly prolonged
- Denervation/reinnervation changes are present in the distal leg muscles
- Nerve conduction study and EMG findings are normal in the upper extremities

If this pattern is present bilaterally in an elderly patient, a definite conclusion cannot be reached. There may be bilateral L5–S1 radiculopathies with successful reinnervation in the paraspinal and proximal muscles, and the borderline SNAPs may be related to advanced age. However, this pattern is also consistent with a distal polyneuropathy that is mild enough that it reduces only the lower extremity SNAPs into the borderline range and spares the upper extremities.

EXAMPLE CASES

Case 29–1

History and Physical Examination

A 50-year-old woman was referred for tingling in the middle and index fingers of the right hand for several months. She also reported associated diffuse aching of the arm for the past 3 to 4 weeks. Examination showed normal strength and deep tendon reflexes. Sensory examination showed a patchy area of decreased sensation over the finger pads of the second and third digits of the right hand. There was no Tinel's sign at the wrist, and a Phalen's maneuver did not increase symptoms.

Summary

The clinical presentation is pain in the arm associated with paresthesias of the middle and index fingers with no other localizing findings by history or physical examination. Because sensation to the index and middle fingers is mediated via the median nerve, brachial plexus, and C6–C7 nerve roots, the most likely diagnoses include CTS and cervical radiculopathy. Other less likely possibilities include a brachial plexus lesion or a high median neuropathy at either the pronator teres or the ligament of Struthers. Unfortunately, there are no other localizing findings to help sort out the clinical differential diagnosis. There is no history of neck pain or paraspinal muscle spasm suggesting radiculopathy and no local findings such as a Tinel's sign or positive Phalen's maneuver suggesting a median neuropathy at the wrist. The motor

CASE 29–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = μV			Latency (ms)			Conduction Velocity (m/s)			F-wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	8.0		≥4	3.6		≤4.4				24		≤31
	Antecubital fossa	APB	7.8			7.6			57		≥49			
Ulnar (m)	Wrist	ADM	9.8		≥6	3.2		≤3.3						≤32
	Below elbow	ADM	8.8			7.5			54		≥49	26		
	Above elbow	ADM	8.6			8.8			59		≥49			
Median (s)	Wrist	Index finger	57		≥20	3.2		≤3.5	62		≥50			
Ulnar (s)	Wrist	Little finger	48		≥17	2.9		≤3.1	58		≥50			
Radial (s)	Forearm	Snuffbox	37		≥15	2.2		≤2.9	62		≥50			
Median (mixed study)	Palm	Wrist	126		≥50	1.7		≤2.2	58		≥50			
Ulnar (mixed study)	Palm	Wrist	38		≥12	1.8		≤2.2	56		≥50			
Mixed difference						–0.1		≤0.3						

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis; ADM = abductor digiti minimi.

Note: All sensory and mixed latencies are peak latencies. All sensory and mixed nerve conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 29–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right biceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right pronator teres	↑	+2	0	NL	↓	NL	NL	NL
Right triceps brachii	↑	+1	0	NL	↓	+1	NL	NL
Right extensor digitorum communis	↑	+1	0	NL	NL	NL/+1	NL	NL
Right medial deltoid	NL	0	0	NL	NL	NL	NL	NL
Right first dorsal interosseous	NL	0	0	NL	NL	NL	NL	NL
Right abductor pollicis brevis	NL	0	0	NL	NL	NL	NL	NL
Right extensor indicis proprius	NL	0	0	NL	NL	NL	NL	NL
Right flexor carpi ulnaris	NL	0	0	NL	NL	NL	NL	NL
Right C7 paraspinal	↑	0	0	NL	NL	NL	NL	NL
Right C6 paraspinal	↑	+1	0	NL	NL	+1	NL	+1

↑ = increased; ↓ = slightly reduced; NL = normal.

examination is normal, so there is no pattern of weakness suggesting either a median nerve or cervical root problem.

This situation of diffuse non-localizing pain associated with paresthesias is commonly seen in the outpatient setting. It is in such cases that the electrophysiologic examination often plays a key role in localizing the lesion. Before proceeding to the nerve conduction and EMG study, we must consider all of the diagnoses mentioned previously. Of greatest interest will be the SNAPs in the index and middle fingers. If either of these SNAPs is reduced, the lesion must be at or distal to the dorsal root ganglion, either in the median nerve or brachial plexus. Conversely, normal SNAPs in these two fingers suggest a more proximal lesion at the root level.

Continuing on to the nerve conduction studies, the median and ulnar motor studies are normal, including the F responses. Likewise, the median and ulnar sensory potentials are normal and very robust. When potentials are borderline or just slightly above the upper limit of normal, it is important to compare them with the contralateral side to look for a significant asymmetry. In this case, there is no need to do so because the median SNAP amplitude is 57 μV in the index finger on the involved side. With such a high normal amplitude on the involved side, we are very unlikely to find the amplitude on the other side to be twice as high, the level required for a significant asymmetry. The radial nerve sensory study also is performed and is normal.

Finally, the median and ulnar palm-to-wrist mixed nerve studies are performed, comparing their two respective latencies. Both are normal with no significant difference in latency. The median and ulnar palmar mixed nerve studies are essential to exclude the possibility of a median neuropathy at the wrist. In fact, approximately 10 to 20% of patients with median neuropathy at the wrist will go undiagnosed in the EMG laboratory if only the median motor and sensory studies are performed without an additional median-versus-ulnar comparison study, such as the palmar mixed nerve studies.

Moving next to the EMG study, particular attention is focused on muscles innervated by the C6 and C7 nerve roots because the patient's paresthesias are in that distribution. Fibrillation potentials and decreased recruitment of MUAPs are found in the pronator teres, triceps brachii, and extensor digitorum communis muscles. In addition, the MUAPs in the triceps brachii and extensor digitorum communis muscles are slightly reinnervated. Muscles innervated by the C5–C6 nerve roots (biceps brachii, medial deltoid) are normal, as are muscles innervated by the C8–T1 nerve roots (abductor pollicis brevis, first dorsal interosseous). Finally, the C6 and C7 paraspinal muscles are sampled, which show increased insertional activity and fibrillation potentials at the C6 paraspinal level.

At this point, we are ready to formulate our electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are consistent with a right C7 radiculopathy.*

Despite the non-localizing clinical symptoms, the EMG study clearly demonstrates that the lesion is at the cervical root level. A median nerve lesion (at the carpal tunnel or proximally) is essentially excluded by the combination of normal median motor, sensory, and palmar mixed nerve studies. Despite the presence of a cervical radiculopathy, the F responses are normal. This is not surprising because the median and ulnar F responses travel via the C8–T1 nerve roots. Any radiculopathy affecting the C5, C6, or C7 nerve roots will always result in normal median and ulnar F waves.

Several important questions can be addressed at this point.

Can the Lesion be Localized to an Isolated Nerve Root?

The needle EMG study shows clear neuropathic abnormalities in the triceps brachii, extensor digitorum communis, and pronator teres. The abnormalities are in the distribution of two different nerves: the radial and median. Thus, the EMG abnormalities cannot be explained by an isolated peripheral nerve lesion. The normal SNAPs also suggest that the lesion is proximal to the dorsal root ganglion. The best way to assess the segmental localization is to analyze the pattern of abnormalities in the limb muscles. Why is the C7 nerve root the most likely? First, the three abnormal muscles (pronator teres, triceps brachii, extensor digitorum communis) all have C7 nerve root innervation in common, although they also each receive some C6 innervation, and the latter two receive some C8 innervation. How does one exclude a C6 or C8 radiculopathy? Muscles innervated by the C6 nerve root but without any C7 innervation (i.e., biceps brachii, medial deltoid) are normal. Similarly, muscles innervated by the C8 nerve root but without any C7 innervation (i.e., abductor pollicis brevis, first dorsal interosseous) are normal. To summarize, although the abnormal muscles have the C6 and C7 nerve roots in common, other muscles with C6 or C8 innervation, but without a C7 contribution, are normal. Therefore, a C6 radiculopathy is less likely, given the normal findings in other C6-innervated muscles. A C8 radiculopathy is unlikely for similar reasons and also would not explain the abnormalities in the pronator teres, which has no C8 innervation. Therefore, determination of the segmental level of a radiculopathy relies on the pattern of muscles that are abnormal as well as those that are normal.

How are the Paraspinal Muscles Helpful in the Diagnosis of Radiculopathy?

In the case discussed here, the cervical paraspinal muscles show clear neuropathic changes. The paraspinal muscles are especially important to examine because abnormalities there imply a lesion at or proximal to the roots. Note that the fibrillation potentials in this case were more prominent at the C6 paraspinal level, yet the electrophysiologic impression was that of a C7 radiculopathy. Because of the wide overlap in innervation of the paraspinal muscles, the level of the radiculopathy should not be based on findings in the paraspinal muscles. Abnormalities in the paraspinal muscles are best used to indicate that the lesion is at or proximal to the roots, whereas the pattern of abnormalities in the limb muscles is used to identify the segmental level.

Case 29–2

History and Physical Examination

A 36-year-old man was referred to the EMG laboratory for evaluation of a possible lower extremity radiculopathy. Eight weeks ago, he had bent down to lift a chair and developed acute pain in the right back and buttock with radiating paresthesias into the calf and lateral foot. His past medical history was notable for several episodes of low back pain over the last several years.

Neurologic examination demonstrated normal muscle bulk and tone in the lower extremities. Straight-leg raising elicited pain and paresthesias into the right leg at 45 degrees. Muscle strength was normal in the left leg. Strength testing in muscles around the right hip was difficult because of pain. In the distal right leg, ankle dorsiflexion appeared normal and plantar flexion appeared to be slightly weak. When asked to stand on tiptoe, the patient was able to do so on the left side but not on the right. Sensory examination demonstrated a subtle sensory loss on the right sole and lateral foot. All deep tendon reflexes were normal and symmetric except for the right ankle reflex, which was absent.

Summary

In contrast to the previous case, the history and examination here both are quite suggestive of a radiculopathy. The several-year history of low back pain, with a recent exacerbation consisting of radiating pain and paresthesias into the calf and lateral foot, is very characteristic of a lumbosacral radiculopathy due to disc disease. On examination, there are clear mechanical signs: straight-leg raise elicits pain and paresthesias in the right leg at 45 degrees. When a nerve root is entrapped by spondylosis or disc herniation, symptoms are often provoked when the nerve is stretched during a straight-leg raise maneuver.

On examination, there is difficulty assessing proximal strength because of pain. This is not an uncommon situation in patients with radiculopathy or other painful conditions. However, when distal muscle strength is tested using maneuvers that do not disturb the proximal hip girdle, there is a suggestion of ankle plantar flexion weakness. That weakness is brought out when the patient is asked to stand on tiptoe. He can do so on the left but not the right, suggesting weakness of the gastroc–soleus muscle. In addition, there is evidence of a subtle sensory loss along the right sole and lateral foot. This sensory disturbance is in the distribution of the S1 dermatome,

CASE 29–2. Nerve conduction studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = μV			Latency (ms)			Conduction Velocity (m/s)			F-wave latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Tibial (m)	Ankle	AHB	3.2	5.3	≥4	5.3	4.8	≤5.8				58	52	≤56
	Popliteal fossa	AHB	2.8	4.8		13.6	13.0		40	46	≥41			
Peroneal (m)	Ankle	EDB	4.4	4.8	≥2	5.8	5.7	≤6.5				52	47	≤56
	Below fibula	EDB	4.0	4.8		10.6	10.4		45	46	≥44			
	Lateral popliteal fossa	EDB	3.9	4.6		13.5	13.3		47	48	≥44			
Sural (s)	Calf	Posterior ankle	13	12	≥6	3.7	3.6	≤4.4	48	47	≥40			
Peroneal (s)	Lateral calf	Lateral ankle	11	10	≥6	3.6	3.8	≤4.4	49	47	≥40			
H reflex	Popliteal fossa	Soleus				NR	32	≤34						

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.
Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 29–2. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right tibialis anterior	NL	0	0	NL	NL	NL	NL	NL
Right medial gastrocnemius	↑	+3	0	NL	↓↓	NL	NL	NL
Right extensor hallucis longus	↑	+1	0	NL	↓	NL	NL	NL
Right peroneus longus	↑	+1	0	NL	↓	NL	NL	NL
Right biceps femoris	↑	+1	0	NL	↓	NL	NL	NL
Right gluteus maximus	↑	+2	0	NL	↓	NL	NL	NL
Right gluteus medius	↑	+1	0	NL	NL	NL	NL	NL
Right tensor fascia latae	↑	0	0	NL	NL	NL	NL	NL
Right vastus lateralis	NL	0	0	NL	NL	NL	NL	NL
Right iliacus	NL	0	0	NL	NL	NL	NL	NL
Right S1 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right L5 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right L4 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right L3 paraspinal	NL	0	0	NL	NL	NL	NL	NL

↑= increased; ↓= slightly reduced; ↓↓ = moderately reduced; NL = normal.

as well as the distribution of the sciatic, sural, and plantar nerves. Sensory loss secondary to radiculopathy usually is subtle or vague because there is so much overlap between adjacent dermatomes. Finally, all of the deep tendon reflexes are normal, with the notable exception of an absent right ankle jerk. The ankle jerk is mediated via the tibial nerve, sciatic nerve, lumbosacral plexus, and S1 nerve root.

Altogether, there are abnormalities in muscle strength (ankle plantar flexion), sensation (lateral foot and sole), and deep tendon reflexes, along with back pain and radiating paresthesias. Clinically, the most likely diagnosis is

an S1 radiculopathy. The only other possible diagnosis is a lesion of the proximal sciatic nerve or the lower lumbosacral plexus, although back pain would not typically be associated with either of these. Finally, before proceeding to the nerve conduction and EMG studies, we must remember that the patient's acute pain developed 8 weeks ago.

When the tibial and peroneal motor conduction studies are performed, the tibial motor amplitudes on the involved right side are found to be low. For this reason, the amplitudes are compared with the contralateral, asymptomatic side. A clear asymmetry is found in the tibial motor studies but not in the peroneal. Along with the relatively decreased tibial CMAP amplitudes, there is slight slowing of conduction velocity and slight prolongation of the F responses. These findings are consistent with mild axonal loss in the tibial motor fibers. The localization of the axonal loss is not clear, however, and at this point could be due to a lesion in the tibial nerve, sciatic nerve, lumbosacral plexus, or lumbosacral nerve roots. Moving next to the sural and superficial peroneal sensory studies, the amplitudes are normal, and there are no significant asymmetries compared with the contralateral side. The sural response is especially important because that is the distribution where the patient has sensory symptoms and subtle sensory loss. The normal sural response after an 8-week course strongly suggests that the lesion is proximal to the dorsal root ganglion.

Finally, because an S1 radiculopathy is a strong possibility, H reflex studies are performed. The latency is normal on the asymptomatic side, but the response is absent on the involved side. The absent H reflex correlates with the clinically absent ankle jerk. If the ankle jerk is present clinically, the H response must be present. If the ankle jerk is absent clinically, however, an H reflex may occasionally be present. It is important to compare the latency of the H reflex on the asymptomatic side with that on the symptomatic side, if present. Any prolongation of the H reflex latency suggests a proximal lesion, provided the distal tibial conductions are normal. Thus, after the nerve conduction studies are completed, there is evidence of axonal loss affecting the tibial motor fibers, with a normal sural sensory response and an absent H reflex. The normal sural SNAP suggests that the lesion is proximal to the dorsal root ganglion.

Moving next to the EMG study, distal and proximal muscles innervated by different nerve roots are sampled in the leg. Fibrillation potentials with decreased recruitment of MUAPs are found in several muscles, including the medial gastrocnemius, extensor hallucis longus, peroneus longus, biceps femoris, gluteus maximus, and gluteus medius. These findings are most prominent in the medial gastrocnemius. In addition, the MUAP morphology in these muscles is normal. Several muscles studied are completely normal, including the tibialis anterior, vastus lateralis, and iliacus. Finally, the lumbosacral paraspinal muscles from the L3 to S1 level also are normal.

At this point, we are ready to formulate our electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are most consistent with a subacute right S1 radiculopathy. Although much less likely, this study cannot completely exclude a lower lumbosacral plexopathy.*

Several important questions can be addressed at this point.

How is the Level of the Radiculopathy Localized to S1?

The nerve conduction and EMG findings in this case are classic for an S1 radiculopathy, with the notable exception of the normal paraspinal muscles. In radiculopathy associated with significant axonal loss, an axonal loss pattern of abnormalities may be seen in the distal motor nerve conduction studies. If an L5 or S1 radiculopathy is associated with axonal loss, signs of axonal loss may be seen in the peroneal and tibial nerve conduction studies, respectively. In the case discussed here, evidence of axonal loss was present in the right tibial motor conduction study. Because the lesion in radiculopathy is proximal to the dorsal root ganglion, the SNAP remains normal even though the patient has sensory complaints in that distribution. The EMG study in this case showed prominent fibrillation potentials in muscles innervated by the L5 and S1 myotomes. The normal tibialis anterior (L4–L5) makes an L5 radiculopathy less likely. In addition, the medial gastrocnemius (S1–S2), which is the most abnormal muscle, has no L5 innervation. Muscles with S1 innervation, both distally and proximally, are abnormal. Thus, there is no distal-to-proximal gradient, as might occur in a polyneuropathy. In addition, because the SNAPs are normal, a neuropathy or plexopathy is less likely. In this context, the absent H reflex also points toward an S1 radiculopathy.

Why are the Paraspinal Muscles Normal if this is a Radiculopathy?

On EMG, although there are fibrillation potentials in several muscles, the MUAP morphology is completely normal. This implies that enough time has passed in the distal muscles for denervation to occur but not enough time for reinnervation. The only part of the study that is surprising for a radiculopathy is the absence of denervation in the paraspinal muscles. In some cases of radiculopathy, abnormalities are not seen in the paraspinal muscles; this can occur for several reasons. First, not all fascicles are equally affected in radiculopathy. It would be ideal if in a radiculopathy all of the muscles in the involved myotome were equally affected, but often that is not the case. In some cases, the fascicles to the dorsal rami are normal, thus sparing the paraspinal muscles. Second, there may be some sampling error in the examination of any muscle. Third and most important, reinnervation occurs first in the paraspinal muscles, and is usually most successful there. If denervation is mild and

reinnervation is successful, the changes in MUAP morphology may be very mild and difficult or impossible to detect.

Can a Lumbosacral Plexopathy be Excluded?

The EMG abnormalities alone are equally consistent with a lesion of the lower lumbosacral plexus. The only strong evidence for radiculopathy and against plexopathy is preservation of the SNAPs. Because the patient has sensory symptoms in the distribution of a normal SNAP (i.e., the sural SNAP), and the lesion is subacute with axonal loss and enough time has passed for wallerian degeneration to have taken place, it is much more likely that the abnormalities represent a lesion of the nerve root and not of the plexus. Because of the absence of abnormalities in the paraspinal muscles, however, it is important to state in the impression that a lumbosacral plexopathy, although less likely, cannot be completely excluded based on this study, although the normal SNAPs argue against this possibility.

Suggested Readings

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30 Brachial Plexopathy

The brachial plexus is a complicated anatomic structure formed by the ventral rami of the lower cervical and upper thoracic nerve roots. Different fascicles from those roots intermix widely within the plexus to ultimately form all the nerves of the upper extremity (Figure 30–1). In cases of suspected brachial plexopathy, nerve conduction studies and electromyography (EMG) often are used to localize the lesion accurately and to assess its severity. Notwithstanding its usefulness, the electrophysiologic evaluation of brachial plexopathy is demanding for the electromyographer. Detailed knowledge of the anatomy of the upper extremity roots, plexus, and peripheral nerves is required. Extensive bilateral studies, with emphasis on the sensory conduction studies and needle EMG, frequently are needed to localize the lesion. Proper localization is key, not only to exclude a disorder of the nerve roots, which may closely resemble brachial plexopathy clinically, but also to suggest possible etiologies, as certain disorders preferentially affect different parts of the brachial plexus. In addition, assessing the severity is important, especially in cases of trauma, where the results often help decide whether surgery should be considered.

ANATOMY

The brachial plexus is located between the lower neck and axilla, running behind the scalene muscles proximally and behind the bony clavicle and the pectoral muscles distally. The plexus is divided anatomically into *roots*,

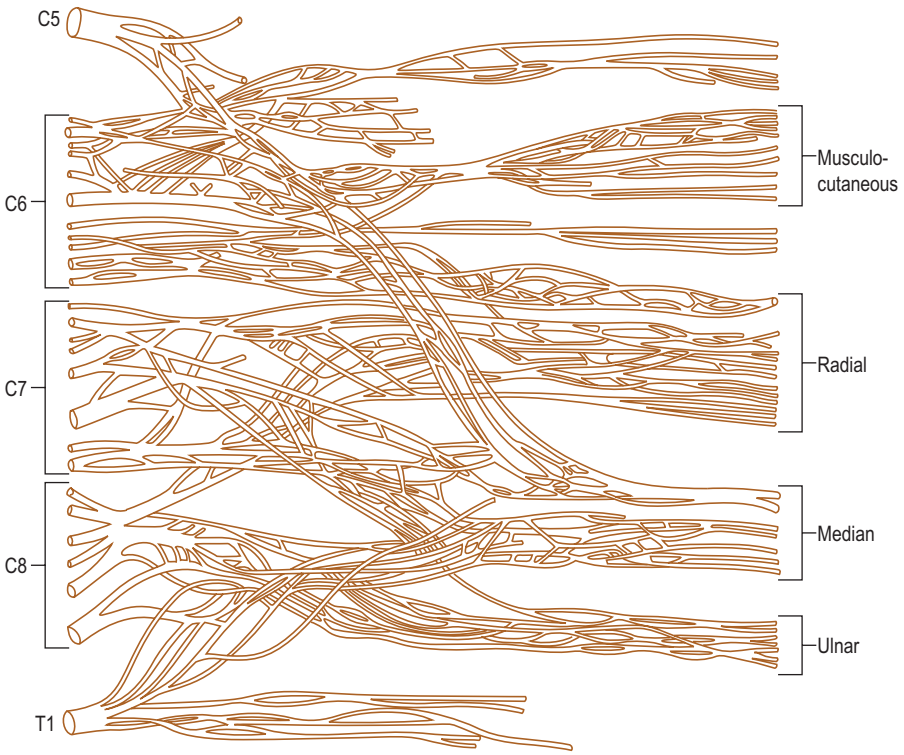

FIGURE 30–1 Microdissection of brachial plexus anatomy. The brachial plexus is a complicated anatomic structure, with nerve fibers from the lower cervical and upper thoracic roots intermixing widely to ultimately form the peripheral nerves. (From Kerr, A.T., 1918. Am J Anat 23, 285, with permission.)

DOI: 10.1016/B978-1-4557-2672-1.00030-1

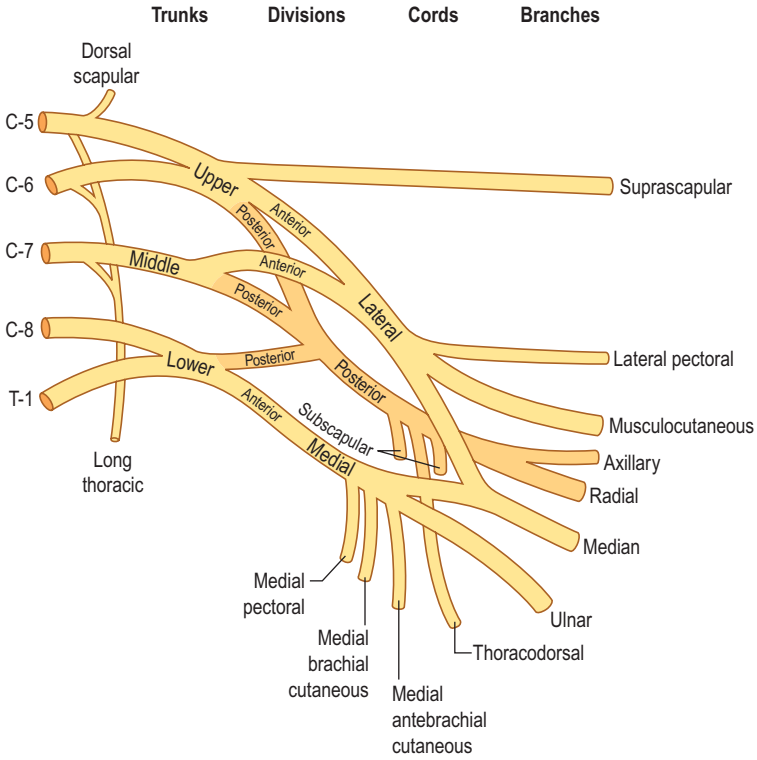

FIGURE 30–2 Brachial plexus anatomy. The brachial plexus is divided into roots, trunks, divisions, cords, and finally nerves.
(From Hollinshead, W.H., 1969. Anatomy for surgeons, volume 2: the back and limbs. Harper & Row, New York, with permission.)

trunks, *divisions*, *cords*, and finally *nerves* (Figure 30–2), although, strictly speaking, the roots and peripheral nerves are not considered part of the plexus proper. Two important nerves, the long thoracic and dorsal scapular, originate directly from the roots, proximal to the brachial plexus. The *long thoracic nerve* comes off the C5–C6–C7 roots, innervating only the serratus anterior muscle. The *dorsal scapular nerve* is formed primarily from the C5 root and less so from the C4 root, innervating the rhomboid muscles. After the take-off of these two nerves, the anterior rami of the C5–T1 nerve roots come together above the level of the clavicle to form the three trunks of the brachial plexus. The *upper trunk* is formed from the C5–C6 roots. The C7 root continues as the *middle trunk*, and the *lower trunk* is formed from the C8–T1 roots.

Each trunk then divides into an *anterior* and *posterior division*. From these six divisions, the cords are formed, located below the level of the clavicle. The three posterior divisions unite to form the *posterior cord*. The anterior divisions of the upper and middle trunks join to form the *lateral cord*. This leaves the anterior division of the lower trunk to continue as the *medial cord*.

All major nerves in the upper extremity originate either from the cords and trunks of the brachial plexus or, less commonly, directly from the roots (Table 30–1). Although the brachial plexus is generally formed from the C5–T1 nerve roots, anomalies are not infrequent. For example, in some individuals the brachial plexus is formed predominantly from the C4–C7 roots and is said to be *prefixed*. In others the plexus is *postfixed*, receiving most of its innervation from the C6–T2 roots.

Table 30–1. Innervation of Major Upper Extremity Nerves

Nerve	Innervation
Dorsal scapular	C4–C5 roots directly
Long thoracic	C5–C6–C7 roots directly
Suprascapular	Upper trunk
Radial	Posterior cord
Axillary	Posterior cord
Thoracodorsal	Posterior cord
Musculocutaneous	Lateral cord
Median	Lateral and medial cords
Ulnar	Medial cord
Medial antebrachial cutaneous	Medial cord
Medial brachial cutaneous	Medial cord

CLINICAL

Because the upper extremity receives its entire motor and sensory innervation from the brachial plexus, brachial plexopathies may present with a variety of clinical patterns,

depending on the part of the plexus affected. These are the same important patterns that form the basis of localization on nerve conduction studies and needle EMG as well.

Panplexus

A complete brachial plexopathy results in weakness, sensory loss, and decreased or absent reflexes in the entire arm. Provided the roots remain intact, the serratus anterior and rhomboids usually are the only muscles spared because they are innervated by nerves that come directly off the roots, proximal to the plexus. The assessment of these two muscles is key, both clinically and electrically, in differentiating a severe lesion at the level of the plexus from one originating at the roots.

Upper Trunk Plexopathy

The upper trunk is formed from the C5–C6 roots. Thus, upper trunk lesions result in weakness of nearly all muscles with C5–C6 innervation. Most affected are the deltoid, biceps, brachioradialis, supraspinatus and infraspinatus muscles. Muscles that receive partial upper trunk innervation, such as the pronator teres (C6–C7) and triceps (C6–C7–C8), may be partially affected. Sensory loss involves the lateral arm, lateral forearm, lateral hand, and thumb. This territory corresponds to the sensory distributions of the axillary and lateral antebrachial cutaneous nerves, as well as the median and radial sensory branches to the thumb and index finger (Figure 30–3). The biceps and brachioradialis tendon jerks are depressed or absent, but the triceps reflex is spared.

Middle Trunk Plexopathy

Middle trunk lesions are very rare. Because the middle trunk is formed directly from the C7 root, middle trunk lesions mimic C7 radiculopathies. Weakness involves primarily the triceps, flexor carpi radialis, and pronator teres muscles. Sensory abnormalities predominantly affect the middle finger, and less so the index and ring fingers (sensory branches of the median nerve) and posterior forearm (posterior cutaneous nerve of the forearm). Only the triceps reflex is abnormal on reflex testing.

Lower Trunk Plexopathy

The lower trunk is formed from the C8–T1 roots. The entire ulnar nerve, the medial brachial cutaneous nerve, and the medial antebrachial cutaneous nerve are ultimately supplied from fibers passing through the lower trunk. In addition, both the median and radial nerves receive partial motor innervation from the lower trunk. Accordingly, lower trunk lesions involve all ulnar muscles, in addition to median C8–T1-innervated muscles (e.g., abductor pollicis brevis [APB], flexor pollicis longus, flexor digitorum profundus) and radial C8-innervated muscles (e.g., extensor indicis proprius [EIP], extensor pollicis brevis). Sensory loss involves the medial arm, medial forearm, medial hand, and fourth and fifth fingers. This territory corresponds to the distribution of the medial brachial cutaneous, medial antebrachial cutaneous, ulnar sensory, and dorsal ulnar cutaneous sensory nerves (Figure 30–4). In pure lower trunk plexopathies, there are no reflex abnormalities.

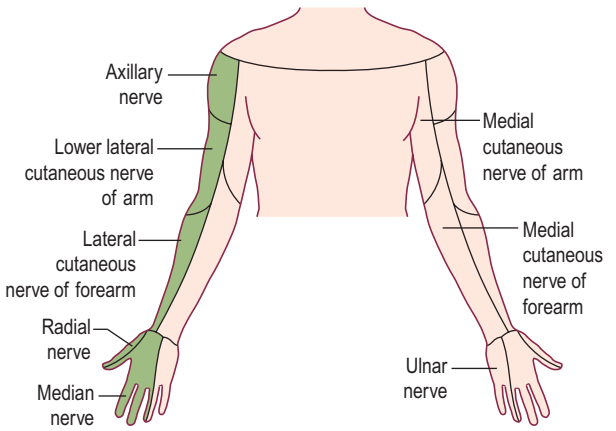

FIGURE 30–3 Upper trunk brachial plexopathy sensory loss. This territory corresponds to the sensory distributions of the axillary nerve, lower lateral cutaneous nerve of the arm (a.k.a. the lateral brachial cutaneous nerve), and lateral cutaneous nerve of the forearm (a.k.a. the lateral antebrachial cutaneous nerve), as well as the median and radial sensory branches to the index finger and thumb.
(Adapted with permission from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia.)

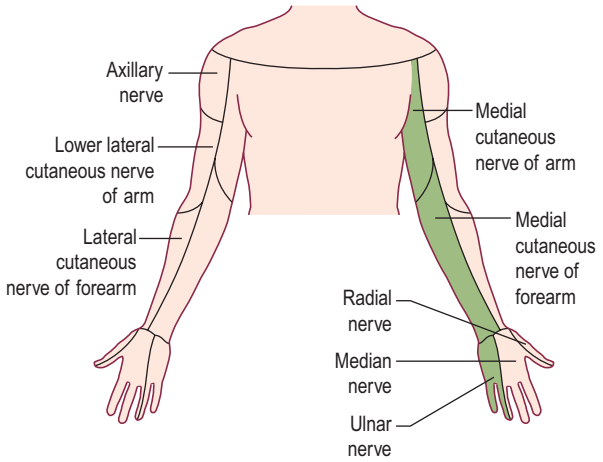

FIGURE 30–4 Lower trunk brachial plexopathy sensory loss. This territory corresponds to the distribution of the medial cutaneous nerve of the arm (a.k.a. the medial brachial cutaneous nerve), medial cutaneous nerve of the forearm (a.k.a. the medial antebrachial cutaneous nerve), ulnar sensory, and dorsal ulnar cutaneous sensory nerves.
(Adapted with permission from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia.)

Lateral Cord Plexopathy

The entire musculocutaneous nerve and the C6–C7 portion of the median nerve are derived from the lateral cord. Accordingly, lateral cord lesions result in median weakness of arm pronation (pronator teres) and wrist flexion (flexor carpi radialis) and musculocutaneous weakness of elbow flexion (biceps). Sensory loss involves the lateral forearm, lateral hand, and first three fingers. This territory corresponds to the distribution of the lateral antebrachial cutaneous and median sensory nerves. On reflex testing, the biceps reflex is abnormal, but the triceps and brachioradialis reflexes are preserved.

Posterior Cord Plexopathy

The radial, axillary, and thoracodorsal nerves are derived from the posterior cord. Accordingly, posterior cord lesions result in complete radial palsies (wristdrop and fingerdrop, arm extension weakness) in addition to weakness of shoulder abduction (deltoid) and adduction (latissimus dorsi). Sensory loss involves the lateral arm, posterior arm and forearm, and radial dorsal hand. This territory corresponds to the sensory distribution of the radial (superficial radial, posterior cutaneous nerve of the forearm) and axillary nerves. On reflex testing, the triceps and brachioradialis reflexes are abnormal.

Medial Cord Plexopathy

The medial cord is the direct continuation of the anterior division of the lower trunk. Thus, medial cord lesions are nearly identical to lower trunk plexopathies, except for intact radial C8 fibers, which pass through the posterior division of the lower trunk and then through the posterior cord. Medial cord lesions result in weakness of all ulnar muscles and C8–T1 median muscles (APB, flexor pollicis longus, flexor digitorum profundus – median). Notably, finger extensors, especially to the index finger (radial innervated), are spared. Sensory loss is identical to that seen in lower trunk lesions, involving the medial arm, medial forearm, medial hand, and fourth and fifth fingers.

ETIOLOGY

Traumatic Brachial Plexopathy

Traumatic injuries are the most common cause of brachial plexopathies. Most frequently, traumatic brachial plexopathies are the result of automobile, motorcycle, or bicycle accidents. Penetrating knife or gunshot wounds may injure the brachial plexus. Traumatic brachial plexopathies may occur in newborns, usually as a result of traction during delivery.

Most traumatic plexopathies are the result of traction and stretch injuries. Injuries in which the head is pushed away from the shoulder (e.g., the head and shoulder striking the pavement when a person is thrown from a moving vehicle) typically result in upper plexopathies, affecting the C5–C6 fibers (Figure 30–5). Such injuries result in characteristic weakness of shoulder abduction, elbow flexion, and arm supination, known as *Erb's palsy*. This is also the most common type of brachial plexopathy seen in newborns, presumably as a result of the head being delivered down, away from the shoulder. The most common risk factor for an Erb's palsy in a newborn is shoulder dystocia in a large infant. In contrast, injuries in which the arm and shoulder are pulled up typically result in lower plexopathies, affecting the C8–T1 fibers. Severe hand weakness, known as *Klumpke's palsy*, characteristically occurs in these latter injuries, with preservation of upper arm and shoulder girdle muscles. One of the most common scenarios in which this occurs is when an individual (often unconscious) is dragged by one arm.

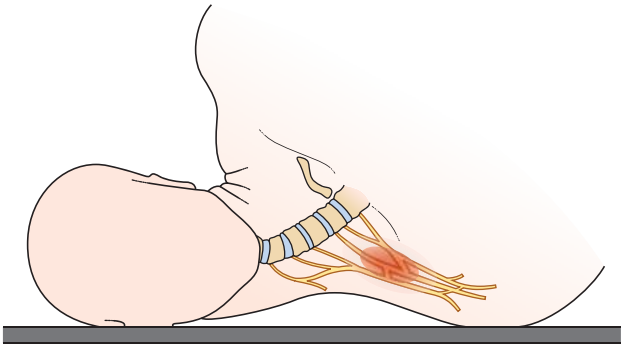

FIGURE 30–5 Traumatic upper trunk plexopathies. Most traumatic plexopathies are the result of traction and stretch injuries. Although the entire brachial plexus can be injured, the upper trunk is most commonly injured when the head is pushed away from the shoulder, as might occur when the head and shoulder strike the pavement after a person is thrown from a moving vehicle.

It is important to understand that severe traction injuries may result in damage to the roots as well as the plexus. A traction injury can cause frank root avulsion, in which the roots are physically separated from the spinal cord. This is the most serious type of injury, with no chance for recovery. Nerve conduction studies and needle EMG are useful in differentiating root avulsion from plexus lesions, or lesions that involve both the roots and the plexus.

Neoplasms and Other Mass Lesions

Brachial plexopathy may result from local tumor invasion. For example, Pancoast tumors of the lung may spread and invade the plexus directly. More commonly, tumors metastasize to nearby lymph nodes, where they grow and compress the plexus. Lymphomas, breast cancer, and lung cancer are the most frequent causes. Lymphomas and leukemia can also infiltrate nerve directly, in the absence of a mass lesion. Rarely, primary nerve sheath tumors (e.g., schwannomas, neurofibromas, or neurofibrosarcomas) may affect the brachial plexus. In unusual cases, non-neoplastic mass lesions, such as hematomas and unusual vascular anomalies (e.g., aneurysm, arteriovenous malformation), can compress the brachial plexus.

Characteristically, neoplastic brachial plexopathy results in a slowly progressive syndrome often associated with prominent pain. In some cases, it may be difficult or impossible to distinguish these lesions clinically from more proximal lesions of the cervical nerve roots. Nerve conduction studies and needle EMG often are very useful in distinguishing brachial plexus from cervical root lesions in these cases.

Neuralgic Amyotrophy (Brachial Plexitis)

Neuralgic amyotrophy is a common although underappreciated disorder that frequently affects individual upper extremity nerves or the brachial plexus. The condition is known by various names, including *Parsonage–Turner syndrome*, *brachial plexitis*, *idiopathic brachial plexopathy*, *and brachial amyotrophy*. In many but not all cases, the syndrome is preceded by an antecedent event that triggers the immune system, usually a viral illness or immunization or, occasionally, surgery. The onset of shoulder pain typically follows within several days to a few weeks. The pain is severe, often awakening the patient from sleep. Early on, muscle weakness may be difficult to detect on examination because of the prominent pain. However, as the pain subsides, typically after 1 to 2 weeks, significant underlying weakness becomes apparent. Muscle atrophy follows. Although paresthesias and sensory loss may also be present, it is not unusual to find only mild or minimal sensory abnormalities on examination.

In some cases, all or part of the brachial plexus may be affected. In others, individual upper extremity nerves, including nerves that come directly off the roots, may be affected in isolation, in a pattern that more resembles a mononeuropathy multiplex. Certain nerves, especially the long thoracic and anterior interosseous nerves, are frequently involved in neuralgic amyotrophy. A long thoracic nerve palsy results in characteristic winging of the scapula, due to weakness of the serratus anterior muscle. An anterior interosseous nerve palsy is recognized principally by weakness of the long flexors of the thumb and index finger (flexor pollicis longus and flexor digitorum profundus – median): the patient is unable to make an "OK" sign. In some cases, involvement of the phrenic nerve has been reported, either in isolation or in conjunction with other mononeuropathies. Exceptionally, lower cranial neuropathies (IX–XII) have accompanied otherwise classic presentations of neuralgic amyotrophy.

Most episodes of neuralgic amyotrophy are primarily unilateral. On close examination, however, especially with needle EMG, some abnormalities on the contralateral side are not unusual. Likewise, most cases are a one-time event. Recurrent episodes can occur but are distinctly uncommon. Recurrent episodes of painful brachial neuritis should raise the possibility of hereditary neuralgic amyotrophy, a rare, dominantly inherited disorder associated with mutations in the *SEPT9* (septin-9) gene on chromosome 17q25 that has a similar clinical presentation to the idiopathic cases. Minor dysmorphic features may be present on physical examination of these patients (i.e., hypotelorism, short stature, cleft palate, epicanthal folds, ring-shaped skin creases on limbs and neck, partial syndactyly).

Postoperative Brachial Plexopathy

Brachial plexopathy is the most common peripheral nervous system complication occurring after coronary artery bypass and other similar chest surgery. These lesions are thought to result from stretch injury following chest wall retraction or occur secondary to compression from hematomas associated with internal jugular catheters. Nearly all involve principally the lower trunk or medial cord of the plexus.

In lesions of the lower trunk, patients note sensory disturbance in the fourth and fifth fingers (ulnar distribution), which may continue up the medial forearm and arm (medial brachial and medial antebrachial cutaneous nerves). Weakness involves all C8–T1 muscles, including median and ulnar hand intrinsics, all forearm long finger flexors (Figure 30–6), and, less so, the finger extensors (principally the extensors to the thumb and index finger). In some cases, pain may be a prominent symptom. Because the presumed injury is secondary to stretch and compression, without any tearing or shearing of nerve and basement membrane, most patients make a good recovery over several months. Rarely, patients may not recover completely; occasionally, patients are left with chronic pain that is difficult to treat.

Delayed Radiation Injury

Radiation may result in a progressive brachial plexopathy, typically presenting years after the radiation exposure. Radiation ports often include the region of the brachial plexus, especially in the treatment of lymphomas and breast, lung, and neck cancers. The risk of radiation-induced plexopathy increases with the dose of radiation; it is more common after doses of more than 5700 rads.

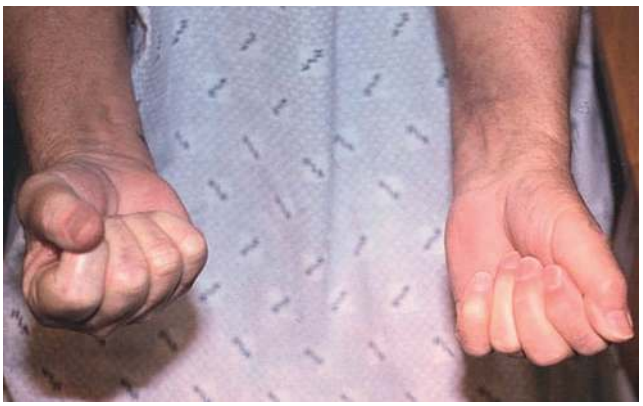

FIGURE 30–6 Postoperative brachial plexopathy. Postoperative brachial plexopathies characteristically affect C8–T1 fibers that travel through the lower plexus. Weakness of intrinsic hand muscles and the long finger flexors results. In the patient shown here, weakness of the long finger flexors on the left is recognized as the inability to make a grip and fully flex the fingers and thumb at the distal interphalangeal joints.

When a patient with a prior history of malignancy who has been treated with radiation develops a slowly progressive brachial plexus lesion, the differential diagnosis usually rests between radiation-induced brachial plexopathy and direct invasion from recurrent tumor. Several clinical and electrophysiologic findings may be of help in distinguishing between the two. First, pain is an earlier and more prominent finding in direct neoplastic invasion. Likewise, the presence of a Horner's syndrome is much more common in direct neoplastic invasion. In contrast, sensory symptoms (i.e., paresthesias and numbness) appear more commonly and earlier in cases of radiation damage. In addition, patients with radiation-induced plexopathy usually are symptomatic for a much longer time, often many years, before coming to medical attention.

On electrophysiologic testing, the presence of myokymic discharges and fasciculations is especially helpful in differentiating radiation-induced from neoplastic plexopathy. Myokymic discharges are characteristic of radiation-induced brachial plexopathy. They may be seen clinically but are more often appreciated on needle EMG. Although conduction block across the brachial plexus has been described in patients with radiation plexitis, it is a nonspecific finding that has also been reported, although less frequently, in plexopathy associated with neoplasm. Other findings on nerve conduction studies and EMG, including the region of the plexus involved, and the presence of clinical weakness are generally not helpful in differentiating radiation-induced from direct neoplastic brachial plexopathy.

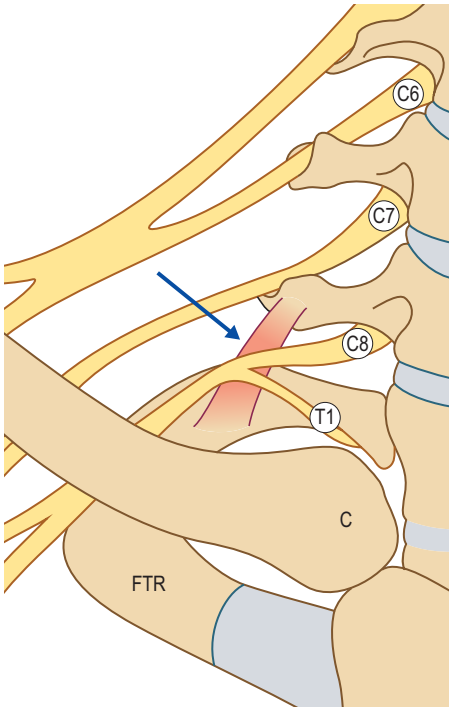

FIGURE 30–7 Neurogenic thoracic outlet syndrome anatomy. Most cases of true neurogenic thoracic outlet syndrome are caused by a fibrous band that runs from a rudimentary cervical rib to the first thoracic rib (arrow), entrapping the lower trunk of the brachial plexus. C, clavicle; FTR, first thoracic rib.
(Adapted from Levin, K.H., Wilbourn, A.J., Maggiano, H.J., 1998. Cervical rib and median sternotomy-related brachial plexopathies: a reassessment. Neurology 50, 1407–1413, with permission.)

Thoracic Outlet Syndrome

The term *thoracic outlet* refers to the exit of the brachial plexus and the major arteries and veins from the shoulder and axilla into the arm. Several types of thoracic outlet syndrome (TOS) occur, depending on which structure is entrapped. Impingement of the subclavian and axillary vessels may result in vascular TOS. Entrapment of the brachial plexus itself results in true neurogenic TOS.

In the past, the diagnosis of neurogenic TOS was made frequently, and many patients underwent surgical procedures to decompress the thoracic outlet. These procedures included removal of cervical ribs, first rib resections, lysis of fibrous bands, as well as sectioning of some of the scalene muscles. However, impingement of the cervical nerve roots at the intervertebral foramina and the common entrapment neuropathies in the arm were not well appreciated at that time. It has since become apparent that true neurogenic TOS is quite rare. Most patients diagnosed with TOS in the past actually had either a cervical radiculopathy or an entrapment of either the ulnar nerve at the elbow or the median nerve at the wrist.

Most cases of true neurogenic TOS are caused by a fibrous band that runs from a rudimentary cervical rib to the first thoracic rib, entrapping the lower trunk of the brachial plexus (Figure 30–7). Accordingly, sensory and motor loss develops in the C8–T1 distribution. Anatomically, the fibrous band most often preferentially affects the T1 fibers. This results in a characteristic pattern of signs and symptoms, including prominent wasting and weakness of the thenar and, less prominently, the hypothenar muscles (Figure 30–8). The explanation for the relative vulnerability of the thenar muscles is not completely clear, but it may be that the thenar muscles are more T1 innervated, whereas the hypothenar muscles receive more C8 innervation.

In addition to the median and ulnar intrinsic hand muscles, the long flexors to the fingers (i.e., flexor digitorum profundus) and thumb (flexor pollicis longus) also are C8–T1 innervated and may be affected. Radial C8 weakness (e.g., EIP) can occur but is less common. Paresthesias and sensory loss affect the fourth and fifth fingers, medial hand, and medial forearm. These sensory changes are in the distribution of the ulnar and the medial antebrachial cutaneous sensory nerves, both of which pass through the lower trunk of the brachial plexus.

Neurogenic TOS is most often confused clinically with the more common ulnar neuropathy at the elbow or C8–T1 radiculopathy. Several pieces of clinical information are helpful in differentiating among these conditions. A history of neck pain with radiation down the arm, provoked by neck movement, strongly favors the diagnosis of radiculopathy. Local tenderness and pain around the elbow commonly accompany ulnar neuropathy at the elbow. In all three

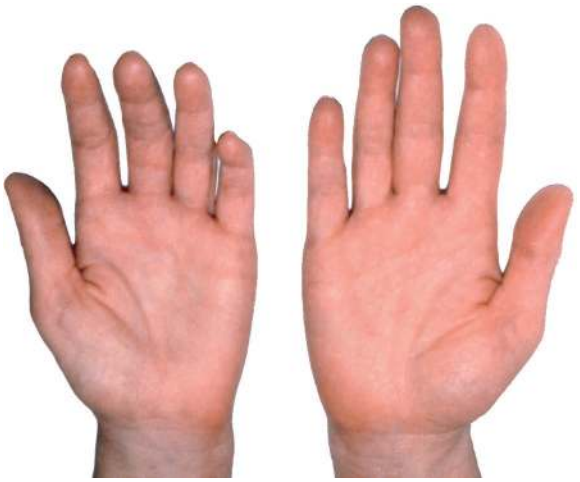

FIGURE 30–8 Hand atrophy and posture in a patient with neurogenic thoracic outlet syndrome. Neurogenic thoracic outlet syndrome preferentially affects the T1 fibers. This results in a characteristic pattern of wasting and weakness of the thenar and, less prominently, the hypothenar muscles (left hand). The explanation for the relative vulnerability of the thenar muscles is likely that they are more T1 innervated, whereas the hypothenar muscles receive more C8 innervation.

conditions, atrophy and weakness may affect both the thenar and hypothenar muscles. With ulnar neuropathy at the elbow, however, thumb abduction will be spared (median innervated). In neurogenic TOS, thumb abduction not only is involved but is often preferentially affected. In a C8–T1 radiculopathy, thumb abduction may be weak but is not out of proportion to weakness of the other C8–T1-innervated muscles. On sensory testing, abnormalities are restricted to the fifth and medial fourth fingers and medial hand in ulnar neuropathy at the elbow. In both neurogenic TOS and C8–T1 radiculopathy, sensory disturbance extends more proximally into the medial forearm, in the distribution of the medial antebrachial cutaneous sensory nerve.

ELECTROPHYSIOLOGIC EVALUATION

The principal goals of the electrophysiologic study in suspected brachial plexopathy are to localize the lesion accurately and to assess its severity. In addition, every study should exclude the possibility of radiculopathy or multiple peripheral nerve lesions mimicking a brachial plexus lesion. Before embarking on the electrophysiologic study, a firm understanding of normal brachial plexus anatomy is essential. Likewise, the electromyographer should have a good idea from the clinical examination where in the brachial plexus the pathology is likely to be.

The electrophysiologic evaluation of brachial plexopathy relies primarily on the sensory nerve action potentials (SNAPs) and a detailed needle EMG examination. Motor nerve conduction studies, although helpful in some cases, are generally not useful in differentiating between a plexopathy and radiculopathy.

Box 30–1. Recommended Nerve Conduction Study Protocol for Brachial Plexopathy

Routine sensory conduction studies:

1. Sensory potentials: lateral antebrachial cutaneous, radial, median, ulnar and medial antebrachial cutaneous (see Table 30–3)
2. Compare with the unaffected side, especially if potentials are low or near the lower limit of normal

Routine motor conduction studies:

1. Routine median motor study, recording abductor pollicis brevis, stimulating wrist and antecubital fossa
2. Routine ulnar motor study, recording abductor digiti minimi, stimulating wrist and below and above elbow

Special considerations:

- In suspected lower trunk/medial cord lesions, routine median and ulnar motor conduction studies can be performed, but also stimulating at the axilla and Erb's point. For proximal median motor conduction studies to be performed properly, collision studies are required to eliminate the confounding effect of co-stimulating the ulnar nerve.
- Comparison of the motor studies to the contralateral side may be helpful.
- In suspected posterior cord lesions, radial motor conduction studies should be performed to exclude radial neuropathy at the spiral groove.
- Stimulating Erb's point, recording the biceps, triceps, deltoid, or spinati can be performed bilaterally in suspected upper or middle trunk lesions, to assess the amount of axonal loss.

F responses:

1. Bilateral median and ulnar F responses, especially in suspected lower trunk or medial cord lesions.

Nerve Conduction Studies

Sensory nerve conduction studies play a central role in the assessment of possible brachial plexopathy (Box 30–1). All sensory nerve fibers in the plexus lie distal to the dorsal root ganglion. Thus, brachial plexus lesions often result in abnormal SNAPs, which are one of the most useful pieces of information to help differentiate plexus from root lesions. In the arm, the lateral antebrachial cutaneous, radial, median, ulnar, and medial antebrachial cutaneous sensory conduction studies are all easily performed. In brachial plexopathy, one or more of these SNAPs usually are abnormal, depending on the location and etiology of the lesion (Table 30–2). In some cases, an abnormal SNAP may be discovered only by comparing it with the contralateral side. Bilateral studies are most helpful when the SNAP amplitude on the symptomatic side is at or just below the lower limit of normal. In some cases, a SNAP may have an amplitude in the normal range, but side-to-side comparison reveals a clear asymmetry. In general, there must be a 50% difference in amplitude from side to side for a study to be considered abnormal (i.e., the abnormal side has a 50% or lower amplitude than the normal side).

Motor studies are less useful in the assessment of brachial plexopathy. Their usefulness lies primarily in excluding multiple entrapment neuropathies that can mimic a

Table 30–2. Sensory Potentials to Check in Brachial Plexopathy

SNAP	Cord	Trunk
Lateral antebrachial cutaneous	Lateral	Upper
Radial to the thumb	Posterior	Upper
Median to the thumb	Lateral	Upper
Radial to the snuffbox	Posterior	Upper/middle
Median to the index finger	Lateral	Upper/middle
Median to the middle finger	Lateral	Middle
Median to the ring finger	Medial	Middle/lower
Ulnar to the ring finger	Medial	Lower
Ulnar to the little finger	Medial	Lower
Dorsal ulnar cutaneous	Medial	Lower
Medial antebrachial cutaneous	Medial	Lower

SNAP, sensory nerve action potential.

Note: SNAPs are abnormal in lesions at or distal to the dorsal root ganglion including plexopathies. In the evaluation of a possible brachial plexopathy, the pattern of the abnormal SNAPs helps to localize the lesion.

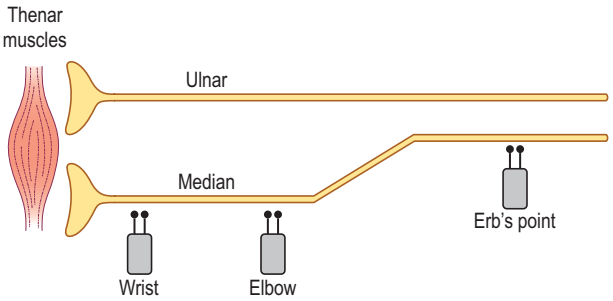

FIGURE 30–9 Co-stimulation of adjacent nerves at Erb's point. During routine median and ulnar motor conduction studies, co-stimulation occurs at the wrist and elbow sites only if an excessive stimulus is used. In contrast, co-stimulation of ulnar and median fibers occurs routinely at proximal stimulation sites (e.g., axilla and Erb's point). During ulnar motor conduction studies recording the abductor digiti minimi, co-stimulation is not a major problem because there are no median-innervated muscles in the hypothenar eminence. In contrast, during median motor conduction studies recording the thenar muscles, co-stimulation results in a median compound motor action potential contaminated by ulnar motor fibers in the thenar eminence.

brachial plexus lesion. The routine median, ulnar, and radial motor studies all record from distal C8- or C8–T1-innervated muscles. Accordingly, routine median and ulnar motor studies are useful only in assessing medial cord or lower trunk lesions. Likewise, radial motor studies are useful only in assessing posterior cord or lower trunk lesions. Lesions of the lateral cord or of the upper or middle trunks do not result in any abnormalities on routine motor studies.

If a brachial plexus lesion associated with axonal loss affects the lower trunk or medial cord, median and ulnar compound muscle action potentials (CMAPs) may have reduced motor amplitudes, with mild slowing of distal latency and conduction velocity. Median and ulnar F responses may be prolonged, especially when compared with the asymptomatic side. Radial motor nerve conduction studies may show similar findings in a lower trunk or posterior cord lesion.

Conduction studies can be performed across the brachial plexus but should be approached with caution. Most brachial plexopathies are primarily axonal loss lesions. Hence, no focal slowing or conduction block will be seen across the lesion in most cases. Conduction block and focal slowing typically are seen only in some cases of radiation plexitis and inflammatory demyelinating polyneuropathy. Motor conduction studies across the plexus require stimulation at the axilla and at Erb's point. In some individuals, it may be difficult or impossible to obtain supramaximal stimulation even with maximum machine output at proximal sites, especially at Erb's point. Submaximal stimulation, if not recognized, may give the mistaken impression of a conduction block.

The other major problem with proximal stimulation is co-stimulation of adjacent nerves (Figure 30–9). Co-stimulation often occurs at the axilla and always occurs at Erb's point. When routine ulnar motor conduction studies are performed, stimulating at the axilla or at Erb's point, this results in depolarization of both ulnar and median C8–T1-innervated muscles. This is not a major problem when the abductor digiti minimi (ADM) is used for recording because there are no median-innervated muscles in the hypothenar eminence that could potentially contaminate the ADM CMAP. However, when routine median motor nerve conduction studies are performed recording the APB, co-stimulation at the axilla or Erb's point is problematic because both median- and ulnar-innervated muscles are present in the thenar eminence, where the recording electrodes are placed. With co-stimulation, the median CMAP will be contaminated by the contribution from ulnar fibers, making the amplitude larger and perhaps also affecting the distal latency.

The problem of proximal co-stimulation during median motor studies can be eliminated only by the use of a collision study (Figure 30–10). The basic idea of a collision study is to collide out the ulnar fiber contribution from proximal stimulation by also stimulating the ulnar fibers distally. Collision studies require two separate stimulators that can be set to give their individual shocks at different times. The first stimulator is placed over the ulnar nerve at the wrist and the second over the proximal site (axilla or Erb's point). Recording electrodes are placed on the median-innervated APB as usual. The stimulators are individually set to give a supramaximal shock over the ulnar nerve at the wrist and at the proximal site. By subtracting the distal latency from the proximal latency, one can then calculate the amount of time in milliseconds it takes for the depolarization to travel from the proximal to the distal

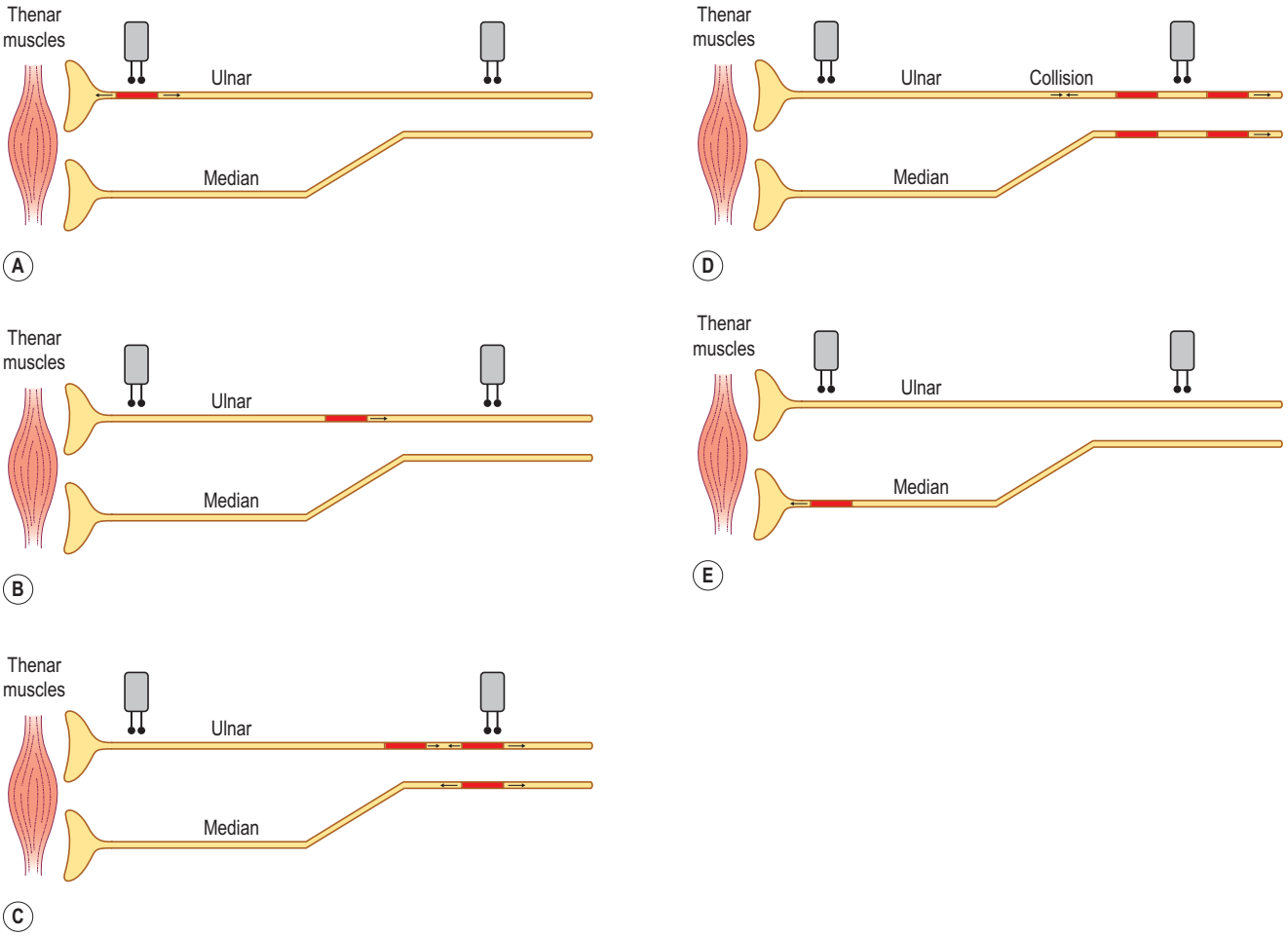

FIGURE 30–10 Collision study. Stimulation at Erb's point activates both median and ulnar nerve fibers. During median nerve conduction studies, co-stimulation of ulnar fibers can be eliminated with collision studies. Collision studies require two stimulators that are set to give their individual shocks at different times. The first stimulator is placed over the ulnar nerve at the wrist and the second over Erb's point. Individually, the stimulators are set to give a supramaximal shock to the ulnar nerve at the wrist and at Erb's point, respectively. A collision study then is performed, wherein a stimulus given at the first stimulator is followed by a delay before the second stimulator discharges. **A:** The first stimulus depolarizes the ulnar nerve and travels both distally and proximally. **B:** The distal pulse results in an ulnar compound muscle action potential (CMAP) from the ulnar-innervated thenar muscles. **C:** The second stimulus at Erb's point is given at a time before the first stimulus antidromically passes the proximal stimulation site. Co-stimulation of both median and ulnar fibers results. **D:** The depolarization in the ulnar fibers collides with the antidromic impulse from the first stimulus, resulting in elimination of the impulse. The median fibers are not affected by the collision, and continue to travel down the nerve. **E:** The true proximal median CMAP is then recorded; it can be used both to calculate a proximal conduction velocity and to look for evidence of conduction block.

stimulation site (and vice versa). The collision study is performed by giving a stimulus at the first stimulator (at the wrist) followed by a slight delay before the second stimulator (proximal site) discharges. Ideally, the delay should be as long as possible, but not longer than the time it takes for a depolarization to travel from the distal to proximal stimulation sites. The first stimulus depolarizes the ulnar nerve and the pulse travels both distally and proximally. The distal pulse results in an ulnar CMAP from ulnar-innervated thenar muscles. The second stimulus is slightly delayed but is given before the first stimulus passes the proximal stimulation site. The second stimulus, which is given at the proximal site (axilla or Erb's point), results in co-stimulation of both median and ulnar fibers. The depolarization in the ulnar fibers, which travels distally down the arm, collides with the proximally traveling impulse from the first stimulus and is thereby blocked, leaving only the impulse from the median fibers to continue to travel down the arm. The true proximal median CMAP is then recorded and can be used both to calculate a proximal median conduction velocity and to look for evidence of a conduction block (Figure 30–11). If collision studies are not performed for proximal median studies across the plexus, conduction block and focal slowing may be missed.

Erb's point stimulation also can be used to record other muscles. Either surface or needle electrodes can be used to record many of the major upper extremity muscles (e.g., deltoid, triceps, supra/infraspinatus, biceps). Stimulating at Erb's point, one can compare the amplitude and latency of the resultant CMAPs from side to side. Although a single stimulus site cannot be used to look for conduction block,

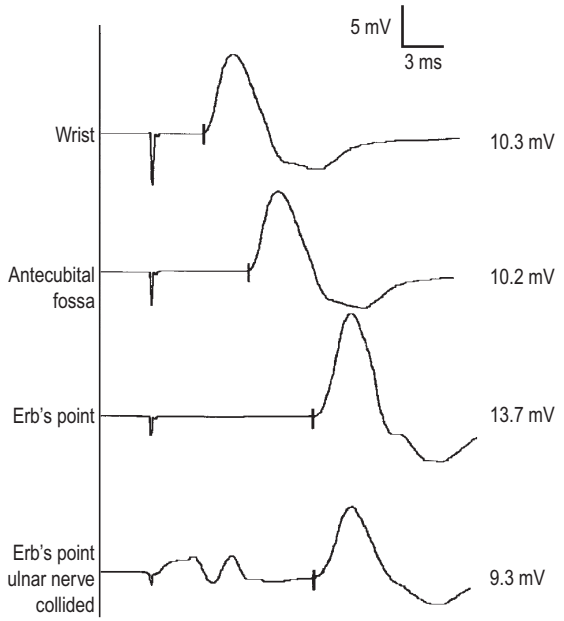

FIGURE 30–11 Median motor conduction studies and co-stimulation at proximal sites. Recording the abductor pollicis brevis, stimulating wrist **(top trace)**, antecubital fossa **(second trace)**, and Erb's point **(third trace)**. Note the higher amplitude at Erb's point from co-stimulation and co-recording of ulnar muscles in the thenar eminence. In the collision study **(bottom trace)**, a supramaximal stimulus is given over the ulnar nerve at the wrist 4 ms before the stimulation at Erb's point. An initial thenar ulnar compound muscle action potential (CMAP) is seen from the first stimulus, followed by the one from the collided Erb's point stimulus, which represents the true proximal median CMAP.

CMAP amplitude can be used to help assess the amount of axonal loss. In some instances, more distal sites such as the axilla can also be used to look for conduction block (see Chapter 31).

Electromyographic Approach

The EMG approach is straightforward in suspected brachial plexopathy (Table 30–3). An extensive EMG study of many muscles must be performed to tease out the correct pattern. Ideally, enough muscles to represent all the trunks, cords, and nerves should be studied. In addition, assessment of the most proximal muscles is of paramount importance to help differentiate a plexus from a root lesion. Because the paraspinal muscles, rhomboids, and serratus anterior come directly off the roots, they should be normal in plexopathies; however, they often are abnormal in root lesions. Nevertheless, it is important to remember that root avulsion can accompany brachial plexopathies, especially in the case of traumatic brachial plexus injuries. When EMG abnormalities are mild or borderline, comparison to the contralateral side is useful.

As in other neuromuscular conditions, the needle EMG is used to look for evidence of active denervation, motor unit action potential (MUAP) abnormalities, recruitment pattern abnormalities, and unusual spontaneous discharges. As mentioned earlier, the presence of myokymic discharges and fasciculations is especially important in differentiating radiation-induced plexopathy from direct neoplastic invasion. Myokymic discharges are recognized as the spontaneous bursting of single MUAPs, resulting in grouped repetitive discharges of the same MUAP. Usually, myokymic bursts fire every 0.5 to 2.0 seconds; typical firing frequencies range from 20 to 70 Hz within bursts.

The needle EMG is also used to evaluate the severity of the lesion. Most important is the assessment of axonal continuity following traumatic lesions. Absence of axonal continuity (absent CMAP, profuse denervation, no MUAPs activated despite good effort) is an ominous sign. If no axonal continuity can be demonstrated, especially in the case of suspected nerve root avulsion, consideration often is given to surgical exploration, nerve grafts, or tendon transfers, in an attempt to increase function. If the lesion is acute, it is useful to wait and repeat the needle EMG study 3 to 6 months later before considering surgical intervention. Often, evidence of early reinnervation (i.e., nascent MUAPs) can be detected on EMG a few months before clinical improvement is noted. In most cases, if there is any evidence of axonal continuity, further observation is indicated before surgical intervention.

Table 30–3. Recommended Electromyography Protocol for Brachial Plexopathy

1. Examine at least one muscle in each peripheral nerve distribution (median, ulnar, radial, anterior interosseous, posterior interosseous, axillary, musculocutaneous, suprascapular).
2. Sample muscles innervated by the same nerve but from different roots.
3. All clinically weak or paralyzed muscles should be examined.
4. Proximal muscles must be examined, including the paraspinal muscles. In suspected upper trunk lesions, examine the rhomboids and/or serratus anterior as well.
5. If findings are borderline or equivocal, compare with findings on the contralateral side.

Example Muscles	
Median	Pronator teres, abductor pollicis brevis
Anterior interosseous	Flexor pollicis longus
Posterior interosseous	Extensor indicis proprius, extensor digitorum communis
Ulnar	First dorsal interosseous, flexor digitorum profundus
Radial	Extensor carpi radialis, brachioradialis, triceps
Axillary	Deltoid
Musculocutaneous	Biceps brachii
Suprascapular	Supraspinatus , infraspinatus
Dorsal scapular	Rhomboids
Dorsal rami	Cervical paraspinals

COMMON ELECTROPHYSIOLOGIC PATTERNS OF BRACHIAL PLEXOPATHY

Upper Trunk Plexopathy

Upper trunk lesions may result in abnormal lateral antebrachial cutaneous sensory responses. In addition, radial and median sensory responses may be abnormal, especially when recording the thumb. Median and ulnar motor conduction studies and F responses are normal. Needle EMG abnormalities may involve the deltoid, biceps, brachioradialis, supraspinatus and infraspinatus muscles. The triceps, pronator teres, and flexor carpi radialis may be partially involved. Most important, the rhomboids, serratus anterior, and cervical paraspinal muscles are spared, unless the lesion also involves the nerve roots. One curious phenomenon which may be seen on needle EMG following an upper trunk plexopathy which also involves the C5 root proper is the "breathing arm." This phenomenon results from aberrant regeneration wherein fibers originally supplying the phrenic nerve grow back and innervate upper trunk muscles. This results in synkinesis, wherein some upper trunk muscles spontaneously fire in a rhythmic pattern. When closely observed, one will note that the firing only occurs when the patient breathes, specifically during inspiration. The phrenic nerve is derived from the C3, C4, and C5 roots. Any trauma which injures the C5 root before the branch to the phrenic nerve can result in this syndrome. This phenomenon was first described in Erb's obstetric brachial plexus, but it can be seen with other trauma or after surgery.

Middle Trunk Plexopathy

Middle trunk lesions may affect the median SNAP, especially when recording the middle finger. The radial SNAP also may be abnormal. Median and ulnar motor conduction studies and F responses are normal. Needle EMG may show abnormalities in C7-innervated muscles (e.g., triceps, pronator teres, flexor carpi radialis).

Lower Trunk Plexopathy

Lower trunk lesions affect the ulnar, dorsal ulnar, and medial antebrachial cutaneous SNAPs. Because the median- and ulnar-innervated hand muscles are derived from the lower trunk, their respective motor conduction studies and F responses may be abnormal as well. If axonal loss is present, CMAP amplitudes may be reduced, with mild prolongation of distal latency and mild slowing of conduction velocity. The vast majority of these lesions are axonal rather than demyelinating, so motor conduction studies across the brachial plexus (although theoretically appealing) most often are not helpful. Needle EMG may show abnormalities in all ulnar-innervated muscles as well as the median- and radial-innervated muscles that contain C8 or T1 fibers, including the flexor pollicis longus, APB, and EIP.

Lateral Cord Plexopathy

Lateral cord lesions affect the lateral antebrachial SNAP and the median SNAPs recording the thumb, index, or middle fingers. Median and ulnar motor conduction studies and F responses are normal. Needle EMG may show abnormalities in the biceps and proximal median forearm muscles (pronator teres, flexor carpi radialis). Distal median-innervated muscles in the forearm and hand, including the flexor pollicis longus and APB, are normal.

Posterior Cord Plexopathy

Posterior cord lesions result in abnormal radial SNAPs. Routine median and ulnar motor conduction studies and F responses are normal. Because the radial-innervated extensor indicus proprius muscle is derived from the lower trunk, the radial motor study recording the EIP may be abnormal. If axonal loss is present, CMAP amplitudes may be reduced, with mild prolongation of distal latency and mild slowing of conduction velocity. Needle EMG may show abnormalities in both distal and proximal radial-innervated muscles (e.g., extensor indicis proprius, extensor carpi radialis, brachioradialis, triceps). In addition, abnormalities may be seen in the deltoid, teres minor, and latissimus dorsi.

Medial Cord

Medial cord lesions are identical to lower trunk plexopathies, except that radial-innervated C8 muscles are normal on EMG. Medial cord lesions may affect the ulnar, dorsal ulnar, and medial antebrachial cutaneous SNAPs. Because the median- and ulnar-innervated hand muscles are derived from the medial cord, their respective motor studies and F responses may be abnormal as well. If axonal loss is present, CMAP amplitudes may be reduced with mild prolongation of distal latency and mild slowing of conduction velocity. Needle EMG abnormalities are limited to all ulnar-innervated muscles and the distal median-innervated muscles that contain C8–T1 fibers (e.g., APB, flexor pollicis longus).

Neurogenic Thoracic Outlet Syndrome

True neurogenic TOS is actually a lower trunk plexopathy. In this entrapment neuropathy, the T1 fibers tend to be preferentially affected, leading to a distinctive pattern on nerve conduction studies and EMG (Figure 30–12). An axonal loss pattern develops (low CMAP amplitude) in both the median and ulnar motor nerves, preferentially affecting the median-innervated thenar muscles. Median and ulnar distal latencies and conduction velocities may be slightly slowed. Stimulating more proximally at Erb's point

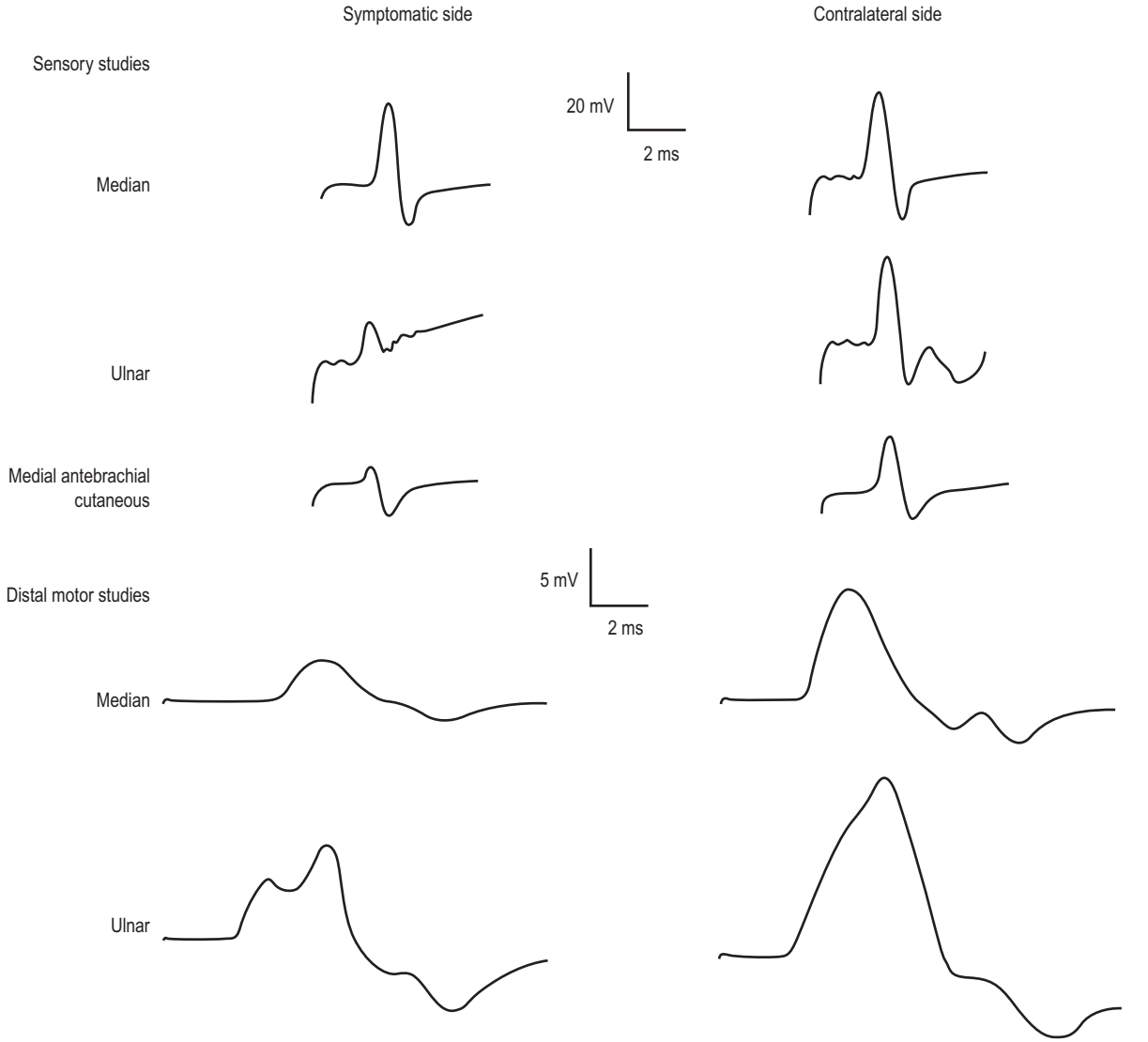

FIGURE 30–12 Nerve conduction studies in thoracic outlet syndrome (TOS). A distinctive pattern of motor and sensory conduction studies occurs in TOS. C8 and especially T1 fibers passing through the lower trunk are affected in true neurogenic TOS. On sensory conduction studies, ulnar and medial antebrachial cutaneous sensory nerve action potentials (SNAPs) are abnormal, but median SNAPs are spared. Whereas both ulnar and medial antebrachial cutaneous sensory fibers travel through the lower trunk, median sensory fibers are derived from the upper and middle trunks. A different pattern is seen on motor conduction studies. Although both median- and ulnar-innervated motor fibers travel through the lower trunk, the median-innervated thenar muscles typically are more affected than are the ulnar-innervated hypothenar muscles, probably reflecting greater T1 innervation of thenar compared to hypothenar muscles.

is of little use in true neurogenic TOS, where the lesion usually is due to axonal loss with no evidence of proximal conduction block.

The sensory nerve conduction studies also reveal a distinctive pattern. Despite the decreased median CMAP amplitude, the median SNAP is normal. This is because the median sensory fibers do not travel through the lower trunk but rather through the upper and middle trunks, which are not involved in neurogenic TOS. The ulnar sensory response, however, is abnormal because the ulnar sensory fibers travel through the lower trunk. In most cases, the ulnar SNAP is low in amplitude but not absent. The medial antebrachial cutaneous SNAP is also usually low in amplitude or absent in true neurogenic TOS (Figure 30–13). Because this nerve is predominantly T1 innervated and travels through the lower trunk and medial cord, it also is subject to damage in neurogenic TOS.

Needle EMG abnormalities are found in median- more than ulnar-innervated C8–T1 muscles and less so in radial-innervated C8 muscles.

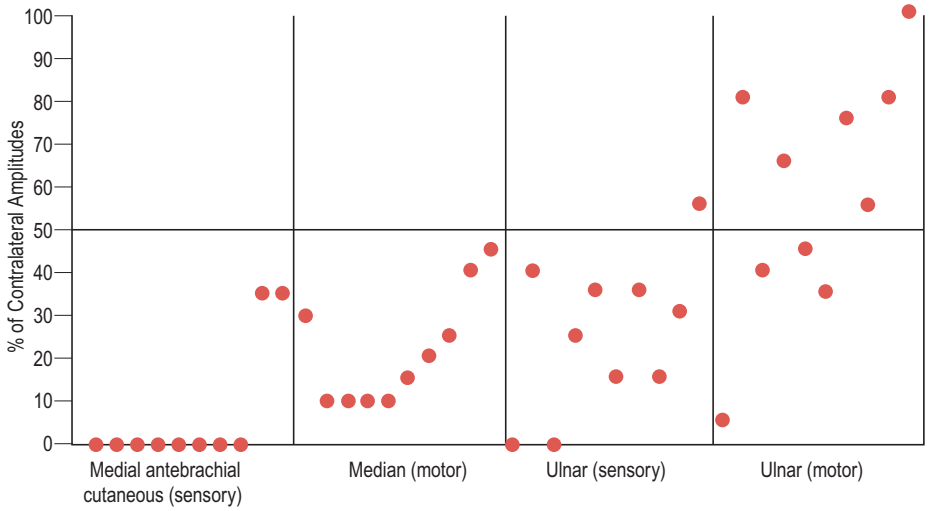

FIGURE 30–13 Nerve conduction studies in patients with neurogenic thoracic outlet syndrome. The sensory nerve action potential (SNAP) and compound muscle action potential amplitudes recorded on the affected side as a percentage of the amplitude on the contralateral side in 10 patients with neurogenic thoracic outlet syndrome. The sensory studies reveal a distinctive pattern. The ulnar sensory response is abnormal because the ulnar sensory fibers travel through the lower trunk. In most cases, the ulnar SNAP is low but not absent. The medial antebrachial cutaneous SNAP is also usually low in amplitude or absent in true neurogenic TOS. Because this nerve is predominantly T1 innervated and travels through the lower trunk and medial cord, it is preferentially subject to damage in neurogenic TOS.
(From Levin, K.H., Wilbourn, A.J., Maggiano, H.J., 1998. Cervical rib and median sternotomy-related brachial plexopathies: a reassessment. Neurology 50, 1407–1413, with permission.)

EXAMPLE CASES

Case 30–1

History and Physical Examination

A 68-year-old man developed numbness and weakness in the left hand after coronary artery bypass surgery. He had no history of weakness or numbness before the operation. On awakening from surgery, he noted numbness in the fourth and fifth fingers with loss of dexterity. There was no associated pain.

When the patient was examined 11 days after the operation, there was hypesthesia of the left fourth and fifth fingers and the hypothenar eminence. There was a suggestion of hypesthesia along the medial forearm. Motor testing showed normal muscle bulk throughout. All of the intrinsic hand muscles on the left were moderately weak, including the APB, interossei, and ADM. The left long finger and thumb flexors were moderately weak, and the wrist and finger extensors were mildly weak; the index finger extensor was the weakest. Strength was otherwise normal, as were the deep tendon reflexes.

CASE 30–1. Nerve Conduction Studies

			Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F-Wave Latency (ms)		
Nerve Stimulated	Stimulation Site	Recording Site	RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	10.3	8.2	≥4	3.2	3.5	≤4.4				24	26	≤31
	Antecubital fossa	APB	10.2	7.6		6.2	6.8		60	54	≥49			
Ulnar (m)	Wrist	ADM	9.5	6.6	≥6	2.9	3.3	≤3.3				25	28	≤32
	Below elbow	ADM	9.3	6.1		6.1	6.1		62	55	≥49			
	Above elbow	ADM	9.1	5.8		7.6	8.0		65	53	≥49			
Median (s)	Wrist	Index finger	22	20	≥20	3.5	3.3	≤3.5	48	50	≥50			
Ulnar (s)	Wrist	Little finger	18	8	≥17	2.7	2.9	≤3.1	52	48	≥50			
Radial (s)	Forearm	Snuffbox	19	15	≥15	2.3	2.3	≤2.9	56	59	≥50			
Lateral antebrachial (s)	Elbow	Lateral forearm	17	18	≥10	2.2	2.4	≤3.0	70	67	≥55			
Medial antebrachial (s)	Elbow	Medial forearm	16	NR	≥5	2.2	NR	≤3.2	70	NR	≥50			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; APB = abductor pollicis brevis; ADM = abductor digiti minimi.
Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 30–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Left first dorsal interosseous	NL	0	0	NL	↓	NL	NL	NL
Left APB	NL	0	0	NL	↓	NL	NL	NL
Left EIP	NL	0	0	NL	↓↓	NL	NL	NL
Left flexor carpi ulnaris	NL	0	0	NL	↓	NL	NL	NL
Left flexor digitorum profundus IV	NL	0	0	NL	↓↓	NL	NL	NL
Left biceps brachii	NL	0	0	NL	NL	NL	NL	NL
Left pronator teres	NL	0	0	NL	NL	NL	NL	NL
Left triceps brachii	NL	0	0	NL	NL	NL	NL	NL
Left C7 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Left C8 paraspinal	NL	0	0	NL	NL	NL	NL	NL

↓ = slightly reduced; ↓↓ = moderately reduced; NL = normal; APB = abductor pollicis brevis; EIP = extensor indicis proprius.

Summary

The history is that of an older gentleman who noted numbness and weakness of the left hand on awakening from coronary artery bypass surgery. The neurologic examination is notable for hypesthesia of digits 4 and 5 and the medial forearm, and weakness without wasting of the intrinsic hand muscles, long finger and thumb flexors, and wrist and finger extensors on the left side.

Nerve conduction studies done 11 days after the surgery show that the left ulnar CMAP amplitude is slightly low compared with the right side, although it is within normal limits. The median motor study is normal bilaterally, as are the median and ulnar F responses. The left ulnar SNAP is of low amplitude, and the medial antebrachial cutaneous SNAP is unrecordable. The remainder of the SNAPs on the left side, including the median, radial, and lateral antebrachial cutaneous SNAPs, and all of the SNAPs on the right side are normal. The abnormal ulnar and medial antebrachial cutaneous SNAPs correspond to the areas of hypesthesia found on the neurologic examination. Given that both of these sensory potentials are abnormal, wallerian degeneration with axonal loss must have taken place, and the lesion must be at or distal to the dorsal root ganglion, in nerve fibers that subserve the lower trunk or medial cord of the brachial plexus. The relatively low CMAP amplitude in the left ulnar nerve, which is mediated by fibers from the lower trunk and medial cord, also lends support to this localization.

The needle EMG examination shows no spontaneous activity in any of the left upper extremity or cervical paraspinal muscles examined. There is mildly reduced MUAP recruitment in the first dorsal interosseous, APB, and flexor carpi ulnaris muscles, and moderately reduced recruitment in the EIP and flexor digitorum profundus muscles. All of the MUAPs are normal in configuration. Note that the needle abnormalities are found in C8–T1-innervated muscles innervated by the median (APB), ulnar (first dorsal interosseous, flexor carpi ulnaris, flexor digitorum profundus IV), and radial (EIP) nerves, which are derived from the medial and posterior cords of the brachial plexus. The C6–C7-innervated muscles innervated by the median and radial nerves (pronator teres, triceps) are normal, as are the biceps and the C7 and C8 paraspinal muscles.

The abnormalities on the needle examination add several important pieces of information. First, the lesion must be fairly proximal along the C8–T1 fibers to involve muscles innervated by both the medial and posterior cords. However, the paraspinal muscles are normal, and the SNAPs are abnormal, placing the lesion at or distal to the dorsal root ganglion. The nerve conduction studies pointed to a lesion in either the medial cord or the lower trunk. Putting all this information together, the lesion must be in the lower trunk of the brachial plexus rather than at the level of the nerve roots. We can now form an electrophysiologic impression.

IMPRESSION: *There is electrophysiologic evidence of an acute axonal lesion of the lower trunk of the brachial plexus on the left.*

The history of numbness in digits 4 and 5 and weakness of the hand immediately after coronary artery bypass surgery should suggest a lesion of the brachial plexus, usually as a result of stretch injury from retraction of the

chest wall. In this case, the clinical history, examination, and electrodiagnostic study pointed toward an acute lesion of the lower trunk of the brachial plexus. The nerve conduction studies revealed the lesion to be axonal. The patient subsequently recovered full function over a period of 8 months.

This case raises several important questions.

If the Lesion is Axonal, Why are there no Fibrillation Potentials?

The abnormal SNAPs, low CMAP, and reduced recruitment of normal configuration MUAPs indicate that there has been enough time for wallerian degeneration to occur. However, active denervation potentials (i.e., fibrillation potentials and positive sharp waves) generally take 10 days to 2 weeks to appear in the most proximal muscles and even longer in more distal muscles. Consistent with the clinical history of 11 days, this lesion is acute. Note the importance of being able to accurately judge MUAP recruitment. In this case, the only abnormality noted on the needle examination was reduced recruitment of MUAPs, which was helpful in localizing the lesion to the lower trunk of the brachial plexus.

Could this be a Case of a Non-localizing Ulnar Neuropathy, with a Superimposed C8–T1 Radiculopathy?

Remember that the paraspinal muscles do not have to be abnormal in radiculopathies, especially in a case such as this one, in which the patient was studied just 11 days after developing weakness, by which time fibrillation potentials, for example, may not yet have developed. However, the absent SNAP from the left medial antebrachial cutaneous nerve, which comes directly off the medial cord of the brachial plexus, places the lesion at or distal to the dorsal root ganglion and outside the distribution of the ulnar nerve. The most parsimonious explanation of the data is a lower trunk brachial plexopathy. The importance of the abnormal medial antebrachial cutaneous SNAP is underscored here: without it, the results of the nerve conduction studies and needle EMG might be explained on the basis of an acute non-localizing ulnar neuropathy with a superimposed acute C8–T1 radiculopathy.

Case 30–2

History and Physical Examination

A 49-year-old woman was referred for evaluation of right hand numbness. She had noted slowly worsening numbness of the fourth and fifth digits of the right hand over 10 years, without pain. Symptoms initially were intermittent but had become more persistent in the last month. She also had noticed weakness of the right hand, especially when opening jars or turning the car key in the ignition.

Her past medical history was significant for Hodgkin's lymphoma 20 years ago that was treated with mantle radiotherapy. A recurrence in the right neck 14 years ago was treated successfully with local radiotherapy.

Examination was notable for normal cranial nerves, with no evidence of a Horner's syndrome. There was decreased bulk in the right thenar and hypothenar areas, with weakness of right thumb abduction and the interossei. Hypesthesia was present in the right fifth and medial aspect of the fourth fingers. Bulk, strength, and sensation were normal in the left arm. No reflexes were present in either arm. Strength and reflexes were normal and symmetric in the lower extremities. There were undulating,

CASE 30–2. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F-Wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	5.4		≥4	4.7		≤4.4				33		≤31
	Antecubital fossa	APB	4.5			9.8			47		≥49			
Ulnar (m)	Wrist	ADM	6.5		≥6	3.0		≤3.3				30		≤32
	Below elbow	ADM	5.2			6.9			51		≥49			
	Above elbow	ADM	5.0			9.2			54		≥49			
Median (s)	Wrist	Index finger	7	12	≥20	3.2	2.8	≤3.5	54	62	≥50			
Ulnar (s)	Wrist	Little finger	38	13	≥17	3.0	3.0	≤2.8	47	58	≥50			
Radial (s)	Forearm	Snuffbox	8	10	≥15	2.7	2.5	≤2.9	57	61	≥50			
Medial antebrachial (s)	Elbow	Medial forearm	5	3	≥5	2.6	2.7	≤3.2	59	54	≥50			
Sural (s)	Calf	Posterior ankle	14		≥6	3.6		≤4.4	47		≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; APB = abductor pollicis brevis; ADM = abductor digiti minimi.
Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 30–2. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right first dorsal interosseous	MK	0	0	NL	↓↓	+1	+1	+1
Right APB	MK	0	0	NL	↓↓	+2	+1	+1
Right EIP	MK	0	0	NL	↓↓	+1	+1	+1
Right pronator teres	NL	0	0	NL	NL	NL	NL	NL
Right biceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right flexor digitorum profundus IV	MK	0	0	NL	NL	NL	NL	NL
Right triceps brachii	NL	0	0	NL	↓↓	+1	+1	+1
Right C6 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right C7 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right C8 paraspinal	NL	0	0	NL	NL	NL	NL	NL

↓↓ = moderately reduced; NL = normal; MK = myokymic discharges; APB = abductor pollicis brevis; EIP = extensor indicis proprius.

wormlike movements of several muscles in the distal right forearm and hand.

Summary

The history is that of a woman with the insidious onset over 10 years of right hand numbness affecting digits 4 and 5 and wasting and weakness of the intrinsic hand muscles on the right. Symptoms are not accompanied by pain. There is a remote history of Hodgkin's lymphoma treated with mantle radiation. Neurologic examination is notable for hypesthesia in the right fifth and medial aspect of the fourth digit, with weakness of the right intrinsic hand muscles and areflexia in the upper extremities bilaterally. Undulating, wormlike movements are noted in the distal right forearm and hand muscles. The remainder of the neurologic examination is normal.

Nerve conduction studies reveal that the right median distal motor latency and F response are slightly prolonged. The right ulnar motor CMAP amplitude is borderline low, and the F response is normal. The right ulnar SNAP is of normal amplitude and approximately three times the size of the left ulnar SNAP, although it is slightly slow. The SNAP from the medial antebrachial cutaneous nerve, which comes off the medial cord of the brachial plexus, is of normal amplitude on the right and of slightly low amplitude on the left. The median and radial SNAPs are of low amplitude bilaterally, as is the left ulnar SNAP. The right sural SNAP is normal. Note that the right ulnar SNAP, which is normal in amplitude, corresponds to the area of numbness noted on the neurologic examination. Remember that there are three possible explanations for finding a normal SNAP in an area of numbness: (1) the lesion is hyperacute (i.e., <6–10 days old for sensory fibers) and there has not been enough time for wallerian degeneration to occur; (2) the lesion is proximal to the dorsal root ganglion, either at the level of the nerve roots or more centrally located in the spinal cord or brain; or (3) the lesion is one of proximal demyelination, possibly conduction block, which leaves the axon relatively intact.

The needle examination should be helpful in distinguishing among these possibilities. Clearly the lesion is not hyperacute because the needle EMG shows large, long reinnervated MUAPs in several muscles subserved by the C7–T1 myotomes in the distribution of the ulnar, median, and radial nerves. The pronator teres, biceps brachii, and cervical paraspinal muscles are normal. The lesion is unlikely to be proximal to the dorsal root ganglion, given the normal paraspinal muscles in conjunction with the abnormal SNAPs. Finally, the finding of myokymic discharges in several of the limb muscles is a very helpful clue. Myokymic discharges are bursts of rhythmic, grouped repetitive discharges of single MUAPs that originate along segments of demyelinated nerve, presumably from spontaneous depolarization or ephaptic transmission along the areas of demyelination. These discharges seen on the needle examination correspond to the undulating, wormlike movements seen in the distal right forearm and hand on the clinical examination.

To summarize, most of the SNAPs in the upper extremities are of low amplitude bilaterally, with the exception of the right ulnar and medial antebrachial cutaneous SNAPs, which are normal, even though this is the area where the patient describes decreased sensation. Although one might suspect that these findings indicate a distal dying back generalized peripheral neuropathy, the fact that the sural SNAP is normal makes this possibility unlikely. One should next consider the possibility of a

brachial plexopathy, especially in light of the history of prior mantle radiation therapy. The needle examination is helpful in that it shows reduced recruitment of reinnervated MUAPs in several muscles subserved by the C7–T1 myotomes, but with normal cervical paraspinal muscles. Thus far, the electrophysiologic findings are consistent with a lesion primarily affecting the middle and lower trunks of the brachial plexus on the right. The needle examination points toward a lesion primarily affecting the lower trunk of the brachial plexus.

We can now form our impression.

IMPRESSION: *There is electrophysiologic evidence of a chronic brachial plexus lesion on the right, primarily affecting the middle and lower trunks. The myokymic discharges are consistent with radiation-induced brachial plexopathy. In addition, the abnormal sensory responses on the left suggest a similar asymptomatic process in the left brachial plexus.*

The history of insidious onset of numbness and weakness in the upper extremity in a patient who has received prior radiation therapy should suggest a delayed radiation-induced plexopathy. Prominent characteristics of delayed radiation-induced plexopathy include the insidious onset over several years, the lack of pain on presentation, and the undulating, wormlike movements on clinical examination, which suggest myokymia.

This case raises several important questions.

If there is Numbness over Digits 4 and 5 of the Right Hand, Why is the Ulnar SNAP Normal?

The ulnar and medial antebrachial cutaneous SNAPs are normal, even in the face of clinical numbness, because they are distal to a primarily demyelinating lesion. The myokymic discharges in several muscle groups belonging to the C7–T1 myotomes lend support to the demyelinating nature of the lesion. Myokymia is common in delayed-onset radiation-induced plexopathy, and its finding on EMG helps to distinguish between neoplastic and radiation-induced brachial plexopathy. The chronic changes in the MUAPs, the slightly prolonged distal median motor latency, and the abnormal sensory potentials in other nerves indicate that there also has been axonal loss. One might have performed more proximal ulnar nerve stimulation in the upper arm and at Erb's point to look for a conduction block across the brachial plexus; such has been reported in radiation-induced brachial plexopathy and would provide further evidence of proximal demyelination. However, one must be cautious with Erb's point stimulation because of the inherent technical difficulty of achieving supramaximal stimulation in that area. As already noted, the other possible explanations for a normal SNAP in an area of sensory loss include a hyperacute lesion or a lesion proximal to the dorsal root ganglion. However, both the clinical history and the finding of reinnervated MUAPs point toward a chronic rather than hyperacute lesion. Furthermore, the low-amplitude median and radial SNAPs and the normal cervical paraspinal muscles indicate that the lesion is at or distal to the dorsal root ganglion, leaving proximal demyelination as the most reasonable explanation.

Do the Abnormal SNAPs on the Left Side Indicate a Brachial Plexopathy on that Side?

The abnormal SNAPs on the left indicate that there may be a brachial plexopathy on that side as well, although the possibility was not fully investigated because the patient was asymptomatic on that side. The normal sural SNAP was important in ruling out a chronic generalized peripheral neuropathy. Deep tendon reflexes are absent in both upper extremities but present and normal in the lower extremities, a finding that also supports bilateral brachial plexus dysfunction, although it is asymptomatic on the left side.

Case 30–3

History and Physical Examination

A 15-year-old boy was referred for persistent weakness and numbness of the left arm 4 months after a traumatic injury from a bicycle accident. Examination showed marked wasting of the left shoulder girdle and upper arm. He was completely unable to abduct the shoulder or to flex the arm at the elbow. Arm extension was present but weak. Wrist flexion and extension as well as intrinsic hand function were relatively intact. The left biceps and brachioradialis deep tendon reflexes were absent. All other reflexes were present and normal. Sensation was diminished over the lateral arm and forearm.

Summary

The history is that of a young boy who sustained a traumatic injury from a bicycle accident, resulting in persistent and profound weakness and wasting of the left arm over 4 months, primarily affecting the shoulder girdle and upper arm musculature on the left. The neurologic examination is notable for weakness and wasting of shoulder abduction and arm flexion and extension, sensory loss over the lateral arm and forearm, and depressed biceps and brachioradialis reflexes.

On nerve conduction studies, the left median and ulnar motor conduction studies and F responses are normal. The median and ulnar SNAPs are normal and symmetric bilaterally. The left radial SNAP is just at the lower limit of normal and is clearly abnormal in comparison with the right side (less than half the amplitude). This finding emphasizes the need to perform bilateral sensory studies when a brachial plexus lesion is suspected; otherwise the left radial SNAP may have been considered normal. The left lateral antebrachial cutaneous SNAP is absent, with the right side normal.

The needle EMG study shows increased insertional activity and florid fibrillation potentials in muscles in the left C5–C6-innervated myotomes, spanning several nerves including the musculocutaneous (biceps), axillary

CASE 30–3. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = μV			Latency (ms)			Conduction Velocity (m/s)			F-Wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB		10.2	≥4		3.3	≤4.4					25	≤31
	Antecubital fossa	APB		9.6			6.9			58	≥49			
Ulnar (m)	Wrist	ADM		11.4	≥6		2.8	≤3.3					24	≤32
	Below elbow	ADM		11.0			6.3			62	≥49			
	Above elbow	ADM		10.9			9.7			61	≥49			
Median (s)	Wrist	Index finger	33	25	≥20	2.7	2.8	≤3.5	56	55	≥50			
Ulnar (s)	Wrist	Little finger	27	23	≥17	2.4	2.6	≤3.1	58	54	≥50			
Radial (s)	Forearm	Snuffbox	39	16	≥15	2.0	2.2	≤2.9	57	55	≥50			
Lateral antebrachial (s)	Elbow	Lateral forearm	14	NR	≥10	2.0		≤3.0	58		≥55			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; APB = abductor pollicis brevis; ADM = abductor digiti minimi.
Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 30–3. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Left biceps brachii	↑	+3	0	None				
Left medial deltoid	↑	+3	0	None				
Left brachioradialis	↑	+3	0	None				
Left infraspinatus	↑	+3	0	None				
Left triceps brachii	NL	0	0	NL	↓	+1	+1	+1
Left pronator teres	↑	+2	0	NL	↓↓↓	+2	+2	+2
Left first dorsal interosseous	NL	0	0	NL	NL	NL	NL	NL
Left extensor digitorum communis	NL	0	0	NL	NL	NL	NL	NL
Left extensor indicis proprius	NL	0	0	NL	NL	NL	NL	NL
Left serratus anterior	NL	0	0	NL	NL	NL	NL	NL
Left rhomboids	NL	0	0	NL	NL	NL	NL	NL
Left C5 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Left C6 paraspinal	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓ = slightly reduced; ↓↓↓ = markedly reduced; NL = normal.

(medial deltoid), radial (brachioradialis), suprascapular (infraspinatus), and median (pronator teres) nerves. In addition, there are no MUAPs activated in these muscles, with the exception of the pronator teres, which also has some C7 innervation. There, the MUAPs are very large, long, and polyphasic, with markedly reduced recruitment. In the triceps (C6–C7–C8 innervation) there is mildly reduced recruitment of large, long, and polyphasic MUAPs. Of note, the serratus anterior, rhomboids, and C5 and C6 paraspinal muscles, which carry C5–C7 fibers but come directly off the nerve roots before the brachial plexus, are entirely normal.

In summary, the combination of the abnormal SNAPs and the abnormalities noted on EMG in the limb muscles with sparing of the serratus anterior, rhomboids, and upper cervical paraspinal muscles points toward a severe, chronic lesion primarily affecting the upper trunk of the brachial plexus.

IMPRESSION: *There is electrophysiologic evidence of a severe upper trunk brachial plexopathy on the left. There is no evidence of axonal continuity in muscles that are subserved entirely by the upper trunk. A follow-up study in 3 to 6 months may be helpful to determine whether there has been reinnervation of muscles of the upper trunk.*

This case raises several important questions.

Is the Lesion in the Brachial Plexus Itself, or is there Evidence of Avulsion of the Nerve Roots?

The abnormal radial and lateral antebrachial cutaneous sensory potentials indicate that the lesion is at or distal to the dorsal root ganglion, that is, distal to the nerve roots, in the brachial plexus itself. The sparing of the serratus anterior, rhomboids, and upper cervical paraspinal muscles is a key finding to corroborate that there has not been root avulsion. Because those muscles come directly off the roots, proximal to the brachial plexus, there should be abnormal EMG findings in some of these muscles if the roots had been avulsed. Note, however, that in rare cases of root avulsion the paraspinal muscles are normal on EMG, which may indicate relative sparing of the dorsal rami in some root injuries.

What is the Prognosis for Recovery?

This study was performed 4 months after the original injury. The presence of profuse fibrillation potentials with no activation of MUAPs in C5–C6-innervated muscles and reduced recruitment of large MUAPs in C6–C7-innervated muscles indicate that the lesion is severe and chronic, with extensive axonal loss. There is no evidence at this point of reinnervation in any muscles innervated solely by the C5–C6 roots. Although root avulsion carries a poorer prognosis than an injury to the plexus itself, this patient has a very severe lesion. A follow-up study in 3 to 6 months has been recommended in order to document whether and to what extent reinnervation may occur. At 4 months, it is still too early to make any definite statements about prognosis or what treatment options would be best, including possible muscle or tendon transfers if reinnervation remains poor.

If there is so Much Axonal Loss, Why are the CMAPs Normal?

The CMAPs are normal because recording was done from median- and ulnar-innervated hand muscles, which are subserved by the C8–T1 myotomes. Because those fibers were not affected, one would expect the CMAPs to be normal when recording from these muscles. If one were to record over the biceps or medial deltoid, stimulating the musculocutaneous or axillary nerves, respectively, one would expect to find a very low or unrecordable CMAP amplitude.

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31 Proximal Neuropathies of the Shoulder and Arm

Electromyographers occasionally are called on to evaluate the proximal nerves in the shoulder and arm. Isolated lesions of these nerves, including the suprascapular, axillary, musculocutaneous, long thoracic, and spinal accessory, are far less frequent than the common entrapment and compressive neuropathies of the median, ulnar, and radial nerves. The electrophysiologic evaluation of proximal neuropathies in the shoulder and arm relies principally on needle electromyography (EMG). Nerve conduction studies of these nerves are limited and are complicated by technical factors. In addition, nearly all lesions in these nerves are axonal loss, and cannot be localized by focal slowing or conduction block. Similar to other mononeuropathies, the goals of the electrophysiologic study are to localize the lesion as accurately as possible, to exclude a more widespread lesion or proximal radiculopathy, and to assess the underlying severity.

SUPRASCAPULAR NEUROPATHY

Anatomy

The suprascapular nerve comes off the upper trunk of the brachial plexus, receiving innervation from both the C5 and C6 roots. The nerve runs posteriorly under the trapezius, passing through the *suprascapular notch* of the scapula to enter the supraspinous fossa (Figure 31–1). The suprascapular notch is U shaped, located along the superior border of the scapula, and covered by the *transverse scapular ligament*. The suprascapular nerve first supplies motor fibers to the supraspinatus muscle, a shoulder abductor, before proceeding laterally to supply deep sensory fibers to the glenoacromial and acromioclavicular joints, and the coracoacromial ligament. It then wraps around the *spinoglenoid notch* of the scapular spine under the spinoglenoid ligament to enter the infraspinous fossa, where it supplies motor fibers to the infraspinatus muscle, an external rotator of the shoulder. The suprascapular nerve usually carries no cutaneous sensory fibers, although rare anomalous innervations have been reported. In these rare cases, the suprascapular nerve carries cutaneous sensation to the proximal lateral arm, the area usually supplied by the axillary nerve.

Clinical

Suprascapular entrapment most commonly occurs at the suprascapular notch, under the transverse scapular ligament. Less frequently, the nerve can also be entrapped distally at the spinoglenoid notch. The suprascapular nerve is relatively immobile both at its origin at the upper trunk and at the suprascapular notch. Because both the shoulder and scapula are quite mobile, movement, especially repetitive movement, results in stretch and nerve injury (Figure 31–2). Also, like most of the major proximal upper extremity nerves, the suprascapular nerve is often prominently involved in neuralgic amyotrophy (see Chapter 30).

Rare cases of suprascapular nerve entrapment have been reported secondary to a variety of mass lesions, including

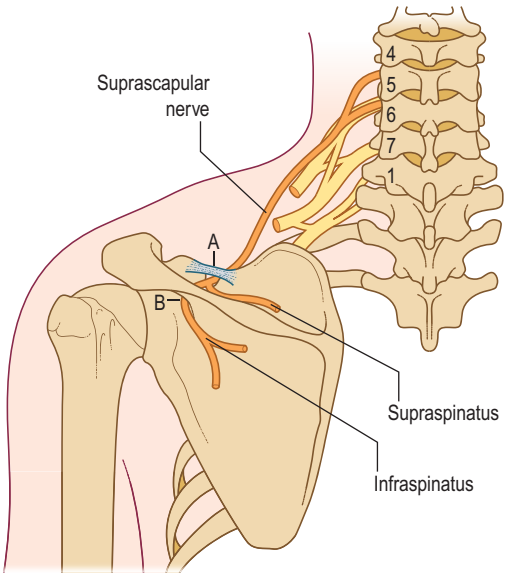

FIGURE 31–1 Anatomy of the suprascapular nerve. The suprascapular nerve originates from the upper trunk of the brachial plexus. The nerve first runs under the suprascapular notch (A) to innervate the supraspinatus muscle. Sensory fibers then are given to the shoulder joint before the nerve wraps around the spinoglenoid notch (B) to supply the infraspinatus muscle.
(Adapted from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia. With permission.)

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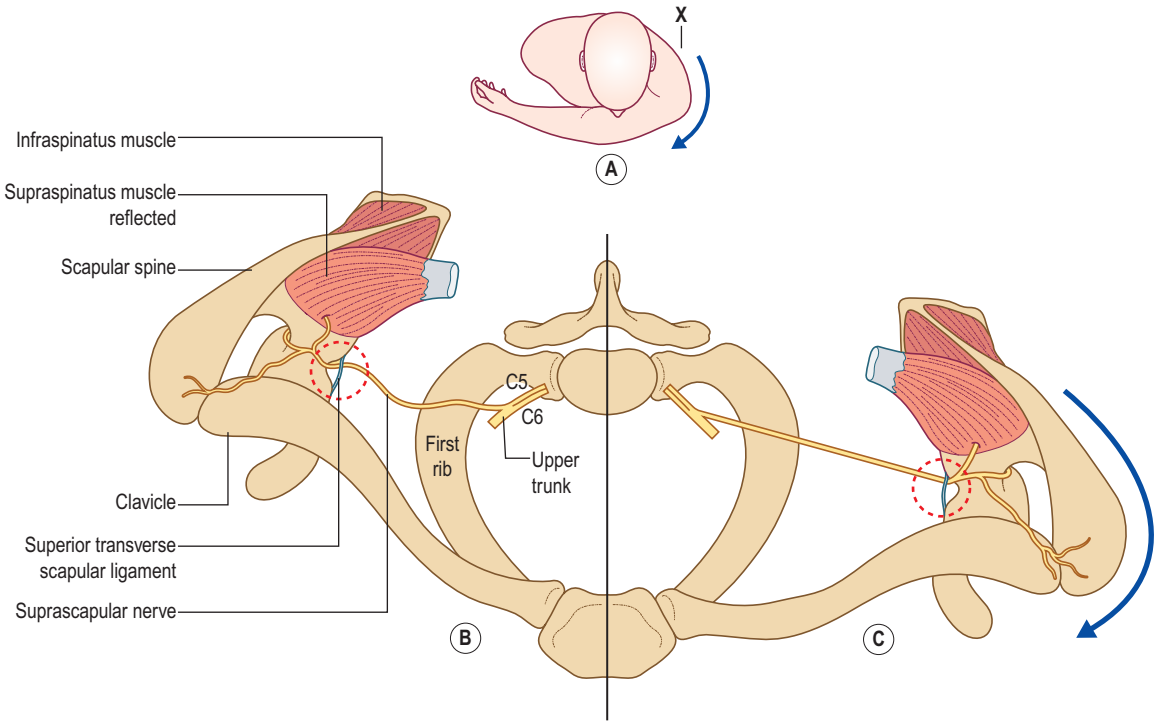

FIGURE 31–2 Suprascapular neuropathy. Suprascapular neuropathy may occur from repetitive protraction of the scapular and tethering of the nerve between the suprascapular notch and the upper trunk of the brachial plexus. Coronal view of the suprascapular nerve from above: (**B**) normal position, (**C**) nerve stretch produced by arm posture in (**A**).
(Reprinted from Kopell, H.P., Thompson, W.A.L., 1959. Pain and the frozen shoulder. Surg Gynecol Obstet 109, 92. By permission of Surgery, Gynecology & Obstetrics, now known as the Journal of the American College of Surgeons.)

ganglion cysts, sarcomas, and metastatic carcinomas. Ganglion cysts are especially common at the spinoglenoid notch. In addition, certain activities, positions, and professions are associated with suprascapular entrapment. For example, weight lifting has been implicated in several reports as a provocative factor in suprascapular entrapment, likely as a consequence of repetitive movement of the scapula, especially during lifts that involve shoulder abduction and protraction. Suprascapular neuropathy has also been reported as a consequence of positioning during surgical procedures, when patients are placed in a knee-chest position with the scapula protracted. Of interest, several professions put patients at risk for suprascapular entrapment. These include professional volleyball players, baseball pitchers, and dancers. In these professions, the clinical and electrophysiologic findings most often suggest a distal lesion at the spinoglenoid notch.

In addition, suprascapular neuropathy, which is sometimes confused clinically with a rotator cuff injury, may also accompany a rotator cuff injury. One might initially assume that both have a common traumatic etiology. However, *a suprascapular neuropathy may actually occur as a result of a rotator cuff tear*, usually a large and full thickness tear. Following a rotator cuff tear, there may be medial retraction of the tendons to the supraspinatus and infraspinatus muscles. This may result in increased tension on the suprascapular nerve both at the suprascapular notch and the spinoglenoid notch (Figure 31–3).

Symptoms and signs depend on the site of nerve entrapment. At the most common site of entrapment, the suprascapular notch, shoulder pain may be prominent. Indeed, there is anatomic and clinical evidence that the suprascapular nerve supplies the majority of deep sensory fibers (including pain fibers) to the shoulder joint. The pain typically is described as deep and boring, occurring along the superior aspect of the scapula and radiating to the shoulder, but usually not more distally. The pain may be exacerbated by shoulder movements, especially adduction of the extended arm. This movement results in protraction of the scapula, which increases the nerve tethering between the upper trunk and the suprascapular notch. Occasionally, the suprascapular notch may be tender to palpation. Weakness involves shoulder abduction (supraspinatus) and external rotation (infraspinatus). Impairment of these motions may or may not be noticed by the patient, because both functions are subserved by other muscles as well. Atrophy may be recognized, especially over the infraspinatus muscle, which is only partially covered by the trapezius muscle (Figure 31–4).

If the entrapment occurs more distally at the spinoglenoid notch, the syndrome is limited to atrophy and weakness of the infraspinatus muscle. Pain usually is absent

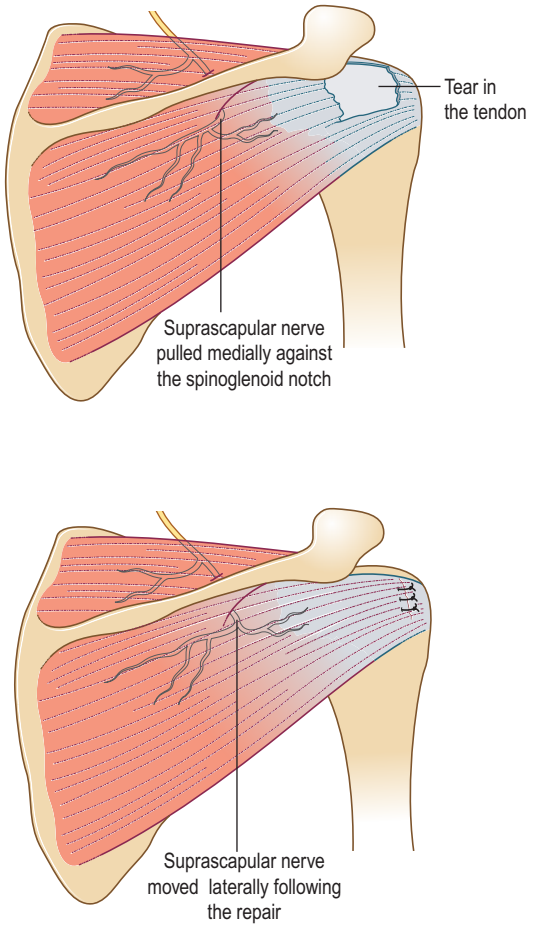

FIGURE 31–3 Suprascapular neuropathy and rotator cuff tear. **Top:** Following a massive rotator cuff tear involving the tendons of the supraspinatus and infraspinatus, the muscles retract medially and can result in traction of the suprascapular nerve at the spinoglenoid notch. **Bottom:** Following repair of the tendon, the traction is relieved. (Adapted with permission of Elsevier, from: Costouros, J.G., Porramatikul, M., Lie, D.T., Warner, J.J.P., 2007. Reversal of suprascapular neuropathy following arthroscopic repair of massive supraspinatus and infraspinatus rotator cuff tears. Arthroscopy 23, 1152–1161.)

because the deep sensory fibers to the shoulder joint have exited more proximally.

Several conditions may be confused with suprascapular neuropathy, including cervical radiculopathy, rotator cuff injury and other orthopedic conditions, and neuralgic amyotrophy. In contrast to suprascapular neuropathy, a C5–C6 radiculopathy may have radiating pain from the neck into the shoulder and arm, associated with sensory abnormalities in the lateral arm, forearm, and thumb. Often, the biceps and brachioradialis tendon reflexes are depressed or absent. Higher cervical radiculopathies (e.g., C3 or C4) may have a similar pain distribution to suprascapular neuropathy but are not associated with significant weakness of the shoulder or arm.

Local orthopedic conditions may be difficult to differentiate clinically from suprascapular neuropathy. Although weakness should not be present, pain often prevents full muscle activation. Exacerbation of pain by palpation (other than at the suprascapular notch) or by passive shoulder movement (other than protraction of the shoulder) would be unusual for suprascapular entrapment.

Lastly, neuralgic amyotrophy often presents with severe proximal arm and shoulder pain and later weakness (see Chapter 30). In some cases, the suprascapular nerve may be primarily involved. However, close clinical and electrophysiologic evaluation usually reveals evidence of more widespread involvement of other nerves.

Electrodiagnosis

The goal of electrodiagnosis is to demonstrate abnormalities of the suprascapular-innervated muscles and exclude cervical radiculopathy, brachial plexopathy, or involvement of other proximal nerves. Because the suprascapular nerve has no cutaneous distribution, there is no corresponding sensory nerve to be recorded. However, as the suprascapular nerve originates from the upper trunk of the brachial plexus, studies of the sensory nerves that pass through the upper trunk should be performed to help exclude a more widespread plexus lesion. These studies should include the

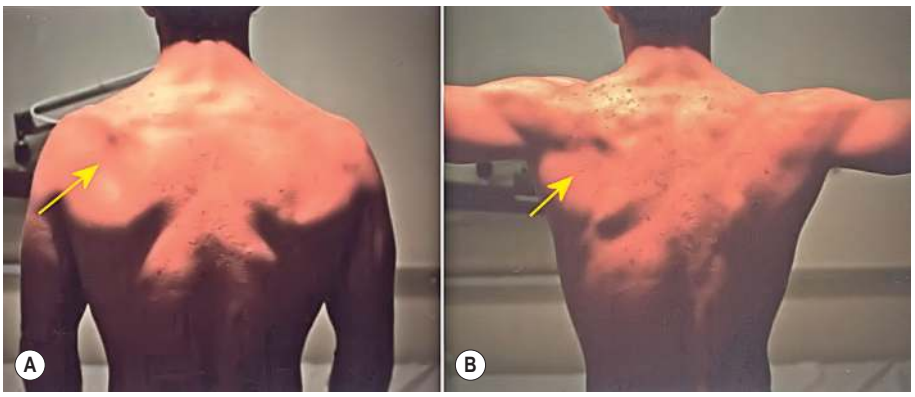

FIGURE 31–4 Suprascapular neuropathy. **A:** Shoulders relaxed; **B:** Shoulders abducted. Note the prominent atrophy of the left inferior scapular area (yellow arrows). Suprascapular neuropathy results in weakness of shoulder abduction and external rotation, without any cutaneous sensory loss.

Table 31–1. Major Upper Extremity Motor Latencies from Erb's Point Stimulation

Nerve	Muscle	Latency (ms) Upper Limit Normal	Distances (cm)*
Axillary†	Deltoid	4.9	15–21
Musculocutaneous†	Biceps	5.7	23–29
Suprascapular	Supraspinatus	3.7	7–12
Suprascapular	Infraspinatus	4.3	10–15

*Distances measured with calipers.

†The axillary and musculocutaneous nerves can also be stimulated in the axilla, with typical distal motor latencies ≤3.3 ms. Both axillary and Erb's point stimulation often are technically difficult. In patients with symptoms limited to one side, comparing latencies and amplitudes from side to side is always preferable to using normal value tables.

Source: From Kraft, G.H., 1972. Axillary, musculocutaneous, and suprascapular nerve latency studies. Arch Phys Med Rehabil 53, 382; and Currier, D.P., 1971. Motor conduction velocity of axillary nerve. Phys Ther 51, 503.

lateral antebrachial cutaneous nerve and the median and radial sensory nerves, especially when recording from the thumb. Often, comparison with the contralateral asymptomatic side can be useful in identifying a mild abnormality, even if the studies are normal on the symptomatic side. Any abnormality present in these sensory studies suggests a more widespread brachial plexopathy. Of course, an abnormality found in the median sensory nerve may indicate a superimposed median neuropathy at the wrist, which may need to be studied further.

Motor conduction studies can be performed, stimulating Erb's point and recording with a monopolar needle electrode in either the supraspinatus or infraspinatus muscle, or both, simultaneously (Table 31–1). A surface recording electrode should not be used to record from the spinati muscles, especially the supraspinatus, because they are covered by the trapezius. A surface reference electrode is placed distally over the shoulder joint. Compound muscle action potential (CMAP) amplitude and latency are measured. Comparing amplitude side to side can give an estimate of the amount of axonal loss present. However, these studies generally do not increase the yield over conventional EMG in terms of localizing the lesion. Typically, the pathophysiology of these entrapment neuropathies is axonal loss. Thus, although motor nerve conduction studies may show reduced amplitudes and slightly prolonged latencies, there really is no information gained over needle EMG, which more easily demonstrates axonal loss. When Erb's point stimulation is performed, high stimulating currents often are required, and supramaximal stimulation can be difficult to ensure.

During needle EMG, both the supraspinatus and infraspinatus muscles should be sampled. Care must be taken to ensure that the EMG needle is not in the more superficial trapezius muscle, by checking that no motor unit action potentials (MUAPs) are activated with a shoulder shrug. In lesions at the suprascapular notch, both the supraspinatus and infraspinatus are abnormal. With spinoglenoid lesions, however, only the infraspinatus is involved. If either of these muscles is abnormal, it is essential to sample other C5–C6 innervated muscles (e.g., deltoid, biceps, brachioradialis), as well as the cervical paraspinal muscles, to exclude a cervical radiculopathy or more widespread brachial plexus lesion.

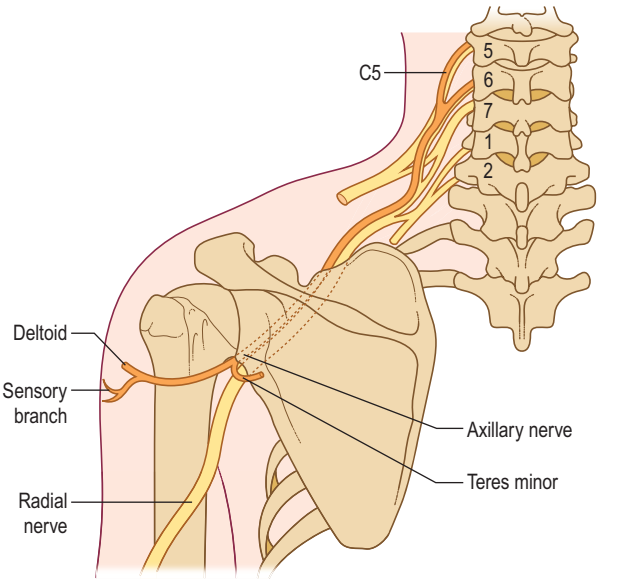

FIGURE 31–5 Anatomy of the axillary nerve. The axillary nerve originates from the posterior cord of the brachial plexus. The nerve innervates the teres minor and deltoid muscles and supplies sensation to the lateral shoulder.
(Adapted from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia. With permission.)

AXILLARY NEUROPATHY

Anatomy

Along with the radial nerve, the axillary nerve originates from the posterior cord of the brachial plexus (Figure 31–5). The axillary nerve is composed primarily of C5–C6 fibers, running through the upper trunk and posterior cord of the plexus. The nerve leaves the axilla through the *quadrilateral space*, which is formed by the humerus and the teres minor, teres major and long head of the triceps muscles (Figure 31–6). Posteriorly in the quadrilateral

space, it often divides into two major trunks. The posterior trunk always supplies the teres minor before terminating as the superior lateral brachial cutaneous nerve (i.e., axillary sensory nerve). The teres minor aids in external rotation of the shoulder while the deltoid is principally a shoulder abductor. The axillary sensory nerve supplies an oval-shaped area over the lateral shoulder. The anterior trunk travels deep to the fascia of the deltoid and always supplies the middle and anterior heads of the deltoid as well as a deep sensory branch to the shoulder joint. The posterior head of the deltoid is most commonly supplied by the posterior trunk, but some variations exist wherein it is supplied by the anterior trunk alone, and in others by a combination of the anterior and posterior trunks.

Clinical

Axillary neuropathies typically result from trauma, especially dislocation of the shoulder and fracture of the humerus. Less commonly, athletes participating in contact sports have developed axillary neuropathies as a result of injury, typically a direct blow to the anterolateral deltoid area. Similar to suprascapular neuropathy, axillary neuropathies have been reported in professional volleyball players. Rare cases of entrapment in the quadrilateral space have been reported but are exceptional. Quadrilateral space syndrome results from compression of the axillary nerve and posterior humeral circumflex artery.

Patients with axillary neuropathies have a well-defined circular area of numbness over the lateral shoulder, along with partial weakness of shoulder abduction and external rotation (Figure 31–7). The degree of weakness varies from patient to patient. The weakness is only partial, because other muscles also contribute to shoulder abduction (i.e., the supraspinatus) and external rotation (i.e., the infraspinatus).

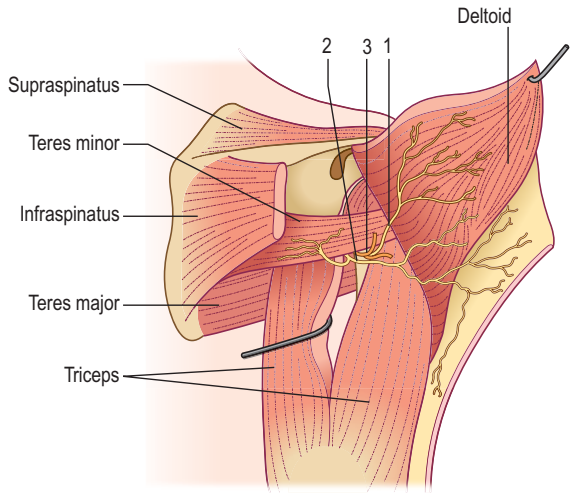

FIGURE 31–6 Posterior view of the quadrilateral space. Anterior (1) and posterior (2) branches of the axillary nerve and circumflex artery (3).
(From Paladini, D., Dellantonio, R., Cinti, A., et al., 1996. Axillary neuropathy in volleyball players: report of two cases and literature review. J Neurol Neurosurg Psychiatry 60, 345–347. With permission.)

Electrodiagnosis

The major goal of electrodiagnosis is to demonstrate abnormalities of axillary-innervated muscles and rule out cervical radiculopathy, brachial plexopathy, or involvement of other proximal nerves. Unfortunately, there is no routine sensory nerve conduction study for the axillary nerve. However, because the axillary nerve originates from the posterior cord and upper trunk, sensory nerves that run through the posterior cord or upper trunk of the brachial plexus should be studied. These include the radial and lateral antebrachial cutaneous sensory nerves and the median sensory nerve, especially when recording the thumb. To detect mild abnormalities, comparison with the contralateral asymptomatic nerve is suggested, even if the studies are normal on the symptomatic side. Abnormalities of any of these sensory studies suggest a more widespread brachial plexopathy.

Axillary motor nerve conduction studies can be performed, stimulating the axilla and Erb's point and recording with a monopolar needle or surface electrode over the deltoid (Table 31–1). A surface reference electrode is placed distally over the deltoid tendon. To calculate a conduction velocity, distances must be measured with calipers.

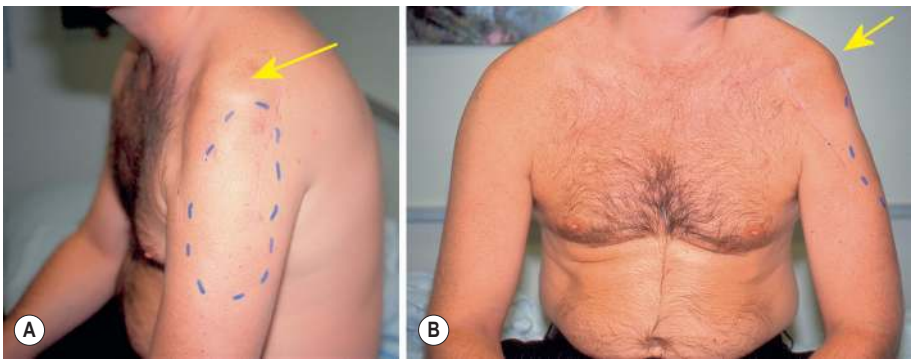

FIGURE 31–7 Axillary neuropathy in a patient following humeral fracture. **A:** Lateral view; **B:** Anterior view. Axillary neuropathy results in atrophy of the lateral shoulder girdle (yellow arrow), weakness of shoulder abduction and external rotation, and sensory loss in an oval area over the lateral shoulder (blue dashed oval).

CMAP amplitude can be compared both from side to side, to assess the amount of axonal loss, and between the axilla and Erb's point on the symptomatic side, to look for conduction block. These studies can be technically difficult to perform, however, especially obtaining supramaximal stimulation, and are best used to assess axonal loss by comparing the symptomatic side to the asymptomatic side. Because these usually are axonal loss lesions, motor studies generally do not increase the yield of localizing the lesion beyond what is obtained from routine needle EMG.

In axillary neuropathies, needle EMG is used to demonstrate denervation, reinnervation, or both in the two axillary innervated muscles, the deltoid and the teres minor. All three heads of the deltoid are easily accessible to needle EMG; the teres minor is more difficult to study. If abnormalities are found in any of these muscles, it is essential to sample other muscles innervated by the upper trunk and posterior cord of the brachial plexus to ensure that the abnormalities found in the axillary-innervated muscles are not part of a more widespread brachial plexus lesion or cervical radiculopathy. Muscles that are important to check include the biceps, supraspinatus, infraspinatus, triceps, and brachioradialis. In addition, the cervical paraspinals should be sampled to help exclude a C5–C6 radiculopathy.

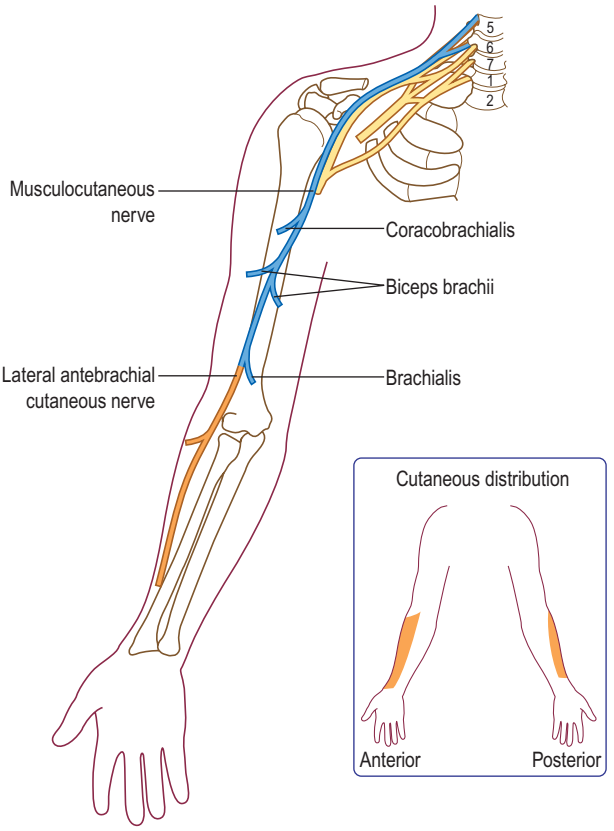

FIGURE 31–8 Anatomy of the musculocutaneous nerve. The musculocutaneous nerve originates from the lateral cord of the brachial plexus. The nerve innervates the biceps, brachialis, and coracobrachialis muscles. It then continues past the elbow as a pure sensory nerve, the lateral antebrachial cutaneous nerve, to supply sensation to the lateral forearm.
(Reprinted from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia. With permission.)

MUSCULOCUTANEOUS NEUROPATHY

Anatomy

The musculocutaneous nerve arises directly from the lateral cord of the brachial plexus (Figure 31–8). In the upper arm, it pierces the coracobrachialis muscle to run in the fascia between the biceps and brachialis muscles. It innervates all three of these elbow flexor muscles, including the biceps, brachialis, and coracobrachialis. The brachialis muscle also commonly receives some innervation from the radial nerve nearby, although clinically, this is of little or no importance. In the region of the elbow, the musculocutaneous nerve runs deep to the brachial fascia, over the brachialis muscle. Past the elbow, its terminal extension continues as a pure sensory nerve, known as the *musculocutaneous sensory* or *lateral antebrachial cutaneous sensory nerve*. In the forearm, the nerve becomes subcutaneous and separates into two terminal divisions (anterior and posterior) to supply sensation to the lateral half of the forearm.

Clinical

Isolated musculocutaneous neuropathies are rare. Patients with nontraumatic musculocutaneous neuropathies have been reported due to strenuous physical activity (e.g., weight lifting, rowing, throwing a football), surgery, and pressure during sleep. There is a single report of a musculocutaneous neuropathy associated with repetitive carrying of items on the shoulder with the arm curled around the object (labeled the "carpet carrier's palsy"). Similarly, there is one report of osteochondroma of the humerus compressing the musculocutaneous nerve.

More commonly, musculocutaneous neuropathies occur as part of more widespread traumatic lesions of the shoulder and upper arm, especially fractures of the proximal humerus. Clinically, musculocutaneous neuropathies result in weakness of elbow flexion, an absent biceps reflex, and sensory loss in the lateral forearm.

More common is entrapment of the distal musculocutaneous sensory nerve. This occurs at the elbow, where the nerve can become entrapped between the biceps tendon or fascia and the brachialis muscle. Characteristically, patients report worsening pain or paresthesias, or both, when the arm is pronated and extended, a position that increases the pressure on the nerve at the elbow site. A hyperextension injury of the elbow, such as may occur during sports-related activities such as tennis, also may cause musculocutaneous sensory neuropathy. Examination in these cases shows isolated altered sensation in the lateral forearm, with normal muscle strength and reflexes. There may be tenderness to palpation over the nerve at the elbow.

Electrodiagnosis

The aim of the electrophysiologic exam is to demonstrate isolated involvement of the musculocutaneous nerve and to exclude a brachial plexopathy, cervical radiculopathy, or involvement of other proximal nerves. The most important nerve conduction study to perform is the lateral antebrachial cutaneous sensory study. This sensory potential can be easily elicited by stimulating just lateral to the biceps tendon at the elbow and recording over the nerve 12 cm distally, on a line connecting the stimulation point to the radial pulse. Comparison with the contralateral side is useful in cases where symptoms are limited to one side. Musculocutaneous neuropathies, both distal and proximal, result in abnormal lateral antebrachial cutaneous sensory nerve action potentials (SNAPs). When an abnormal potential is found, it is important to check other sensory potentials, especially those that pass through either the lateral cord or the upper trunk of the brachial plexus (e.g., median and radial SNAPs). Abnormalities found in these nerves suggest a more widespread brachial plexopathy. As noted earlier, comparison with the asymptomatic side is helpful, especially if the studies are at the lower limits of normal.

Similar to axillary motor studies, proximal motor nerve conduction studies can be performed stimulating the axilla and Erb's point and recording with either a monopolar needle or surface electrode over the biceps (Table 31–1). A surface reference electrode is placed distally over the biceps tendon. The CMAP amplitude can be compared both from side to side, to assess the amount of axonal loss, and between the axilla and Erb's point, to look for a conduction block. A conduction velocity can be calculated but requires calipers to measure the distance accurately. In contrast to the sensory studies, these motor studies are more technically difficult, especially obtaining supramaximal stimulation, and are best used to assess the degree of axonal loss by comparing the symptomatic side with the asymptomatic side. Similar to axillary and suprascapular neuropathies, musculocutaneous neuropathies usually are axonal loss lesions. Accordingly, motor studies generally do not increase the yield of localization over performing the needle EMG alone.

In distal musculocutaneous neuropathies at the elbow, the needle EMG is normal. In proximal lesions, EMG demonstrates denervation or reinnervation, or both, with decreased recruitment of motor unit action potentials (MUAPs) in the biceps. The brachialis and coracobrachialis can also be sampled but are more difficult than the biceps and offer no additional information. If abnormalities are found in the biceps, it is essential to sample other upper trunk and lateral cord innervated muscles to ensure that the abnormalities found are not part of a more widespread brachial plexus lesion or cervical radiculopathy, especially if the lateral antebrachial cutaneous SNAP is normal. Important muscles to check include the pronator teres and flexor carpi radialis (lateral cord) and deltoid, brachioradialis, supraspinatus, and infraspinatus (upper trunk). In addition, the cervical paraspinals need to be sampled to help exclude a C5–C6 radiculopathy.

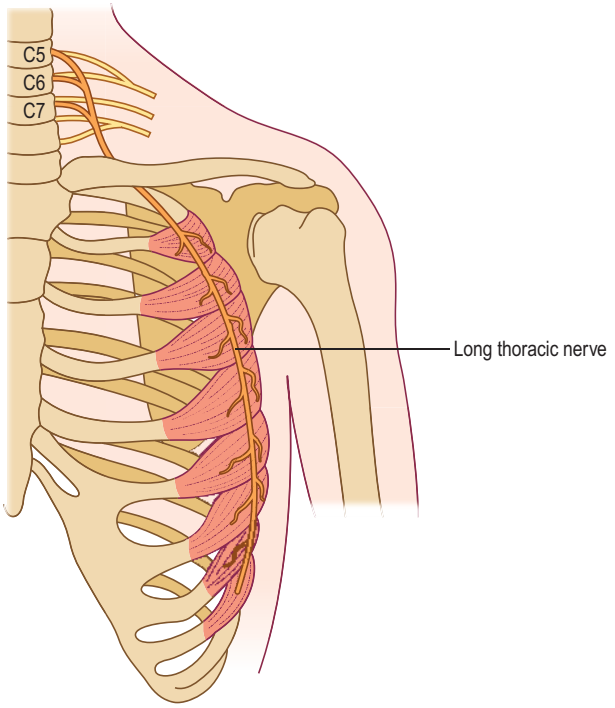

FIGURE 31–9 Anatomy of the long thoracic nerve. The long thoracic nerve originates directly from the C5, C6, and C7 roots, proximal to the brachial plexus proper. It runs inferiorly to supply the serratus anterior muscle. There is no cutaneous sensory innervation. (Reprinted from Fisher, M., 1993. Other mononeuropathies of the upper extremity. In: Brown, W.F., Bolton, C.F. (Eds.), Clinical electromyography, second ed. Butterworth, Boston, p. 271. With permission.)

LONG THORACIC NEUROPATHY

Anatomy

The long thoracic nerve arises directly from the C5–C6–C7 roots, before the brachial plexus proper (Figure 31–9). The nerve runs inferiorly to innervate only one muscle, the serratus anterior. The serratus anterior arises from the first 8 to 10 thoracic ribs and inserts on the costal margin of the scapula. Anatomically, the serratus anterior muscle can be thought of as having an upper portion, supplied by C5–C6 fibers, and a lower portion, supplied by C7 fibers. The upper portion is responsible principally for scapular protraction, and the lower portion for scapular stabilization. Protraction is the movement of the scapula forward along the chest wall.

Clinical

Long thoracic nerve palsies may occur as part of a more widespread traumatic lesion affecting the cervical roots. Although isolated long thoracic palsies have also been reported as a consequence of external compression and stretch, most result from neuralgic amyotrophy (see Chapter 30). Indeed, in some attacks of neuralgic

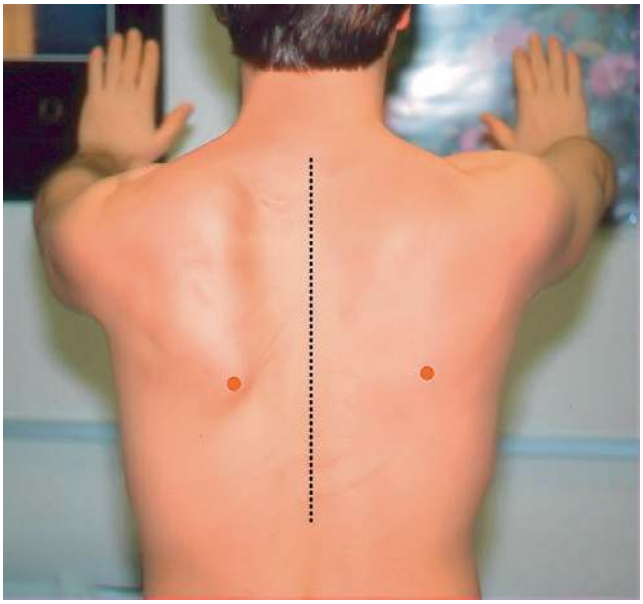

FIGURE 31–10 Long thoracic neuropathy. Isolated weakness of the serratus anterior occurs in long thoracic neuropathies. Serratus anterior weakness results in "winging" of the scapula. Winging becomes most pronounced with the arm extended in front of the body. As the serratus anterior normally pulls the scapula forward, weakness of the serratus anterior results in the scapula being displaced closer to the midline. In this figure, a red circle marks the tip of each scapula. Note the left scapula is displaced closer to the midline than the right scapula.

amyotrophy, the long thoracic nerve is affected in isolation. Patients describe severe pain in the shoulder region that lasts several days to weeks. As the pain abates, patients note difficulty with shoulder movement. Weakness or paralysis of the serratus anterior characteristically results in "winging" of the scapula (Figure 31–10). Winging from serratus anterior dysfunction becomes most pronounced when the arm is extended in front of the body. As the serratus anterior normally pulls the scapula forward against the ribs, weakness of the serratus anterior results in the inferior tip of the scapula being displaced closer to the spine. Because the serratus anterior is a shoulder stabilizer, other shoulder muscles may also appear weak (e.g., deltoid, supraspinatus, infraspinatus). If these muscles are tested with the examiner's hand pressed against the scapula, however, much of the "weakness" will disappear. EMG is especially useful in trying to differentiate true neurogenic weakness from poor shoulder fixation and functional weakness. As the long thoracic nerve has no cutaneous distribution, there is no area of altered sensation or numbness in isolated lesions of the long thoracic nerve.

Electrodiagnosis

The electrodiagnosis of long thoracic nerve palsy is challenging. There is no reliable way to study this nerve with nerve conduction studies. Although Erb's point stimulation can be attempted, with monopolar needle recording, these studies are seldom of practical use and are potentially hazardous because of the risk of pneumothorax. To look for evidence of a more widespread brachial plexus lesion, sensory nerve conduction studies should be performed, studying especially those nerves that travel through the upper and middle trunks of the brachial plexus, and which have the same root innervation as the long thoracic nerve. These studies include the lateral antebrachial cutaneous, median, and radial sensory nerves.

The electrodiagnosis relies on the needle EMG. In long thoracic nerve palsy, abnormalities are limited to the serratus anterior muscle. Unfortunately, the serratus anterior is a difficult muscle to study. Although it can be sampled under the inferior angle of the scapula, it is most approachable with a needle where it arises from the mid-thoracic ribs in the mid-axillary line. Caution must be taken to insert the needle over the rib proper and not into the interspace, where there is a risk of pleural puncture and pneumothorax.

Other C5–C6–C7-innervated limb muscles (e.g., biceps, deltoid, supraspinatus, infraspinatus, triceps, pronator teres) should be sampled to exclude a cervical radiculopathy, brachial plexopathy, or involvement of other proximal nerves. In addition, the cervical paraspinal muscles should be checked to help exclude a more proximal lesion at the roots.

SPINAL ACCESSORY NEUROPATHY

Anatomy

The spinal accessory nerve is a pure motor nerve, with no cutaneous sensory fibers. The spinal accessory nerve is derived from the C1–C4 cervical segments (Figure 31–11). The nerve ascends through the foramen magnum, to return through the jugular foramen. It first supplies motor innervation to the sternocleidomastoid muscle and then runs superficially in the posterior cervical triangle to innervate the trapezius muscle. It is at this latter location where the nerve is most susceptible to injury. Some branches from the cervical plexus may also contribute to the innervation of the upper trapezius directly.

Clinical

Often, spinal accessory nerve palsies occur in the region of the posterior cervical triangle, resulting in isolated weakness of the trapezius. This may occur from stretch or external compression, but most commonly occurs after local surgical procedures. Cervical lymph node biopsy is the most common procedure that injures the spinal accessory nerve, reported to occur in 3–10% of all such procedures. The trapezius is the major suspensory muscle of the shoulder. The upper fibers of the trapezius elevate the scapula and rotate its lateral angle upward; the intermediate fibers adduct and retract the scapula; and the lower fibers depress and rotate the scapula downward.

In distal spinal accessory palsies, atrophy and weakness of the trapezius occur, resulting in a shoulder drop (Figure 31–12). The destabilized scapula moves downward from

the weight of the limb. It also moves laterally away from the spine as a result of the unopposed action of the serratus anterior. In this posture, the head of the humerus cannot articulate properly with the glenoid, resulting in impaired shoulder abduction. Mild scapular winging may also be seen, especially during attempted arm abduction. Indeed, an intact trapezius is needed for proper shoulder fixation, and essentially all movements around the shoulder. A destabilized shoulder from trapezius weakness often results in apparent weakness of other shoulder movements as well. Thus, it is not uncommon for patients with a spinal accessory neuropathy to be misdiagnosed clinically as a brachial plexopathy or other proximal neuropathy, in addition to primary orthopedic problems of the shoulder. Indeed, patients with a spinal accessory neuropathy commonly go many months before the correct diagnosis is reached. Adding to the confusion is that pain and paresthesias may occur, presumably from traction on the brachial plexus as a result of the dropped shoulder. The dropped shoulder can also cause similar symptoms on a vascular basis, from compression of the axillary artery, resulting in pain and paresthesias (Figure 31–13).

In the less common proximal lesions of the spinal accessory nerve, weakness of the sternocleidomastoid muscle, in addition to trapezius weakness, occurs. This manifests as weakness of neck flexion, as well as contralateral turning of the head and neck.

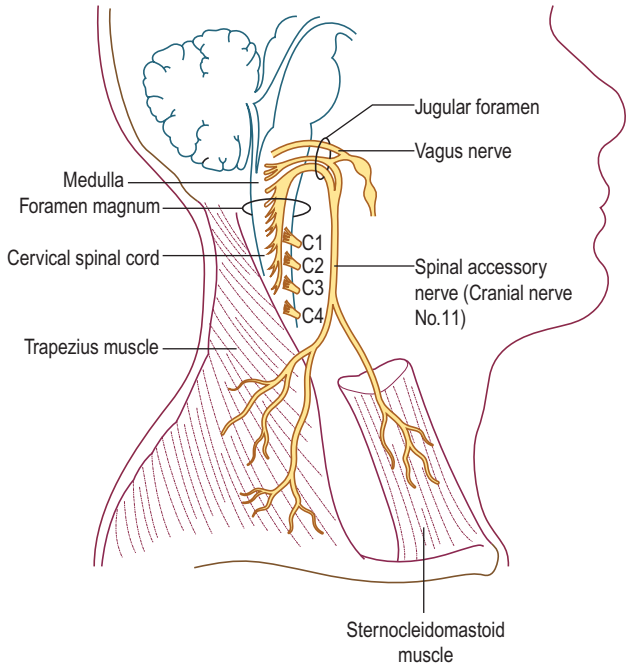

FIGURE 31–11 Anatomy of the spinal accessory nerve. The spinal accessory nerve originates from the C1–C4 roots, ascending through the foramen magnum and then returning via the jugular foramen. The nerve first innervates the sternocleidomastoid muscle before running over the posterior cervical triangle to innervate the trapezius muscle. There is no cutaneous sensory innervation.
(Reprinted from Spence, A., 1982. Basic human anatomy, second ed. Benjamin Cummings, San Francisco. With permission.)

Electrodiagnosis

The spinal accessory nerve is easy to study, especially compared with the other proximal nerves in the upper extremity. This nerve is also used for routine repetitive nerve stimulation studies. Motor studies can be performed with surface recording electrodes over the upper trapezius. The active recording electrode is placed over the muscle belly, with the reference electrode placed distally over the shoulder joint. Stimulation is performed just posterior to the middle of the sternocleidomastoid muscle. The nerve is superficial at this point and can be stimulated with low current intensities. Supramaximal stimulation can easily be achieved here, as opposed to Erb's point stimulation.

The CMAP from the upper trapezius can be compared with the contralateral side. Because the posterior sternocleidomastoid is the only easily accessible stimulation site, the major use of this study is to measure the distal CMAP amplitude and compare it to the contralateral side, in order to estimate the amount of axonal loss. More proximal studies of the spinal accessory nerve are not easily performed.

Because the spinal accessory nerve carries no sensory fibers, there is no corresponding sensory nerve conduction study to perform. In patients who appear to have shoulder weakness from poor fixation, however, it is reasonable to

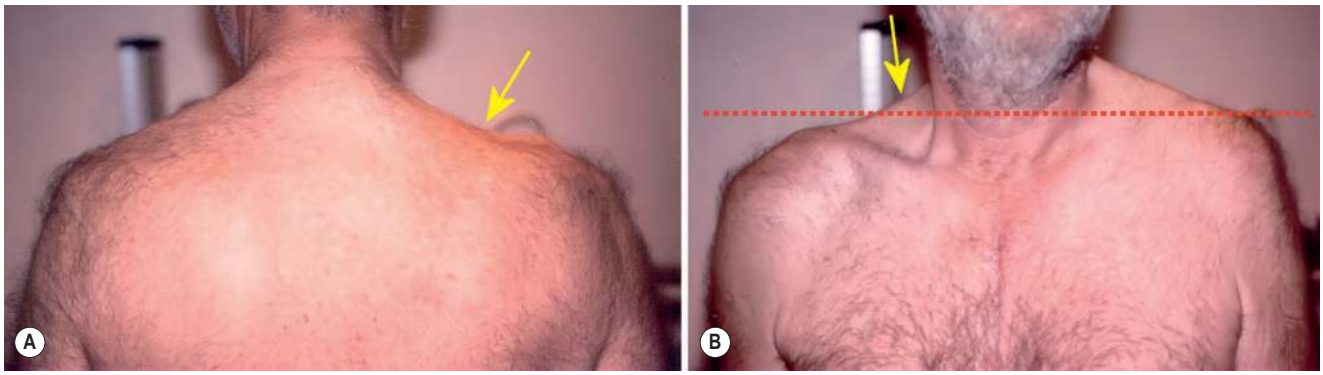

FIGURE 31–12 Distal spinal accessory neuropathy. **A:** Posterior view; **B:** Anterior view. The most common site of injury to the spinal accessory nerve occurs in the region of the posterior cervical triangle, where the nerve runs superficially. A lesion at this site results in shoulder drop (note red dashed line) and atrophy of the trapezius muscle (yellow arrows), but with sparing of the sternocleidomastoid muscle. Note the prominent trapezius atrophy on the patient's right side.

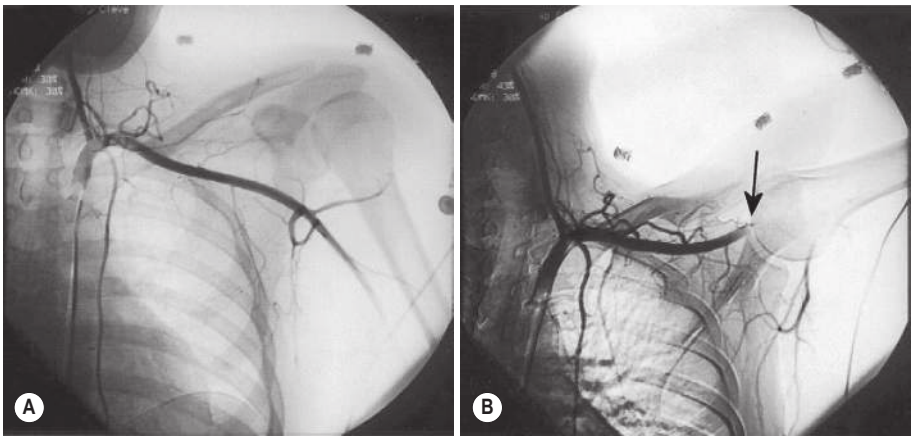

FIGURE 31–13 Neurovascular thoracic outlet syndrome following spinal accessory neuropathy. Shoulder drop from spinal accessory neuropathy may result in traction on the brachial plexus. Rarely, it also may result in frank vascular compression at the thoracic outlet. Axillary artery arteriography in a patient with a spinal accessory neuropathy and shoulder drop, showing normal blood flow with the left arm adducted **(A)** and complete occlusion of the axillary artery with the arm abducted to 90° **(B)**.
(From Al-Shekhlee, A., Katirji, B., 2003. Spinal accessory neuropathy, droopy shoulder, and thoracic outlet syndrome. Muscle Nerve 28, 383–385. With permission.)

study the sensory nerves that travel through the upper trunk of the brachial plexus. These studies, including the lateral antebrachial cutaneous, radial, and median SNAPs, should be sampled bilaterally to help exclude a more widespread lesion affecting the upper brachial plexus.

Needle EMG can be used to assess the trapezius (upper, middle, and lower fibers) as well as the sternocleidomastoid muscle. One must be cautious in studying the trapezius using EMG. If the trapezius in severely atrophied, it is easy to inadvertently pass through this muscle with the needle and thus actually sample underlying muscles (e.g., supraspinatus, rhomboids). The best way to check that the EMG needle is actually in the trapezius muscle is to have the patient shrug his or her shoulder (trapezius action) and see if MUAPs are activated. If this potential problem is not appreciated, one may mistakenly sample a muscle beneath the trapezius and interpret it as normal, when indeed the trapezius muscle would be very abnormal on EMG, if it had been correctly sampled.

Along with checking the spinal accessory-innervated muscles, needle EMG should be used to sample other proximal muscles, especially those that control the shoulder. Because spinal accessory neuropathies may result in apparent weakness of the shoulder, it is essential to confirm that other shoulder girdle muscles are normal on EMG. At a minimum, the supraspinatus, infraspinatus, deltoid, and rhomboids should be sampled. Lastly, similar to all other proximal neuropathies, the cervical paraspinal muscles should be sampled to help exclude a radiculopathy.

EXAMPLE CASES

Case 31–1

History and Physical Examination

A 33-year-old man was referred for progressive atrophy of the left posterior shoulder. For the past year, he noted deep pain in the region of his left posterior shoulder. This was followed by slowly progressive wasting over the scapula. The patient frequently lifted weights at the gym, and he was aware that the lifting and external rotation power of his left shoulder was reduced. There was no history of acute pain, sensory loss, or previous episodes of pain or weakness. There was no family history of similar problems.

Examination showed prominent atrophy of the posterior inferior left scapular area. Otherwise, the patient was quite muscular. On muscle strength testing, external rotation of the shoulder was moderately weak. There was only a suggestion of scapular winging. Shoulder abduction was normal, as were all other upper extremity muscles. Reflexes and sensation were intact.

Summary

The history is that of a male weight lifter who has noted the insidious onset of muscle wasting over the left inferior scapula, with reduced ability to externally rotate the shoulder. There is pain in the posterior shoulder, but no neck pain or sensory loss. Neurologic examination is notable for prominent wasting of the left posterior inferior scapular area, with moderate weakness of external rotation of the shoulder, and a suggestion of scapular winging. Otherwise, strength, deep tendon reflexes, and sensation are intact throughout.

Note that the motor and sensory nerve conduction studies were specifically tailored to evaluate the C5–C6 spinal segments because these are the clinically affected segments in this case. The differential diagnosis of shoulder weakness rests between a cervical radiculopathy, a lesion of the upper trunk or lateral or posterior cord of the brachial plexus, and a lesion isolated to one of the nerves that come off the upper trunk or lateral or posterior cord of the brachial plexus.

Therefore, rather than perform routine median and ulnar motor and sensory nerve conduction studies, the motor conduction studies were limited to stimulation of

CASE 31–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL
Suprascapular (m)	Erb's point	Infraspinatus	10.2	0.4		3.2	3.6	≤4.2			
Median (s)	Wrist	Thumb	23	24	≥10	3.2	3.1	≤3.5	52	54	≥50
Radial (s)	Forearm	Thumb	24	20	≥15	2.3	2.3	≤2.9	56	57	≥50
Lateral antebrachial (s)	Elbow	Lateral forearm	19	20	≥10	2.3	2.4	≤3.0	65	63	≥55

m = motor study; s = sensory study; RT = right; LT = left; NL = normal.
Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies.

CASE 31–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Left supraspinatus	↑	+2	0	NL	↓↓	+2	+1	+1
Left infraspinatus	↑	+3	0	NL	↓↓	+2	+2	+2
Left medial deltoid	NL	0	0	NL	NL	NL	NL	NL
Left biceps brachii	NL	0	0	NL	NL	NL	NL	NL
Left brachioradialis	NL	0	0	NL	NL	NL	NL	NL
Left C5 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Left C6 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Left C7 paraspinal	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓↓ = moderately reduced; NL = normal.

the suprascapular nerve at Erb's point bilaterally, with the infraspinatus (the area of muscle wasting) recorded, and sensory conduction studies, with the radial-to-digit 1, median-to-digit-1, and lateral antebrachial cutaneous SNAPs recorded bilaterally. All of these conduction studies evaluate the C5–C6 spinal segments, including the upper trunk and lateral and posterior cords of the brachial plexus. The CMAP amplitude recording the left infraspinatus is markedly reduced, with a normal distal motor latency. The low CMAP amplitude with a normal distal latency implies axonal loss. Note that the median sensory conduction study was performed stimulating the wrist and recording digit 1, although traditionally digit 2 is used as the recording site for median sensory nerve studies. This is because the innervation to digit 1 is derived from the C6 spinal segment, whereas innervation to digit 2 is derived from the C6–C7 segments. The sensory conduction studies are normal and symmetric bilaterally. The normal SNAPs suggest that this is not a lesion of the brachial plexus. On needle EMG examination, abundant fibrillation potentials are noted in the left supraspinatus and infraspinatus, with reduced recruitment of large, long, polyphasic MUAPs. Needle examination of other muscles in the C5–C6 myotomes, including the medial deltoid, biceps, brachioradialis, and upper cervical paraspinal muscles, is entirely normal. The normal needle examination of other muscles subserved by the C5–C6 myotomes, including the paraspinal muscles, suggests that this is not a cervical radiculopathy.

In summary, the CMAP to the left infraspinatus is markedly reduced, with active denervation and reinnervation restricted to the left supraspinatus and infraspinatus muscles. The remainder of the study is normal. The lesion appears to be restricted to the suprascapular nerve. The presence of a low CMAP amplitude and fibrillation potentials in a patient who has had symptoms over the course of 1 year suggest that the lesion is axonal and severe. The presence of reinnervated MUAPs indicates that the lesion is chronic.

IMPRESSION: *There is electrophysiologic evidence consistent with a chronic axonal lesion of the left suprascapular nerve at the suprascapular notch, affecting both the supraspinatus and infraspinatus*

This case raises several important questions.

What is the Most Likely Clinical Diagnosis?

The most likely clinical diagnosis is that of suprascapular nerve entrapment at the suprascapular notch, because there was involvement of both the supraspinatus and infraspinatus muscles and the patient experienced deep shoulder pain. The pain likely is secondary to involvement of the deep sensory branches that supply the glenoacromial and acromioclavicular joints. The likely etiology was the chronic repetitive movements of the scapula associated with his weight lifting. The patient subsequently underwent surgery, with exploration of the suprascapular notch. At surgery, the nerve was released from the notch, and the patient experienced subsequent relief of the shoulder pain. Follow-up at 1 year revealed near-complete recovery of muscle bulk and strength of both the supraspinatus and infraspinatus muscles.

Why were the Sensory Nerve Action Potentials Normal?

Note that although normal SNAPs may suggest that a lesion is acute, proximal to the dorsal root ganglion, or secondary to proximal demyelination, in this particular case there is no reported numbness or sensory loss in the areas subserved by the sensory nerves studied. Thus, the normal SNAPs simply suggest that the lesion is outside the distribution of the sensory nerves tested, although they subserve the same spinal segments (C5–C6). Remember that there is no cutaneous sensory nerve associated with the suprascapular nerve.

Case 31–2

History and Physical Examination

A 28-year-old man fell while skiing. He sustained significant trauma to his left neck and shoulder, with a fracture and dislocation of the left mid-humerus. His fracture was reduced and casted for 8 weeks. Upon removal of the cast, he underwent several months of intensive physical therapy but continued to have difficulty with his left shoulder. Although his daily activities were not affected, his basketball game had not returned to normal. In addition, he was concerned about the lack of muscle bulk around the left shoulder.

On examination, there was marked atrophy of the lateral left shoulder girdle. On muscle testing, there was mild-to-moderate weakness of left shoulder abduction and external rotation. Otherwise, strength was normal, and deep tendon reflexes were intact throughout. On sensory testing, there was a well-circumscribed area of decreased sensation over the left proximal lateral arm.

Summary

The history is that of a young man who fell while skiing, sustaining significant trauma to the left neck, shoulder, and arm, complicated by a fracture and dislocation of the left mid-humerus. Two months later, on removal of the cast, he noticed loss of muscle bulk around the left shoulder and difficulty with his basketball game. Neurologic examination was notable for marked atrophy of the left lateral shoulder girdle, weakness of shoulder abduction and external rotation, and decreased sensation over the left proximal lateral arm. The remainder of the neurologic examination, including strength, deep tendon reflexes, and sensation, was intact.

Note that, as in the previous case, the motor and sensory nerve conduction studies were specifically tailored to evaluate the C5–C6 spinal segments, because these are also the clinically affected segments in this case. The differential diagnosis of weakness of shoulder abduction and external rotation rests between a cervical radiculopathy, a lesion of the upper trunk, lateral cord, or posterior cord of the brachial plexus, and a lesion isolated to one of the nerves that comes off the upper trunk, lateral cord, or posterior cord of the brachial plexus. Therefore, motor conduction studies were limited to stimulation of the axillary nerve bilaterally, with the deltoid (the area of muscle wasting) recorded. Sensory conduction studies were performed recording the radial,

CASE 31–2. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL
Axillary (m)	Axilla	Deltoid	10.2	0.4		2.5	2.8	≤3.3			
	Erb's point	Deltoid	10.1	0.3		4.2	5.0		62	46	≥50
Median (s)	Wrist	Thumb	33	34	≥10	3.1	3.0	≤3.5	53	55	≥50
Radial (s)	Forearm	Snuffbox	29	25	≥15	2.4	2.4	≤2.9	55	56	≥50
Lateral antebrachial (s)	Elbow	Lateral forearm	17	19	≥10	2.2	2.3	≤3.0	64	62	≥55

m = motor study; s = sensory study; RT = right; LT = left; NL = normal.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies.

CASE 31–2. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Left medial deltoid	↑	+2	0	NL	↓↓	+2	+1	+1
Left teres minor	↑	+3	0	NL	↓↓	+2	+2	+2
Left Infraspinatus	NL	0	0	NL	NL	NL	NL	NL
Left biceps brachii	NL	0	0	NL	NL	NL	NL	NL
Left brachioradialis	NL	0	0	NL	NL	NL	NL	NL
Left triceps	NL	0	0	NL	NL	NL	NL	NL
Left C5 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Left C6 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Left C7 paraspinal	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓↓ = moderately reduced; NL = normal.

median-to-digit-1, and lateral antebrachial cutaneous SNAPs bilaterally, all of which evaluate the C5–C6 spinal segments, including the upper trunk and lateral and posterior cords of the brachial plexus. The CMAP amplitude recording the left deltoid is markedly reduced, with a normal distal motor latency. The low CMAP amplitude with normal distal latency implies axonal loss. Note that, as in the previous case, the median sensory nerve study was performed stimulating the wrist and recording digit 1, as innervation to digit 1 is derived from the C6 spinal segment, whereas sensation to digit 2, which is traditionally used, is derived from the C6–C7 segments and is not as relevant to this case. The sensory studies are normal and symmetric bilaterally. The normal SNAPs imply that this is not a lesion of the brachial plexus. On needle EMG examination, abundant fibrillation potentials are noted in the left deltoid and teres minor, with reduced recruitment of large, long, polyphasic MUAPs. Needle examination of other muscles with C5 or C6 innervation, or both, including the infraspinatus, biceps, brachioradialis, triceps, and upper cervical paraspinal muscles, is entirely normal. The normal examination of other muscles, including the paraspinal muscles, in the same myotomes as the deltoid and teres minor suggests that this is not a cervical radiculopathy.

In summary, there is a low CMAP recording the left deltoid, with active denervation and reinnervation restricted to the left deltoid and teres minor muscles. Needle examination of other muscles in the same myotomes is normal, including the cervical paraspinal muscles, and all of the SNAPs are normal. The lesion appears to be restricted to the axillary nerve. The presence of a low CMAP and fibrillation potentials in a patient who has had symptoms for several months suggests that the lesion is axonal and severe. The presence of reinnervated MUAPs indicates that the lesion is chronic.

IMPRESSION: *There is electrophysiologic evidence consistent with a chronic axonal lesion of the left axillary nerve.*

This case raises several important questions.

What is the Most Likely Etiology of this Patient's Injury?

The most likely etiology of the patient's injury is that of an axillary nerve injury secondary to fracture and dislocation of the mid-humerus. Axillary neuropathies most often occur as a result of trauma, especially dislocation of the shoulder and fracture of the humerus.

Can One be Absolutely Certain that there is not a Cervical Radiculopathy or Lesion of the Brachial Plexus?

The electrodiagnostic abnormalities are limited to the deltoid and teres minor. Although one cannot say with absolute certainty that the lesion is restricted to the axillary nerve, given the clinical history of a mid-humeral fracture and the findings of weakness of shoulder abduction and external rotation and sensory loss over the lateral arm, this is the most likely diagnosis. The possibility of a lesion of the brachial plexus or cervical roots primarily affecting the axillary fibers may be considered, but the clinical context and the electrophysiologic findings make this very unlikely.

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Lumbosacral Plexopathy 32

The anterior rami of the L1–S3 roots come together to form the lumbosacral plexus, from which all major lower extremity nerves are derived. Disorders of the lumbosacral plexus are distinctly uncommon, but when they occur they typically present with a combination of pain, sensory loss, and weakness in the leg, in a manner similar to diseases of the nerve roots. Different patterns of clinical findings may develop, depending on which part of the plexus is affected. It often falls to the electromyographer to distinguish between lesions of the lumbosacral plexus and those of the nerve roots. Differentiating between a disorder of the plexus and nerve roots is critical in establishing the differential diagnosis and guiding further evaluation.

ANATOMY

The lumbosacral plexus is usually thought of anatomically as consisting of an upper lumbar plexus and a lower lumbosacral plexus (Figure 32–1).

Lumbar Plexus Nerves

The lumbar plexus, formed from the L1–L4 roots, lies in the retroperitoneum behind the psoas muscle. Several important nerves are derived from the lumbar plexus.

Femoral Nerve

The anterior rami of the L2–L3–L4 roots divide into anterior and posterior divisions. The three posterior divisions unite to form the femoral nerve, which runs through the pelvis and exits into the thigh under the inguinal ligament. Muscular innervation is supplied to the iliopsoas (hip flexion), pectineus, sartorius, and quadriceps (knee extension) muscles. In addition, sensory branches innervate the medial calf (saphenous nerve) and anteriormedial thigh (medial and intermediate cutaneous nerves of the thigh).

Obturator Nerve

The anterior divisions of the L2–L3–L4 anterior rami form the obturator nerve. The obturator nerve descends through the pelvis to exit through the obturator foramen, supplying muscular innervation to the thigh adductors (adductor longus, adductor brevis, adductor magnus, and gracilis) as well as sensation to a small area of skin on the medial thigh.

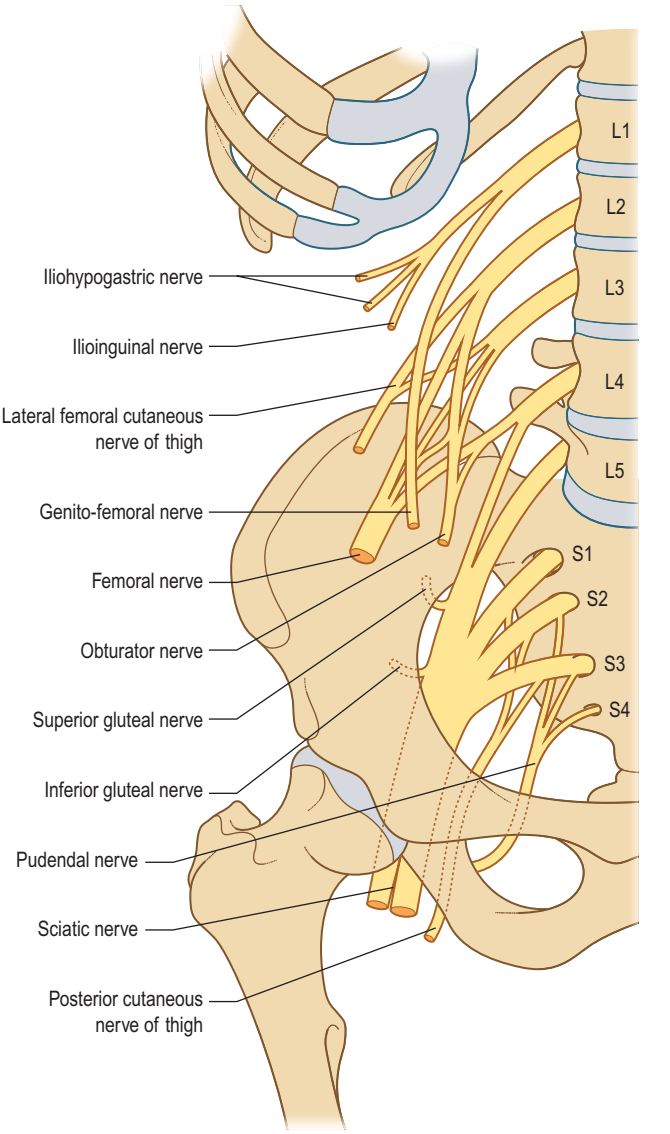

FIGURE 32–1 Anatomy of the lumbosacral plexus. The lumbosacral plexus is divided anatomically into an upper lumbar plexus and a lower lumbosacral plexus. The iliohypogastric, ilioinguinal, lateral femoral cutaneous nerve, genitofemoral, femoral, and obturator are the major nerves derived from the lumbar plexus. The sciatic nerve, superior gluteal nerve, inferior gluteal nerve, posterior cutaneous nerve of the thigh, and the pudendal nerves are derived from the lower lumbosacral plexus.
(From Hollinshead, W.H., 1969. Anatomy for surgeons, volume 2: the back and limbs. Harper & Row, with permission, New York.)

DOI: 10.1016/B978-1-4557-2672-1.00032-5

Iliohypogastric and Ilioinguinal Nerves

These two paired nerves, derived from the L1 root, are similar to the thoracic intercostal nerves. Both run around the pelvic crest to supply muscular innervation to the transverse and internal oblique muscles. In addition, the iliohypogastric nerve supplies sensation to a strip over the lower anterior abdomen. Just inferior to this, the ilioinguinal nerve supplies sensation to (1) an area of skin over the inguinal ligament, (2) a small area of skin over the rostral medial thigh, and (3) the upper part of the scrotum in males or labia in females.

Genitofemoral Nerve

This small nerve is derived from both the L1 and L2 roots. It descends in the pelvis and divides into a genital and a femoral branch at the level of the medial inguinal ligament. The genital branch provides muscular innervation to the cremasteric muscles in males and sensation to the skin over the lower part of the scrotum in males or labia in females. The femoral branch supplies sensation to the area of skin over the femoral triangle.

Lateral Femoral Cutaneous Nerve of the Thigh

The lateral femoral cutaneous nerve (LFCN) is a pure sensory nerve that is derived from the L2–L3 roots and emerges laterally from the psoas muscle, and then crosses obliquely toward the anterior superior iliac spine (ASIS) where it passes under the inguinal ligament. It is here at the ASIS and inguinal ligament that the nerve is susceptible to injury and compression. The average distance between the inguinal ligament and the point at which the LFCN emerges distally from the underlying fascia is 10.7 cm with a range of 10–12 cm. At this point, the nerve typically then divides into anterior and posterior branches that supply sensation to a large oval area of skin over the lateral and anterior thigh. Among individuals, there can be significant anatomic variation to where the nerve crosses in relationship to the ASIS and the inguinal ligament (Figure 32–2).

Lower Lumbosacral Plexus Nerves

The lower lumbosacral plexus is formed primarily from the L5–S3 roots, with an additional component from the L4 root. This L4 component joins the L5 root to form the *lumbosacral trunk* (Figure 32–3), which then descends below the pelvic outlet to join the sacral plexus. The remainder of the lower extremity nerves are derived from the lower lumbosacral plexus.

Sciatic Nerve

Most of the fibers in the lower lumbosacral plexus are destined for the sciatic nerve, which receives innervation from the L4–S3 roots. Leaving the pelvis through the greater sciatic foramen, usually under the piriformis muscle, the sciatic nerve supplies muscular innervation to the knee flexors (hamstrings: semimembranosus, semitendinosus, and long and short heads of the biceps femoris), the lateral division of the adductor magnus muscle, and all muscles innervated by the peroneal and tibial nerves. Sensory innervation is provided to the entire lower leg below the knee, with the exception of the medial calf, which is innervated by the saphenous nerve.

Superior Gluteal Nerve

The superior gluteal nerve (Figure 32–4), derived from L4–**L5**–S1 fibers, leaves the greater sciatic foramen to supply muscular innervation to the tensor fascia latae, gluteus medius, and gluteus minimus muscles (hip abduction and internal rotation). This nerve usually carries no cutaneous sensory fibers.

Inferior Gluteal Nerve

The inferior gluteal nerve (Figure 32–4), derived from L5–**S1**–S2 fibers, supplies only the gluteus maximus muscle, which subserves extension of the hip joint.

Posterior Cutaneous Nerve of the Thigh

The posterior cutaneous nerve of the thigh (Figure 32–4) is derived principally from the S2 root but also has a component from S1 and S3. It leaves the pelvis adjacent to the sciatic nerve to supply sensation to the lower buttock and posterior thigh. Given its proximity, traumatic injuries to the sciatic nerve commonly damage this nerve as well.

CLINICAL

Lumbosacral plexus lesions usually are divided clinically into those affecting the upper lumbar plexus and those affecting the lower lumbosacral plexus, analogous to the underlying anatomic division. Lumbar plexopathies affect predominantly the L2–L4 nerve fibers, resulting in weakness of the quadriceps, iliopsoas, and hip adductor muscles (femoral and obturator nerves). The knee jerk is frequently depressed or absent. Pain, if present, usually is located in the pelvis with radiation into the anterior thigh. Sensory loss and paresthesias occur over the lateral, anterior, and medial thigh and may extend down the medial calf (Figure 32–5).

Lesions of the lower lumbosacral plexus predominantly affect the L4–S3 nerve fibers. Patients describe a deep boring pain in the pelvis that can radiate posteriorly into the thigh with extension into the posterior and lateral calf. The ankle jerk may be depressed or absent. Sensory symptoms and signs may be seen over the posterior thigh and posterior-lateral calf and in the foot (Figure 32–6). Proximally, weakness may be present in the hip extensors (gluteus maximus), abductors and internal rotators (gluteus medius and tensor fascia latae). In the leg, weakness may occur in the hamstrings, as well as in all muscles supplied by the peroneal and tibial nerves. Nerve fibers destined for the peroneal nerve often are preferentially affected in lumbosacral plexopathies, similar to the preferential involvement of peroneal nerve fibers seen in sciatic nerve and L5 root lesions. Accordingly, patients may present with footdrop and sensory disturbance over the dorsum of the foot and lateral calf. In some cases, the pattern of weakness and numbness may be difficult or impossible to differentiate

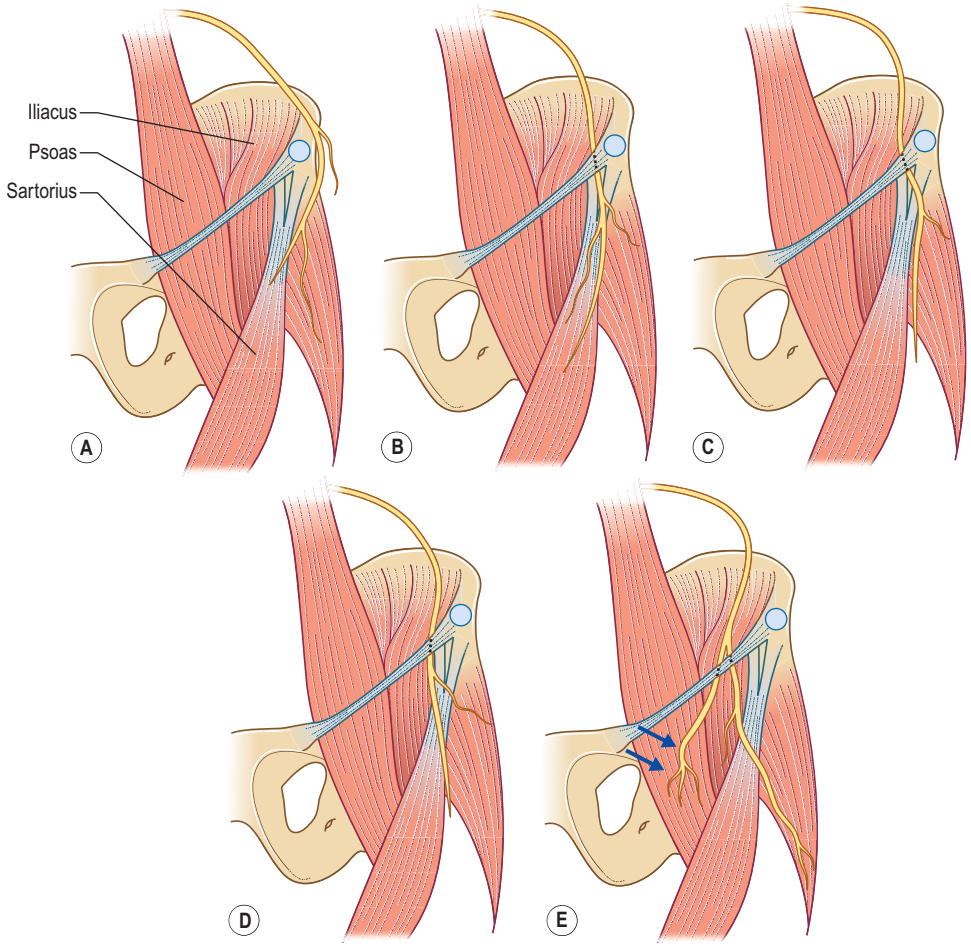

FIGURE 32–2 Anatomic variations in the course of the lateral femoral cutaneous nerve. In a cadaver study of 104 nerves, five different variations in the course of the nerve were identified: **type A,** posterior to the anterior superior iliac spine, across the iliac crest (4%); **type B,** anterior to the anterior superior iliac spine and superficial to the origin of the sartorius muscle but within the substance of the inguinal ligament (27%); **type C,** medial to the anterior superior iliac spine, ensheathed in the tendinous origin of the sartorius muscle (23%); **type D,** medial to the origin of the sartorius muscle located in a space between the tendon of the sartorius muscle and thick fascia of the iliopsoas muscle deep to the inguinal ligament (26%); and type E, most medial and embedded in loose connective tissue, deep to the inguinal ligament, overlying the thin fascia of the iliopsoas muscle (20%). In type E, the medial branch supplies the skin territory usually supplied by the femoral branch of the genitofemoral nerve and represents an additional anatomic variation. **Blue circle:** Anterior superior iliac spine. **Yellow line:** Lateral femoral cutaneous nerve. **Blue arrows:** Fibers normally supplied by the femoral branch of the genitofemoral nerve but in this variant, supplied by the lateral femoral cutaneous nerve. Muscle names written on Type A.
(Adapted with permission from Aszmann, O.C., Dellon, E.S., Dellon, A.L., 1997. Anatomical course of the lateral femoral cutaneous nerve and its susceptibility to compression and injury. Plast Reconstr Surg 100, 600–604.)

clinically from an isolated lesion of the common peroneal nerve. It is in such cases that electrodiagnostic studies are crucial.

ETIOLOGY

Similar to diseases of the nerve roots, lumbosacral plexopathies can be divided into those caused by structural and those caused by nonstructural lesions (Box 32–1). Structural lesions include pelvic tumors, hemorrhage, aneurysms, endometriosis, and trauma. Among nonstructural causes of lumbosacral plexopathy, the most common is diabetes mellitus. Known also as proximal diabetic neuropathy or plexopathy, diabetic amyotrophy classically affects the lumbar plexus. Lumbosacral plexopathy can also occur on a nonstructural basis from radiation damage, usually in the context of prior treatment for a pelvic, abdominal, or spinal tumor. In addition, the lumbosacral plexus may be injured during pelvic or orthopedic surgery, especially when retractors are used. Other nonstructural causes of lumbosacral plexopathy include inflammation, infarction, and postpartum injuries.

COMMON LUMBOSACRAL PLEXOPATHIES

Retroperitoneal Hemorrhage

Retroperitoneal hemorrhage is most commonly seen as a complication of anticoagulation, either with low molecular

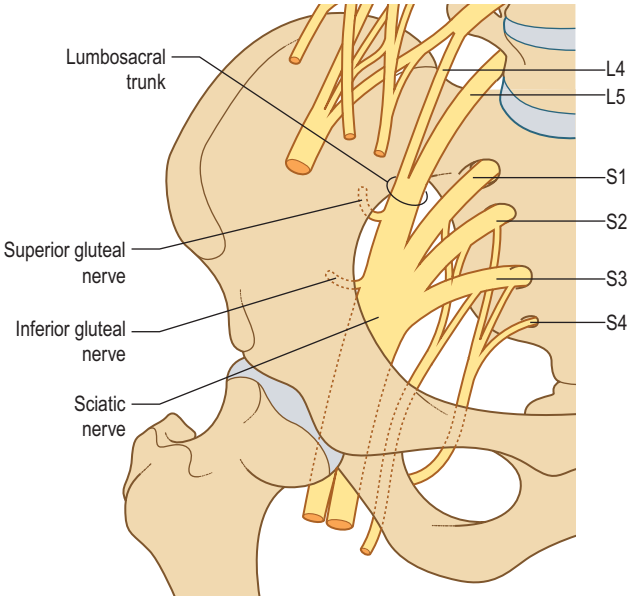

FIGURE 32–3 Lumbosacral trunk: the site of injury in postpartum lumbosacral plexopathy. The lumbosacral trunk is formed from the L5 root with a contribution from the L4 root, which join to descend into the pelvis to reach the sacral plexus. Against the sacrum, these fibers are exposed and susceptible to compression. This is the most common site of entrapment in postpartum lumbosacral plexopathy.
(Adapted from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia, with permission.)

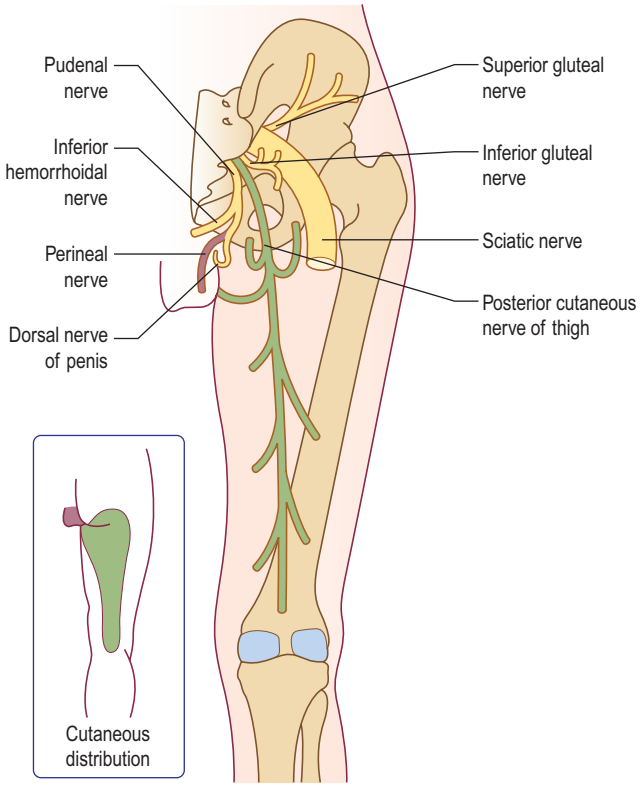

FIGURE 32–4 Anatomy of the major nerves from the lower lumbosacral plexus. **Inset:** Cutaneous distribution of the posterior cutaneous nerve of the thigh.
(From Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia.)

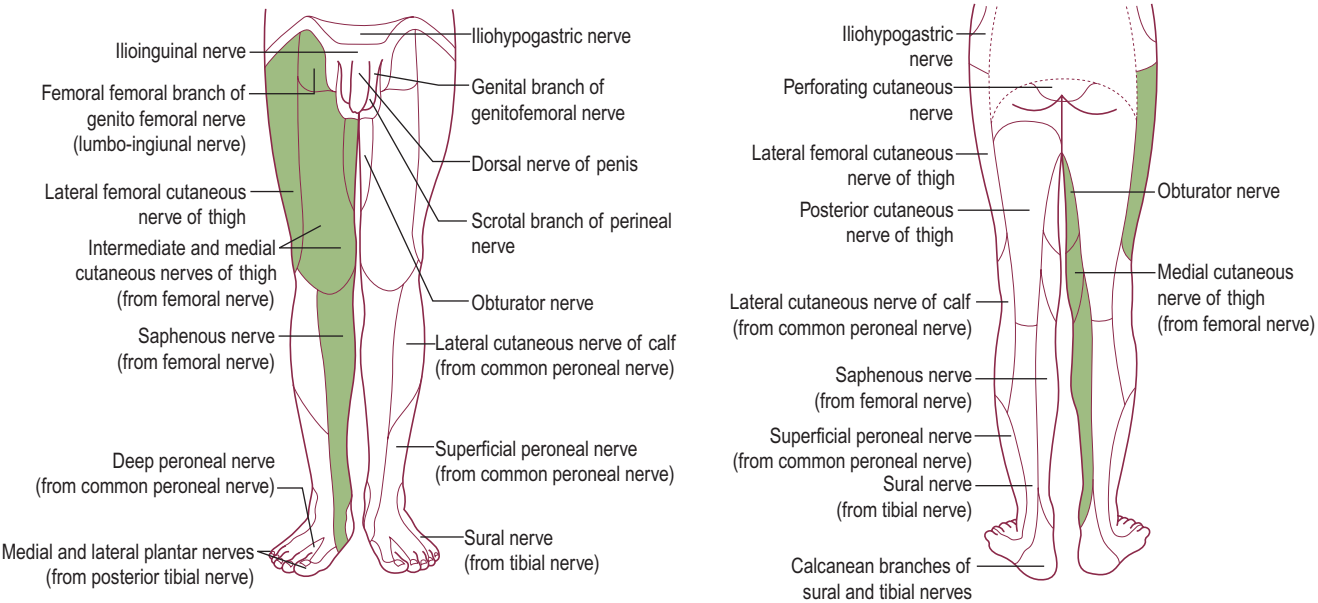

FIGURE 32–5 Sensory abnormalities in lumbar plexopathy. In lesions of the lumbar plexus, sensory abnormalities occur over the lateral thigh (lateral femoral cutaneous nerve), anterior thigh (intermediate cutaneous nerve of the thigh [femoral]), medial thigh (femoral branch of the genitofemoral nerve, medial cutaneous nerve of the thigh [femoral branch] and obturator nerve) and may extend down the medial calf (saphenous nerve [femoral]).
(Adapted from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia.)

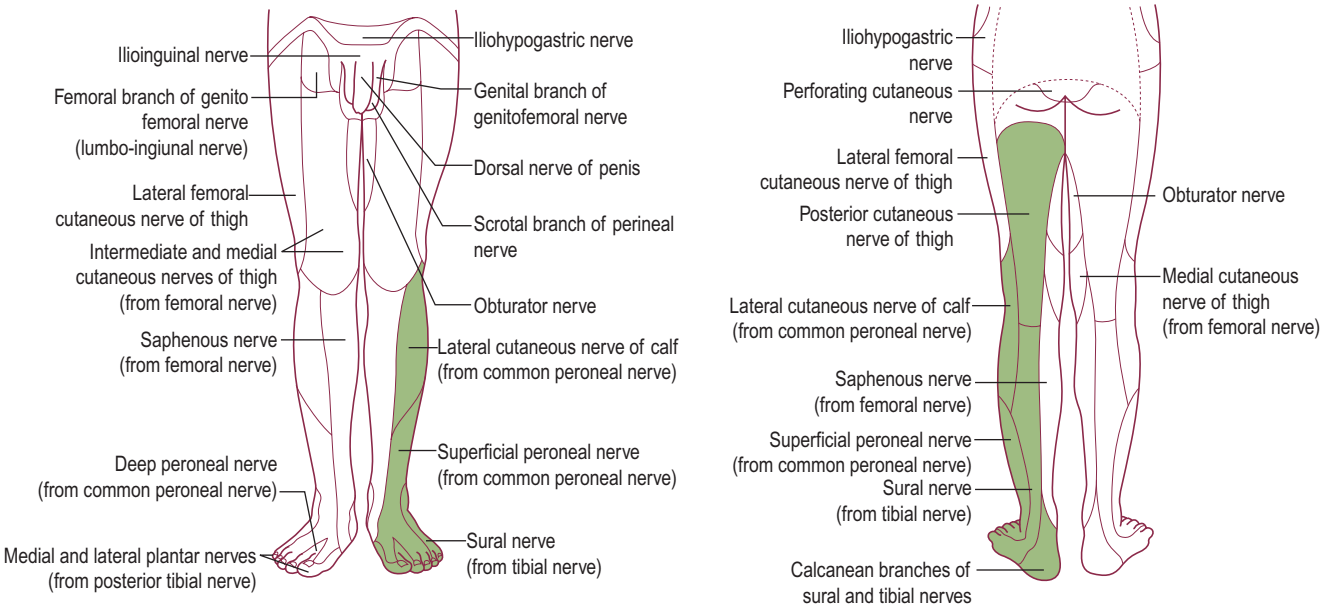

FIGURE 32–6 Sensory abnormalities in lower lumbosacral plexopathy. In lesions of the lower lumbosacral plexus, sensory abnormalities occur over the posterior thigh (posterior cutaneous nerve of the thigh) and posterior-lateral calf and in the foot (peroneal and tibial nerves). (Adapted from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia.)

Box 32–1. Etiology OF Lumbosacral Plexopathy

Structural
- Retroperitoneal hemorrhage (anticoagulation, hemophilia)
- Pelvic or abdominal tumor
- Aneurysm (common or internal iliac artery)
- Endometriosis
- Trauma

Nonstructural
- Inflammatory (plexitis)
- Infarction
- Postpartum
- Diabetes (diabetic amyotrophy)
- Radiation
- Postsurgical (retractor injury)

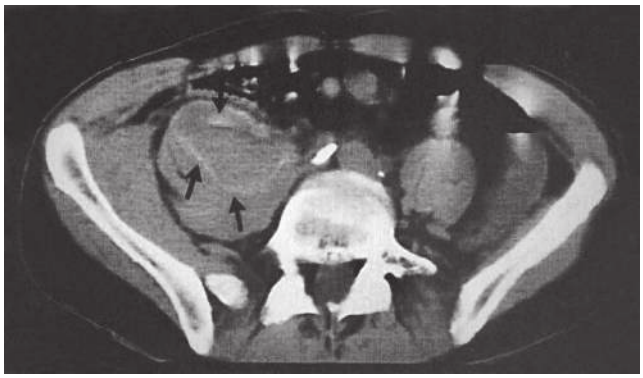

FIGURE 32–7 Retroperitoneal hemorrhage. Axial computed tomographic scan of the pelvis shows hematoma (arrows). Lumbar plexopathy may result from hemorrhage into the retroperitoneal space, most often as a complication of anticoagulation or in association with hemophilia or other coagulation disorders. These hematomas usually are located within the psoas muscle itself, where they can compress the lumbar plexus below. (From Lindner, A., Zierz, S., 2001. Retroperitoneal hemorrhage. N Engl J Med 344, 348. With permission.)

weight heparin (e.g., enoxaparin), unfractionated heparin, or warfarin, but it may also occur in the setting of hemophilia or as a result of an aortic aneurysm rupture. Such hemorrhages usually are located within the psoas muscle itself, where they can compress the lumbar plexus (Figure 32–7). Patients present acutely with significant pain and often hold the hip flexed and slightly externally rotated. Although the entire lumbar plexus is compressed, the major neurologic deficit usually is in the femoral nerve territory, with weakness of hip flexion and knee extension and a reduced or absent knee jerk. However, close examination often reveals some dysfunction beyond the femoral distribution, either in the obturator or lateral femoral cutaneous nerve territories, or both.

Tumors and Other Mass Lesions

Structural causes of lumbosacral plexopathies include local invasion by tumors, most typically from the bladder, cervix, uterus, ovary, prostate, colon, or rectum. In addition, lymphoma and leukemia can directly infiltrate nerves, even in the absence of a mass lesion on imaging studies. Aneurysms or pseudoaneursyms of the internal iliac or common iliac artery have been reported to compress the lumbosacral plexus. Lumbosacral plexopathy also occurs in women with endometriosis, as a result of implantation of abnormal tissue on the plexus. These lesions more often affect the lower lumbosacral plexus. Other than endometriosis, which may result in intermittent symptoms, all of these lesions are usually slowly progressive. Often, pain

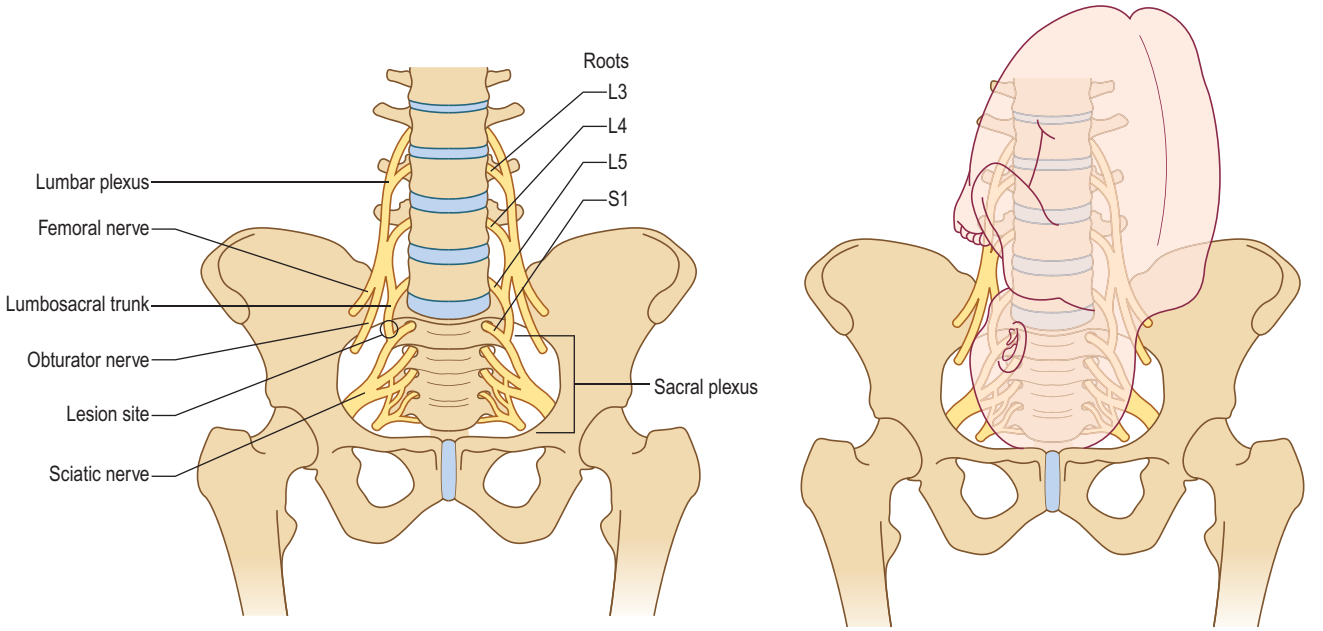

FIGURE 32–8 Postpartum lumbosacral plexopathy. Postpartum lumbosacral plexopathy results primarily from compression of the L4 and L5 fibers forming the lumbosacral trunk. When the lumbosacral trunk crosses the pelvic outlet, the fibers lie exposed and are susceptible to compression. The mechanism of injury likely involves compression of the fetal head against the underlying pelvis and lumbosacral trunk. (From Katirji, B., Wilbourn, A.J., Scarberry, S.L., et al., 2002. Intrapartum maternal lumbosacral plexopathy: foot drop during labor due to lumbosacral trunk lesion. Muscle Nerve 26, 340–347. With permission.)

with some radiation into the leg may be prominent. Clinically, these disorders are difficult or impossible to differentiate from lesions of the lumbosacral roots.

Inflammatory (Idiopathic Lumbosacral) Plexitis

Idiopathic plexitis occurs in the lumbosacral plexus, although it is far less frequent than its upper extremity counterpart, brachial neuritis (now most properly referred to as neuralgic amyotrophy). The underlying pathology is not completely known, although it is probably inflammatory, often occurring within a few weeks of a possible inciting immunologic event, such as a cold, flu, or immunization. In some cases, there is no clear inciting event. Patients initially develop severe deep pain, either proximal in the pelvis or in the upper leg. Although the pain characteristically persists for 1 to 2 weeks, as in idiopathic brachial plexitis, in some patients pain may become a disabling symptom, lasting many months. Because both the upper and lower plexus may be involved, many different patterns of weakness and sensory loss may develop.

The classic presentation is that of acute, severe pain that subsides over several weeks, followed by weakness that recovers over many months to years. In contrast to these monophasic presentations, other patients may present with a progressive course. Some patients have been described with a progressive, painful lumbosacral plexopathy, often with an elevated sedimentation rate, who have improved with steroids or other immunosuppressives. Such cases may represent localized forms of vasculitic neuropathy.

Postpartum Plexopathy

Compression injury to the lumbosacral plexus during labor and delivery, known as *postpartum lumbosacral plexopathy*, is underappreciated and often misdiagnosed. It has been described in the literature under various names, including *maternal peroneal palsy*, *maternal birth palsy*, *neuritis puerperalis*, and *maternal obstetric paralysis*. Although most large series place the incidence of this disorder at one in 2600 births, there are likely many milder cases that never reach medical attention.

The mechanism of injury likely involves compression of the fetal head against the underlying pelvis and lumbosacral plexus (Figure 32–8). Postpartum lumbosacral plexopathy results primarily from compression of the *lumbosacral trunk*. These are the fibers from the L4 and L5 roots, which join together to descend into the pelvis to reach the sacral plexus. When the lumbosacral trunk crosses the pelvic outlet, the fibers lie exposed (no longer protected by the psoas muscle) as they rest against the sacral ala near the sacroiliac joints. At this point, the fibers are most exposed and susceptible to compression. The origin of the superior gluteal nerve lies close by and may also be compressed. The fibers that eventually form the peroneal division of the sciatic nerve lie posteriorly, closest to the bone, and are more vulnerable to compression than the tibial division fibers. Accordingly, peroneal fibers are often most affected, with some women presenting with a postpartum footdrop, not infrequently misdiagnosed as peroneal palsy at the fibular neck.

Weakness may be noticed immediately or within the first few days after delivery. In addition to peroneal weakness,

examination often shows mild weakness of knee flexion (hamstrings) and hip abduction, extension, and internal rotation (glutei, tensor fascia latae), demonstrating that the lesion is clearly beyond the peroneal territory. Sensory disturbance is most marked over the dorsum of the foot and lateral calf but may be patchy and involve the sole of the foot, posterior calf, and thigh.

Several factors predispose to this injury, including a first pregnancy, a large fetal head with a small maternal pelvis (cephalopelvic disproportion), a small mother (less than 5 feet in height), and a prolonged or difficult labor. Women who have experienced a prior episode are predisposed to this complication with additional pregnancies. Although rare patients may be left with permanent weakness, the prognosis is excellent in most cases. The presumed mechanism of injury involves compression that leads to ischemia and mechanical deformation of nerve fibers, which in turn lead to demyelination and, if severe enough, axonal loss. There is no tearing, shearing, or disruption of basement membranes. Thus, even in cases with severe axonal loss, recovery often is complete. Patients with a moderate lesion often recover in a two-step process. In the first stage, relatively rapid improvement occurs over days to weeks from remyelination of demyelinated fibers. This is followed by relative stabilization and a much slower recovery over many months to years from axonal regrowth and reinnervation.

Diabetic Amyotrophy

Painful lumbosacral plexopathy may occur in patients with diabetes mellitus. This condition is known under various names in the literature, among them diabetic proximal neuropathy, Bruns–Garland syndrome, diabetic mononeuritis multiplex, diabetic polyradiculopathy, and diabetic amyotrophy. The most recent addition to this list of terms is diabetic lumbosacral radiculoplexus neuropathy (DLSRPN). Diabetic amyotrophy classically affects the upper lumbar plexus and nerve roots. Thus, diabetic amyotrophy is actually a radiculoplexopathy. On nerve pathology, the underlying cause appears to be a microscopic vasculitis leading to nerve ischemia. Patients with either mild or long-standing diabetes, usually Type II, may be affected. They typically present with severe, deep boring pain in the pelvis or proximal thigh, which may last weeks (average is approximately 6 weeks). Movement often is difficult. As the pain slowly abates, it becomes apparent that the patient also has significant weakness that is out of proportion to the pain. Diabetic amyotrophy commonly affects the femoral and obturator nerves, with prominent wasting of the anterior and medial thigh musculature. The peroneal nerve may also be involved. The knee jerk often is absent on the involved side. Despite the prominent pain, atrophy, and weakness, there may be very little sensory loss in the L2–L4 distribution. Coexistent weight loss is often present, although not well explained. It is not unusual for patients who develop diabetic amyotrophy to have a coexistent diabetic polyneuropathy; accordingly, such patients will have some sensory disturbance and loss of reflexes in the distal legs as well.

In most cases, diabetic amyotrophy occurs unilaterally. In others, the same process may affect the contralateral side within the first few weeks or months of initial presentation. Recovery often is good but usually quite prolonged, ranging from many months to 1 to 2 years.

Radiation Plexopathy

Similar to radiation-induced brachial plexopathy, lumbosacral plexopathy can also occur from radiation damage, usually as a result of radiation administered years previously for treatment of a tumor. Lumbosacral radiation plexopathy is slowly progressive, usually with little pain. Depending on the radiation port, different parts of the plexus may be involved. The characteristic finding, either clinically or more often on electromyography (EMG), is the presence of fasciculations and myokymia. Clinically, myokymia is recognized as rippling, undulating, or wormlike movement of muscles. Notably, myokymia is not seen in direct tumor invasion of the plexus and is an important marker of radiation-induced damage.

Lateral Femoral Cutaneous Neuropathy (Meralgia Paresthetica)

The lateral femoral cutaneous nerve (LFCN) of the thigh runs as a direct extension off the L2–L3 roots around the pelvic brim and passes under the inguinal ligament to supply an oval area of skin over the lateral and anterior thigh (Figure 32–9). Entrapment of the LFCN may occur as it passes under the inguinal ligament. Strictly speaking, entrapment of the LFCN is not a lumbosacral plexus lesion,

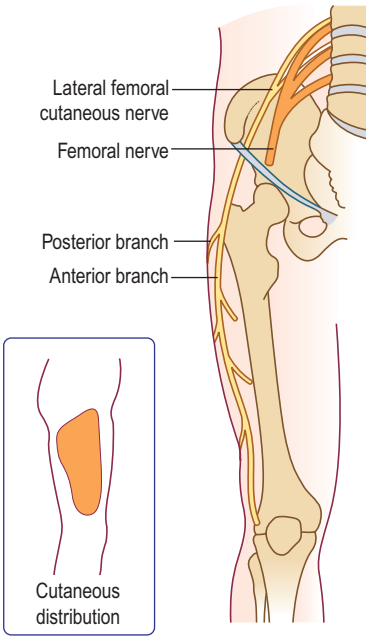

FIGURE 32–9 Anatomy of the lateral femoral cutaneous nerve. (Adapted from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia. With permission.)

but is included in this chapter because of its location and clinical presentation. The clinical syndrome, known as *meralgia paresthetica*, results in a painful, burning, numb patch of skin over the anterior and lateral thigh. Because there is no muscular innervation from this nerve, there is no associated muscle atrophy, weakness, or loss of reflexes. Prolonged standing, or any position wherein the thigh is extended, may provoke symptoms as hip extension results in increased angulation and tension on the nerve. This entrapment is more common in patients who are obese, wear tight underwear, pants or belts, or who have diabetes. Car seatbelts have been implicated in some cases. In addition, the lateral femoral cutaneous nerve can be damaged from surgery in the area of the nerve, including bone grafts, total hip arthroplasty, vascular bypass, hysterectomy, and Caesarean section. Although the vast majority of cases are due to an entrapment at the inguinal ligament, rare cases have resulted from trauma and others from tumors and other mass lesions compressing the upper lumbar plexus more proximally.

ELECTROPHYSIOLOGIC EVALUATION

The role of nerve conduction studies and EMG is to localize the lesion to the plexus and exclude radiculopathies and various mononeuropathies (e.g., femoral, sciatic) that can mimic lumbosacral plexopathy clinically. This usually requires bilateral lower extremity studies, including both nerve conduction studies and needle EMG. *In general, the sensory nerve conduction studies and needle EMG examination of the paraspinal muscles provide the most useful information in differentiating a plexus from a root lesion*. Sensory abnormalities on nerve conduction studies exclude a lesion at or isolated to the nerve roots; on the other hand, denervation or motor unit action potential (MUAP) abnormalities in the paraspinal muscles place the lesion proximal to the plexus, in the nerve roots. Beyond the obvious function of localizing the lesion, electrophysiologic studies are useful in assessing severity and chronicity, as well as in identifying unusual spontaneous activity, such as myokymia, which has special diagnostic significance.

Nerve Conduction Studies

The nerve conduction evaluation of lumbosacral plexopathy is outlined in Box 32–2. Routine peroneal and tibial motor studies should be performed bilaterally, recording the extensor digitorum brevis (EDB) and abductor hallucis brevis (AHB), respectively, along with their respective F responses. Careful attention must be paid to the peroneal motor study, with the electromyographer looking for evidence of peroneal palsy at the fibular neck (either focal slowing or conduction block) in patients with footdrop. In lower lumbosacral plexus lesions that have resulted in axonal loss, the amplitude of the peroneal or tibial compound muscle action potentials (CMAPs) may be reduced on the symptomatic side. In lumbar plexopathies, femoral motor studies can also be performed bilaterally to assess the amount of axonal loss. Likewise, if there has been loss of the fastest conducting axons, there may also be mild prolongation of the distal motor latencies and some slight slowing of conduction velocity. If only the upper lumbar plexus is involved, routine peroneal and tibial motor studies may be completely normal.

The late responses may be useful in suggesting a proximal lesion. In a lower lumbosacral plexopathy, the peroneal and tibial F responses may be more prolonged on the symptomatic side than on the asymptomatic side. Likewise, the H reflex may be prolonged or more difficult to elicit on the involved side. Of course, the finding of prolonged or absent F and H responses on one side cannot be used to differentiate among a sciatic neuropathy, lumbosacral plexopathy, or radiculopathy, but a proximal lesion is implied if the distal conduction studies are normal.

The sensory nerve conduction studies are crucial in identifying a plexus lesion. Both superficial peroneal and sural sensory studies should be performed in a suspected lower lumbosacral plexopathy, and saphenous studies should be done for a suspected lumbar plexopathy. Sensory nerve action potential (SNAP) amplitudes should be carefully

Box 32–2. Recommended Nerve Conduction Study Protocol for Lumbosacral Plexopathy

Routine studies:

1. Tibial motor study, recording abductor hallucis brevis, stimulating the medial ankle and popliteal fossa; bilateral studies
2. Peroneal motor study, recording extensor digitorum brevis, stimulating ankle, below fibular neck and lateral popliteal fossa; bilateral studies. In patients with an isolated footdrop and clinical findings limited to the distribution of the peroneal nerve, recording the tibialis anterior, stimulating below fibular neck and lateral popliteal fossa, should be performed to increase the yield of demonstrating conduction block or focal slowing across the fibular neck.
3. Sural sensory study, stimulating posterior calf, recording posterior ankle; bilateral studies
4. Superficial peroneal sensory study, stimulating lateral calf, recording lateral ankle; bilateral studies
5. Tibial and peroneal F responses; bilateral studies
6. H reflex; bilateral studies

Additional studies for suspected lumbar plexopathy or lateral femoral cutaneous neuropathy:

1. Saphenous sensory study, stimulating medial calf, recording medial ankle; bilateral studies
2. Femoral motor study, stimulating the femoral nerve at the inguinal ligament, recording the rectus femoris; bilateral studies
3. Lateral femoral cutaneous sensory study, stimulating just medial to the anterior superior iliac spine, recording over anterior thigh; bilateral studies

Special consideration:

If symptoms are bilateral, consider studying an upper extremity to exclude polyneuropathy.

compared from side to side. Decreased SNAP amplitudes generally imply a lesion either at the dorsal root ganglion or distally in the plexus or peripheral nerves, but not at the nerve roots.

Occasionally, sensory nerve conduction studies of the LFCN can be performed. These studies, however, often are difficult to perform using surface electrodes, especially in obese patients. The LFCN can be stimulated 1 cm medial to the anterior superior iliac spine (ASIS) and recorded with electrodes placed 12 cm distally over a line drawn between the ASIS and the lateral patella (Figure 32–10). If no response is obtained, one should first move the stimulator slightly medially and then laterally, noting that there are anatomic variations of the LFCN in relationship to the anterior superior iliac spine. However, in most individuals, the nerve lies within 0–2 cm medial to the ASIS. Rarely, the nerve may lie as far as 5–8.5 cm medial to the ASIS. If a response cannot be obtained by moving the stimulator, then one should also try to move the recording electrodes parallel to the initial placement. The nerve is usually located within 2 cm medial to the original line drawn between the ASIS and the lateral patella. Because this response is difficult to obtain in many normal individuals, it ideally should be compared with the contralateral, asymptomatic side, in cases where only one side is affected. Any side-to-side difference in amplitude of more than 50% (comparing the higher to the lower side) is considered abnormal. It is often best to start with the uninvolved, asymptomatic side. Clearly, in obese patients (note, obesity is a risk factor for this condition), the study is even more technically difficult. If no response can be elicited on the asymptomatic side, there is little use in trying to obtain the potential on the involved side. An abnormal response may be seen in an isolated entrapment of the LFCN or in lesions of the upper lumbar plexus.

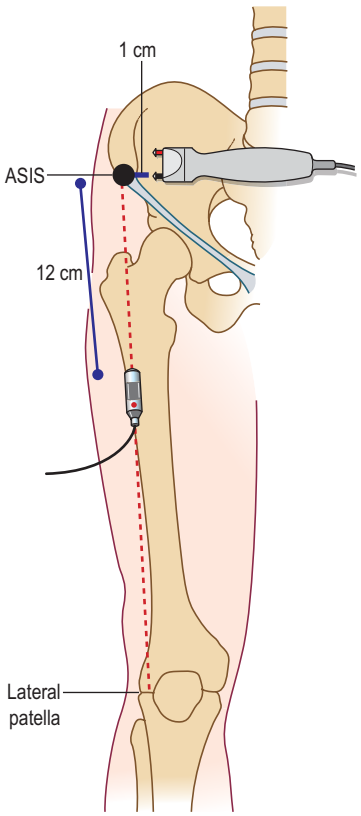

FIGURE 32–10 Lateral femoral cutaneous nerve: standard stimulation and recording sites. The LFCN can be stimulated 1 cm medial to the anterior superior iliac spine (ASIS). The recording electrodes are placed 12 cm distally over a line drawn between the ASIS and the lateral patella. See text for further details.
(Adapted from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia. With permission.)

Electromyographic Approach

Lumbosacral plexopathy cannot be localized by nerve conduction studies alone. Although abnormal sensory conduction studies can define the lesion as at or distal to the dorsal root ganglion, they usually cannot separate a mononeuropathy from a plexopathy (e.g., sciatic neuropathy vs. lower lumbosacral plexopathy; femoral neuropathy vs. lumbar plexopathy). This distinction can only be accomplished with needle EMG (Box 32–3). Similar to the EMG evaluation of suspected radiculopathy, an extensive study must be performed, sampling distal and proximal muscles innervated by different nerves and in different nerve root distributions. In mononeuropathy, abnormalities are limited to one nerve, whereas in plexopathy more than one nerve is involved.

Several muscles assume special significance in the needle EMG evaluation of lumbosacral plexopathy. Among them are the gluteal, thigh adductor, and paraspinal muscles. The gluteal muscles are especially useful in separating a sciatic neuropathy from a lower lumbosacral plexopathy, as any abnormalities in the gluteal muscles place the lesion at or

Box 32–3. Recommended Electromyographic Protocol for Lumbosacral Plexopathy

1. At least two peroneal-innervated muscles (e.g., tibialis anterior, extensor hallucis longus, peroneus longus)
2. At least two tibial-innervated muscles (e.g., medial gastrocnemius, tibialis posterior, flexor digitorum longus)
3. At least one sciatic-innervated muscle in the thigh (e.g., biceps femoris)
4. At least one superior gluteal-innervated muscle (e.g., gluteus medius, tensor fascia latae)
5. Inferior gluteal-innervated muscle (i.e., gluteus maximus)
6. At least two femoral-innervated muscles (e.g., vastus lateralis, iliacus)
7. At least one obturator-innervated muscle (e.g., one of the thigh adductors)
8. Paraspinal muscles: L2, L3, L4, L5, S1

Special considerations:

- If motor unit action potential abnormalities are borderline or equivocal, comparison should be made to the contralateral side.
- If symptoms are bilateral, consider studying an upper extremity to exclude polyneuropathy.

proximal to the plexus, thereby excluding an isolated sciatic neuropathy. Likewise, in the differentiation of femoral neuropathy from lumbar plexopathy, abnormalities in the thigh adductors, which are innervated by the obturator nerve, place the lesion at or proximal to the lumbar plexus, thereby excluding an isolated lesion of the femoral nerve.

Lastly, the evaluation of the paraspinal muscles is extremely important in separating lesions of the plexus from the nerve roots. Abnormalities in the paraspinal muscles place the lesion at the root level. However, the absence of abnormalities in the paraspinal muscles cannot definitively exclude a lesion of the nerve roots. Some patients with true radiculopathy have a normal EMG evaluation of the paraspinal muscles. This reinforces the concept that the EMG examination can only localize the lesion at or proximal to the most proximal muscle with abnormalities. To feel secure in the electrodiagnosis of a lumbosacral plexopathy, it is preferable to see a combination of abnormal sensory studies and a normal EMG examination of the paraspinal muscles.

The classic electrophysiologic picture of an upper lumbar plexopathy is that of normal tibial and peroneal motor conduction studies along with normal F responses and H reflexes. Both the sural and superficial peroneal sensory nerves are normal, but the saphenous sensory response is reduced or absent on the involved side. If there has been axonal loss, the femoral motor amplitude will be lower on the affected side. Needle EMG findings show active denervation or reinnervation in muscles supplied by (1) the femoral nerve and (2) the obturator nerve, but with sparing of the lumbar paraspinal muscles. In some patients, peroneal- and superior gluteal-innervated muscles that have partial L4 innervation (e.g., tibialis anterior, gluteus medius) may be abnormal as well.

The classic electrophysiologic picture of a lower lumbosacral plexopathy is that of reduced tibial and peroneal motor amplitudes on the involved side compared with the contralateral side, with normal or slightly prolonged distal latencies and normal or slightly slowed conduction velocities. Likewise, the tibial and peroneal F responses often are prolonged or absent on the symptomatic size, with similar findings for the H reflex. Both the sural and superficial peroneal sensory nerves are reduced in amplitude or absent, with normal potentials on the contralateral asymptomatic side. Needle EMG shows active denervation or reinnervation in muscles supplied by the (1) sciatic nerve in the thigh, (2) the peroneal nerve, (3) the tibial nerve, and (4) the superior and inferior gluteal nerves, with sparing of lumbosacral paraspinal muscles.

In cases of radiation damage to the lumbosacral plexus, myokymic discharges may be seen on EMG. Electrically, myokymia is recognized as the spontaneous, grouped repetitive discharges of MUAPs, which is highly characteristic of radiation damage. Individual fasciculations commonly accompany myokymia as well. In superficial muscles, myokymia can be recognized clinically by an undulating, wormlike movement of the muscle. However, myokymia is much more easily appreciated on the needle EMG examination, with which deeper muscles can easily be sampled.

In cases of entrapment of the lateral femoral cutaneous nerve, the needle EMG is completely normal, as this nerve is a pure sensory nerve and supplies no muscles. However, in suspected lateral femoral cutaneous neuropathy, it is important to exclude a lumbar plexopathy and especially an L2 radiculopathy. In this regard, the iliacus, thigh adductors, and less so the quadriceps are important muscles to check.

Limitations in the Electrodiagnosis of Lumbosacral Plexopathy

The primary role of nerve conduction studies and EMG in evaluating a lumbosacral plexopathy is to localize the lesion and, secondarily, to assess the severity. In several situations, however, there are significant limitations.

Bilateral Lumbosacral Plexopathy is Difficult to Differentiate from Polyneuropathy

Although most lumbosacral plexopathies are unilateral, some may be bilateral, including those caused by tumor, radiation, and diabetes. In such cases, it may be very difficult to differentiate a lumbosacral plexopathy from a polyneuropathy. Motor and sensory nerve conduction studies may be abnormal bilaterally, and needle EMG may show denervation or reinnervation in the leg muscles bilaterally, with the paraspinal muscles spared.

In these situations, upper extremity studies may be very informative. In most polyneuropathies, some nerve conduction and EMG abnormalities are expected in the distal upper extremities, unless the polyneuropathy is very mild. Finding EMG abnormalities in the proximal hip muscles (e.g., glutei, iliopsoas, thigh adductors) may be helpful, since it would be very unusual to find EMG abnormalities in such proximal muscles in a typical length-dependent, stocking glove polyneuropathy. Indeed, by the time a polyneuropathy affects the upper thigh, the upper extremities should also be considerably affected, both clinically and electrically.

Normal Paraspinal Muscles on EMG do not Exclude a Radiculopathy

Although one expects the paraspinal muscles to be abnormal in radiculopathy and normal in plexopathy, this is not always the case. It is well recognized that the paraspinal muscles are normal in many cases of radiculopathy (approximately 50% in many series). This may be due to fascicular sparing of some fibers, sampling error, or difficulty examining the paraspinal muscles due to poor relaxation. In addition, reinnervation, like denervation, occurs first in the most proximal muscles. Accordingly, if the paraspinal muscles reinnervate before the limb muscles, they may look completely normal on EMG, whereas the limb muscles remain denervated, a pattern equally consistent with plexopathy. If this occurs, only the presence of abnormal SNAPs can help differentiate a plexopathy from a radiculopathy.

If the Lesion is Acute, the Study may be Normal

Patients with painful lumbosacral plexopathy may be referred early in the course of their illness for an evaluation. During the first week, however, nerve conduction studies may remain completely normal, as there has not been enough time for wallerian degeneration to have occurred. Likewise, during the first 10 to 14 days, denervation will not be seen on EMG, and the only abnormality may be decreased recruitment of MUAPs in weak muscles. Because fibrillation potentials take several weeks to develop in the more distal limb muscles, it often is best to wait at least 3 weeks before sending the patient for nerve conduction and EMG studies, unless one is willing to repeat the study after several weeks to look for new changes.

EXAMPLE CASES

Case 32–1

History and Physical Examination

A 15-year-old girl with hemophilia was admitted to the hospital with severe right groin pain. The pain had begun spontaneously 2 weeks previously and slowly increased over several hours. On examination she held her right hip flexed and externally rotated. The right knee jerk was absent. The left knee and both ankle reflexes were normal. Because of pain, testing motor strength in the right lower extremity was very difficult. There was an area of hypesthesia along the right medial calf. The remainder of the neurologic examination was normal.

Summary

The history is that of a young girl with hemophilia who presented with a 2-week history of sudden-onset, severe right groin pain that increased over several hours and persisted. The neurologic examination is notable for an absent right knee jerk and hypesthesia over the right medial calf. The right hip is flexed and externally rotated, and strength cannot be reliably assessed because of the pain.

On nerve conduction studies, the right tibial and peroneal motor conduction studies reveal normal CMAP amplitudes, distal motor latencies, and conduction velocities. The corresponding F responses are normal. Femoral motor studies and contralateral left tibial and peroneal motor studies were not performed because the patient was in severe pain, and the test was curtailed. It was more important to perform bilateral sensory conduction studies to determine whether the lesion was proximal or distal to the dorsal root ganglion. The superficial peroneal and sural sensory studies are normal and symmetric bilaterally, which was expected given the normal sensation in these distributions. The saphenous sensory response is absent on the right side and normal on the left. The abnormal saphenous sensory potential on the right corresponds to the abnormal area of sensation on the neurologic examination and also indicates that there has been enough time for wallerian degeneration to have occurred. Furthermore, the abnormal saphenous SNAP (sensory branch of the femoral nerve) implies that the lesion is at or distal to the dorsal root ganglion, either in the upper lumbar plexus or femoral nerve.

Moving next to the needle EMG study, fibrillation potentials are noted in the right vastus lateralis, thigh adductors, and iliacus. The abnormalities in the thigh adductors clearly indicate that the lesion is beyond the distribution of the femoral nerve. There are no MUAPs activated in the vastus lateralis. In the thigh adductors and iliacus, the MUAPs are of normal size, with moderately reduced recruitment. The remainder of the needle examination, including the right medial gastrocnemius, tibialis anterior, extensor hallucis longus, and L3–L5 paraspinal muscles, are normal. To summarize, abnormalities

CASE 32–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F-Wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Tibial (m)	Ankle	AHB	12.0		≥4	5.1		≤5.8				44		≤56
	Popliteal fossa	AHB	10.0			13.0			50		≥41			
Peroneal (m)	Ankle	EDB	7.6		≥2	4.1		≤6.5						≤56
	Below fibula	EDB	7.5			11.7			45		≥44	46		
	Lateral popliteal fossa	EDB	7.5			13.3			45		≥44			
Peroneal (s)	Lateral calf	Lateral ankle	31	33	≥6	3.9	3.8	≤4.4	51	52	≥40			
Sural (s)	Calf	Posterior ankle	25	20	≥6	3.7	3.8	≤4.4	54	52	≥40			
Saphenous (s)	Medial calf	Medial ankle	NR	7	≥4		4.0	≤4.4		50	≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.
Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 32–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right vastus lateralis	↑	+2	0	None				
Right tibialis anterior	NL	0	0	NL	NL	NL	NL	NL
Right thigh adductors	↑	+2	0	NL	↓↓	NL	NL	NL
Right iliacus	↑	+2	0	NL	↓↓	NL	NL	NL
Right medial gastrocnemius	NL	0	0	NL	NL	NL	NL	NL
Right extensor hallucis longus	NL	0	0	NL	NL	NL	NL	NL
Right L3 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right L4 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right L5 paraspinal	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓↓ = moderately reduced; NL = normal.

are found in the distribution of the femoral (vastus lateralis, iliacus) and obturator (thigh adductors) nerves but not in the paraspinal muscles.

Given the abnormal saphenous potential, the EMG abnormalities in the femoral and obturator innervated muscles, and the normal paraspinal EMG findings, one can now localize the lesion to the upper lumbar (L2–L4) myotomes, at or distal to the dorsal root ganglion, in the distribution of the femoral and obturator nerves. Therefore, the lesion most likely is in the lumbar plexus.

IMPRESSION: *There is electrophysiologic evidence consistent with a subacute lesion of the lumbar plexus on the right.*

This case raises several important questions.

How Does One Determine the Time Course of the Lesion by these Electrodiagnostic Studies?

The abnormal saphenous SNAP indicates that wallerian degeneration has taken place. The presence of fibrillation potentials with reduced recruitment of normal-appearing MUAPs suggests that the lesion is subacute. Although there has been enough time for wallerian degeneration and subsequently denervation potentials to occur, there has not been enough time for reinnervation of MUAPs. In an acute lesion, one would expect to see normal SNAPs with reduced recruitment of normal configuration MUAPs without fibrillation potentials; in a chronic lesion, one would expect to see abnormal SNAPs with large, prolonged (reinnervated) MUAPs with or without fibrillation potentials.

What is the Most Likely Cause of the Lumbar Plexopathy in this Case?

The history of acute onset of groin pain in a hemophiliac, with an absent knee jerk and hypesthesia in the distribution of the saphenous nerve, suggests a retroperitoneal hemorrhage with subsequent compression of the lumbar plexus. The electrodiagnostic studies are consistent with a lesion of the lumbar plexus, most likely caused by compression secondary to a hematoma. A computed tomographic scan of the pelvis confirmed the presence of a psoas hematoma in this patient, which resolved over the course of several months.

Case 32–2

History and Physical Examination

A 67-year-old woman was referred for further evaluation of possible lumbar radiculopathy. She had a long history of mild noninsulin-dependent diabetes. One month ago, she developed severe, boring toothache-like pain in the right hip and thigh that radiated down her leg. Pain was worse with movement and persisted despite 2 weeks of bed rest. A clinical diagnosis of radiculopathy was made. A subsequent magnetic resonance imaging scan of the lumbosacral spine showed bulging disks at both L4–L5 and L5–S1.

On examination, there was moderate weakness of right hip flexion, hip adduction, and knee extension. There was obvious wasting of the right quadriceps. Deep tendon reflexes were absent at the ankles. The left knee jerk was normal, and the right knee jerk was absent. Otherwise, strength and reflexes were normal. There was mild

CASE 32–2. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = μV			Latency (ms)			Conduction Velocity (m/s)			F-Wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Tibial (m)	Ankle	AHB	5.4	6.1	≥4	5.8	5.7	≤5.8				57	56	≤56
	Popliteal fossa	AHB	4.8	5.4		12.7	12.6		40	40	≥41			
Peroneal (m)	Ankle	EDB	4.2	5.2	≥2	5.7	5.4	≤6.5				58	55	≤56
	Below fibula	EDB	4.0	5.1		8.4	8.2		39	41	≥44			
	Lateral popliteal fossa	EDB	4.0	5.1		11.2	11.0		40	42	≥44			
Sural (s)	Calf	Posterior ankle	2	3	≥6	4.2	4.1	≤4.4	43	41	≥40			
Peroneal (s)	Lateral calf	Lateral ankle	4	6	≥6	3.8	3.7	≤4.4	44	42	≥40			
Median (m)	Wrist	APB	6.2		≥4	4.5		≤4.4				32		≤31
	Antecubital fossa	APB	6.1			8.2			54		≥49			
Ulnar (m)	Wrist	ADM	7.2		≥6	3.0		≤3.3				31		≤32
	Below elbow	ADM	7.2			6.5			60		≥49			
	Above elbow	ADM	7.2			8.2			60		≥49			
Median (s)	Wrist	Index finger	13		≥20	3.9		≤3.5	39		≥50			
Ulnar (s)	Wrist	Little finger	12		≥17	2.9		≤3.1	45		≥50			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis; APB = abductor pollicis brevis; ADM = abductor digiti minimi.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 32–2. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right tibialis anterior	NL	0	0	NL	↓	+1	+1	+1
Right medial gastrocnemius	NL	0	0	NL	↓	+1	NL	NL
Right vastus lateralis	↑	+3	0	NL	↓	NL/+1	NL/+1	+1
Right thigh adductors	↑	+2	0	NL	↓	NL/+1	NL/+1	+1
Right iliacus	↑	+2	0	NL	↓	NL/+1	NL/+1	NL/+1
Right tensor fascia latae	NL	0	0	NL	↓	NL	NL	NL
Right S1 paraspinal	↑	+1	0	NL	NL	NL	NL	NL
Right L5 paraspinal	↑	+1	0	NL	NL	NL	NL	NL
Right L4 paraspinal	↑	+1	0	NL	NL	NL	NL	NL
Right L3 paraspinal	↑	+1	0	NL	NL	NL	NL	NL
Left vastus lateralis	NL	0	0	NL	NL	NL	NL	NL
Left tibialis anterior	NL	0	0	NL	NL	NL	NL	NL
Right abductor pollicis brevis	↑	0	0	NL	↓	NL/+1	NL/+1	NL/+1
Right biceps brachii	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓ = slightly reduced; NL = normal.

sensory loss to pinprick and vibration to the mid-shins and in the fingertips bilaterally.

Summary

The history is that of a woman in her late 60s with noninsulin-dependent diabetes mellitus who presents with a 1-month history of severe toothache-like pain in the right hip and thigh radiating down the leg. The pain is worse with movement and has not remitted with extended bed rest. Neurologic examination is notable for distal sensory loss in the upper and lower extremities; absent ankle jerks and right knee jerk; and moderate weakness of the right quadriceps, iliopsoas, and hip adductors. A magnetic resonance imaging scan shows bulging disks at L4–L5 and L5–S1.

Reviewing the nerve conduction studies first, the bilateral tibial and peroneal motor conduction studies are normal, with the exception of borderline conduction velocity slowing. The right median motor conduction study reveals a slightly prolonged distal motor latency, with normal CMAP amplitude and conduction velocity. The bilateral sural and superficial peroneal SNAPs and right ulnar SNAP have low amplitudes with a slightly slowed conduction velocity in the right ulnar sensory nerve. The right median SNAP has a low amplitude, slightly prolonged latency, and moderately slowed conduction velocity. The combination of low amplitude sural and superficial peroneal and ulnar SNAPs suggests a peripheral polyneuropathy, which is consistent with the clinical examination and likely secondary to the diabetes. The slightly prolonged median distal motor latency and low amplitude and moderately slowed median SNAP may suggest a superimposed median neuropathy at the wrist, although the patient has no clinical symptoms suggesting carpal tunnel syndrome.

Moving next to the needle EMG study, there is mild chronic reinnervation (high amplitude, prolonged duration MUAPs) with no active denervation in the right tibialis anterior and medial gastrocnemius muscles, which, along with the abnormalities on the nerve conduction studies, are consistent with a mild chronic distal polyneuropathy.

In addition to these EMG abnormalities, there is severe active denervation in the right vastus lateralis, iliacus, and thigh adductor muscles (all proximal muscles) with reduced recruitment of essentially normal MUAPs, although some are borderline long, large and polyphasic. The presence of fibrillation potentials with reduced recruitment of normal configuration MUAPs marks the course as subacute; denervation has taken place, but reinnervation has not yet occurred. Notably, the right tensor fascia latae shows no active denervation, although there is slightly reduced recruitment of normal configuration MUAPs. In contrast, EMG examination of the left vastus lateralis and tibialis anterior is normal, suggesting that this subacute denervating process is restricted to L2–L4-innervated muscles in the proximal right lower extremity. This asymmetric, proximal severe denervation, in the context of mild distal reinnervation bilaterally, cannot be attributed to the mild chronic distal polyneuropathy.

Thus, there must be a superimposed process primarily affecting the L2–L4 myotomes on the right side, which is severe, subacute, and denervating. The active denervation in the right L3- to S1-innervated paraspinal muscles indicates that the denervating process extends as proximally as the nerve roots. The sural and superficial peroneal SNAPs are not helpful here in assessing whether the lesion also involves the high lumbar plexus, because these nerves are subserved by L5 and S1 fibers. Although side-to-side comparison of the saphenous nerve may have been helpful in evaluating whether the lumbar plexus, in addition to the nerve roots, was involved, the finding of low sural and superficial peroneal SNAPs bilaterally virtually excludes the possibility of finding a saphenous SNAP on either side. Therefore, this study was not performed. However, the clinical presentation of a 1-month history of severe right buttock and leg pain, accompanied by moderate weakness of L2–L4-innervated muscles and an absent right knee jerk, unresponsiveness to bed rest, along with the electrophysiologic findings outlined, are classic findings of diabetic amyotrophy.

In the right upper extremity, there is mild reinnervation in the abductor pollicis brevis, and the biceps is normal. These findings are consistent with both the mild distal polyneuropathy and the median neuropathy at the wrist noted on nerve conduction studies.

In summary, the chronic distal findings in both legs and one arm are consistent with a generalized sensorimotor peripheral neuropathy. In addition to the peripheral neuropathy, there is a superimposed denervating process affecting the L2–L4 myotomes on the right, extending as proximally as the nerve roots. There is also a superimposed median neuropathy at the wrist on the right, which is asymptomatic. We are now ready to formulate our electrophysiologic impression.

IMPRESSION: *There is electrophysiologic evidence consistent with a chronic, generalized sensorimotor peripheral neuropathy. In addition, there is electrophysiologic evidence of a superimposed, subacute denervating process primarily affecting the L2–L4 myotomes on the right, extending as proximal as the nerve roots. There is also electrophysiologic evidence of a median neuropathy at the wrist on the right, which is clinically asymptomatic.*

This case raises several important questions.

What is the Most Likely Clinical Diagnosis?

The most likely clinical diagnosis is that of a generalized sensorimotor peripheral neuropathy (most likely secondary to diabetes), with superimposed diabetic amyotrophy. Pathologically, in cases like this, diabetic amyotrophy

is actually a radiculoplexopathy affecting the upper lumbar myotomes. This case also illustrates that when a patient has a peripheral neuropathy and a radiculopathy, it is not possible electrophysiologically to definitively demonstrate the plexus component.

Would Laminectomy be Recommended?

Review of the lumbosacral magnetic resonance imaging scan revealed two small central disc bulges at the L4–L5 and L5–S1 levels, without compromise of the thecal sac or exiting nerve roots. Thus, there was no structural lesion to account for the patient's symptoms. This situation is not uncommon in patients with diabetes, in whom neurologic and electrophysiologic evaluations suggest a lumbar radiculopathy, but no structural lesion can be found. Under these circumstances, one should seriously consider the diagnosis of diabetic amyotrophy. There is no role for surgery in this case.

Does this Patient have Carpal Tunnel Syndrome?

The patient has a median neuropathy at the wrist, as demonstrated on nerve conduction studies. She has no symptoms referable to these electrophysiologic findings, however, and a clinical diagnosis of carpal tunnel syndrome would not be made. No treatment for the median neuropathy would be recommended based on these findings.

Case 32–3

History and Physical Examination

A 36-year-old woman was referred for a persistent postpartum footdrop. Six weeks earlier, she was admitted in active labor with a 41-week gestational pregnancy. Despite the cervix being fully dilated after 1 hour of labor, no further progression occurred. Persistent late fetal decelerations developed, and, because the patient was small (5 feet tall), the diagnosis of cephalopelvic disproportion was considered. A baby girl was delivered by Caesarean section and was determined to have a normal Apgar score.

On postpartum day 1, the patient complained of numbness and weakness of the right foot, without pain. A complete right footdrop was present. She described a pins-and-needles sensation over the lateral right calf and foot. A medical consultant was called and made the diagnosis of peroneal neuropathy at the fibular neck, likely secondary to anesthesia and bed rest. There was only slight improvement over the next 6 weeks.

When seen 6 weeks later, neurologic examination showed a complete right footdrop, with weakness of foot and great toe dorsiflexion and foot eversion (1/5), foot inversion (2/5), hip abduction (4–/5), hip extension (4+/5), hip internal rotation (3/5), and knee flexion (4/5). Hip flexion and knee extension were normal. Hypesthesia was present over the lateral right calf and along the dorsum and sole of the foot. Knee and ankle reflexes were normal and symmetric bilaterally. The remainder of her strength and sensation were normal throughout.

Summary

The history is that of a woman who noted onset of a footdrop 1 day after a difficult labor and subsequent delivery by Caesarean section after failure to progress. The footdrop has persisted for 6 weeks. The neurologic examination is notable for severe weakness of peroneal-innervated muscles (foot and toe dorsiflexion, foot eversion), moderate to severe weakness of tibial-innervated muscles (foot inversion, knee flexion), and mild to moderate weakness of gluteal-innervated muscles (hip extension, internal rotation). Femoral-innervated muscles (hip flexion and knee extension) have normal strength. Altered sensation is noted over the lateral calf, dorsum,

CASE 32–3. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = μV			Latency (ms)			Conduction Velocity (m/s)			F-Wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Tibial (m)	Ankle	AHB	8.4	9.3	≥4	5.0	4.8	≤5.8				53	52	≤56
	Popliteal fossa	AHB	7.6	9.0		11.5	11.0		45	47	≥41			
Peroneal (m)	Ankle	EDB	3.6	6.6	≥2	4.8	4.6	≤6.5				52	50	≤56
	Below fibula	EDB	3.5	6.4		9.7	9.4		48	49	≥44			
	Lateral popliteal fossa	EDB	3.5	6.3		11.8	11.4		50	50	≥44			
Peroneal (s)	Lateral calf	Lateral ankle	NR	21	≥6		4.1	≤4.4		47	≥40			
Sural (s)	Calf	Posterior ankle	14	15	≥6	3.9	4.0	≤4.4	50	48	≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.
Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 32–3. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right extensor hallucis longus	↑	+3	0	NL	↓↓	NL	NL	+1
Right tibialis anterior	↑	+2	0	NL	↓↓	NL/+1	NL	NL/+1
Right peroneus longus	↑	+2	0	NL	↓↓	NL	NL	NL/+1
Right tibialis posterior	↑	+2	0	NL	↓	NL	NL	NL
Right medial gastrocnemius	NL	0	0	NL	NL	NL	NL	NL
Right biceps femoris – short head	↑	+1	0	NL	↓	NL	NL	NL
Right vastus lateralis	NL	0	0	NL	NL	NL	NL	NL
Right iliacus	NL	0	0	NL	NL	NL	NL	NL
Right tensor fascia latae	↑	+2	0	NL	↓↓	NL	NL	+1
Right gluteus maximus	↑	+1	0	NL	↓	NL	NL	NL/+1
Right S1 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right L5 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right L4 paraspinal	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓ = slightly reduced; ↓↓ = moderately reduced; NL = normal.

and sole of the foot. Reflexes are normal and symmetric bilaterally.

Examining the nerve conduction studies, the tibial and peroneal motor conduction studies and F response studies are normal bilaterally. However, the right peroneal CMAP recording EDB is low compared with the left side, although there is no evidence of conduction block or focal slowing across the fibular neck. Note that had the neurologic deficits been limited to peroneal-innervated muscles, peroneal conduction studies recording tibialis anterior would be indicated, with the electromyographer looking for conduction block or focal slowing across the fibular neck that could be missed if only the EDB is recorded (see Chapter 22). The right superficial peroneal sensory potential is absent, but the sural SNAP is normal and comparable with the left side. The left superficial peroneal SNAP is normal.

On needle EMG examination, extensive fibrillation potentials are noted in several muscles innervated by the peroneal, tibial, and gluteal nerves, with reduced recruitment of essentially normal configuration MUAPs, although some are borderline long and polyphasic. The peroneal-innervated muscles are the most severely involved, including the short head of the biceps femoris. This muscle is crucial to examine in cases of footdrop because it is the only peroneal-innervated muscle proximal to the fibular neck and is spared in lesions of the peroneal nerve at the fibular neck. Of note, the medial gastrocnemius and lumbosacral paraspinal muscles are normal.

The intact sural potential and normal needle examination of the medial gastrocnemius suggest that the S1 fibers are spared. Although the S1 fibers are relatively spared, the superficial peroneal sensory potential (L4–**L5**) is abnormal. Given these findings and the needle EMG abnormalities found in peroneal-, tibial-, and gluteal-innervated muscles, sparing the paraspinal muscles, the lesion appears to be limited to the L4–L5 fibers at or distal to the dorsal root ganglion, spanning several nerves. This would place the lesion in the right lumbosacral trunk. The presence of fibrillation potentials with reduced recruitment of essentially normal MUAPs mark the lesion as subacute, because the active denervation has not yet been accompanied by reinnervation. We are now ready to formulate an electrophysiologic impression.

IMPRESSION: *There is electrophysiologic evidence consistent with a subacute lesion of the lumbosacral trunk on the right side.*

This case raises several important questions.

What is the Most Likely Clinical Diagnosis?

The history, clinical examination, and electrophysiologic findings are all consistent with postpartum lumbosacral plexopathy. Both the clinical and electrophysiologic examinations reveal that the peroneal fibers are the most severely involved. Not uncommonly, patients with postpartum lower extremity weakness are initially thought to have a footdrop secondary to compression of the peroneal nerve at the fibular neck. However, closer neurologic examination and a careful electrophysiologic evaluation show that the lesion is more extensive. The mechanism of nerve injury is thought to be pressure of the fetal head against the pelvis leading to compression of the lumbosacral trunk. Follow-up examination of this patient at 1 year was normal.

How Can One Distinguish between a Lesion of the Lumbosacral Trunk and the Lumbosacral Plexus?

In this case, both the clinical and electrophysiologic examinations point toward a lesion involving the L4–L5 segments, but sparing the high lumbar and S1–S2 segments. Thus, the sural potential is intact and the needle examination of the medial gastrocnemius and iliacus are normal, whereas the superficial peroneal sensory potential is absent and needle examination of several muscles subserved by the L4 and L5 myotomes and spanning several nerves are abnormal. This places the lesion more specifically in the lumbosacral trunk, which joins the sacral plexus below the pelvic outlet, presumably below the site of compression. Neither the L1–L3 roots nor the sacral roots contribute fibers to the lumbosacral trunk.

Can One Completely Exclude an L5 Radiculopathy?

Unfortunately, the answer is no, not completely. In lesions proximal to the dorsal root ganglion, the SNAPs will almost always be normal. The only exception occurs very rarely with an L5 radiculopathy, wherein an abnormal superficial peroneal SNAP may infrequently be seen (see Chapter 29). The absence of abnormalities in the paraspinal muscles in this case support the diagnosis of a lumbosacral plexopathy. However, the paraspinal muscles are not always abnormal in radiculopathy either. Thus, even though this case is classic clinically for a postpartum plexopathy, specifically a lesion of the lumbosacral trunk, and the EDX study is also classic, it is probably advisable to put a proviso in the study impression stating that even though it is very unlikely, the study cannot completely exclude an unusual L5 radiculopathy that has compromised the L5 dorsal root ganglion as well.

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33 Sciatic Neuropathy

Sciatic neuropathies are uncommon in the electromyography (EMG) laboratory. When they occur, patients often present in a manner similar to that of peroneal neuropathy. *Indeed, a footdrop from an early sciatic neuropathy may be difficult or impossible to distinguish clinically from a footdrop from peroneal neuropathy at the fibular neck*. It often falls to the electromyographer to make this differentiation. Demonstration of a sciatic neuropathy on EMG has important diagnostic implications because the differential diagnosis is distinctly different from that of other peripheral nerve entrapment syndromes.

ANATOMY

The sciatic nerve is derived from the L4–S3 roots, carrying fibers that eventually will become the tibial and common peroneal nerves. It leaves the pelvis through the sciatic notch (greater sciatic foramen) under the *piriformis muscle* accompanied by the other branches of the lumbosacral plexus (*inferior and superior gluteal nerves* and *posterior cutaneous nerve of the thigh*). In some individuals, fibers destined to become the common peroneal nerve run through the piriformis muscle before joining the sciatic nerve. Covered by the gluteus maximus, the sciatic nerve next runs medial and posterior to the hip joint between the ischial tuberosity and the greater trochanter of the femur (Figure 33–1). The knee flexors, including the medial hamstrings (*semimembranosus and semitendinosus*) and lateral hamstrings (*long* and *short heads of the biceps femoris*), and the lateral division of the *adductor magnus* are all supplied by the sciatic nerve.

Within the sciatic nerve, fibers that eventually form the common peroneal nerve often are segregated from those that distally become the tibial nerve. The peroneal division of the sciatic nerve runs lateral to the tibial division. The two divisions physically separate from each other in the mid-thigh to form their respective nerves. All sciatic innervated muscles in the thigh are derived from the tibial division of the sciatic nerve, with the important exception of the short head of the biceps femoris, which is derived from the peroneal division. *In essence, the short head of the biceps femoris is the only peroneal-innervated muscle above the level of the fibular neck. This muscle assumes special importance in the EMG evaluation of peroneal palsy, sciatic neuropathy, and other more proximal lesions*. As the sciatic nerve terminates in the common peroneal and tibial nerves, it supplies all motor and sensory innervation below the knee, with the exception of sensation over the medial calf and foot (saphenous sensory territory).

CLINICAL

Sciatic neuropathies caused by trauma, injection, infarction, or compression present acutely. Otherwise, most sciatic neuropathies present in a progressive, subacute fashion. Patients with a complete sciatic neuropathy have paralysis of knee flexion and all movements about the ankle and toes. Sensation is lost in several areas (Figure 33–2), including the lateral knee (lateral cutaneous nerve of the knee), lateral calf (superficial peroneal nerve), dorsum of the foot (superficial peroneal nerve), web space of the great toe (deep peroneal nerve), posterior calf and lateral foot (sural nerve), and sole of the foot (distal tibial nerve). Pain may be perceived in the proximal thigh, radiating posteriorly and laterally into the leg, but it usually does not affect the back. The ankle reflex is depressed or absent on the involved side.

This complete deficit is seen only in severe lesions or late in the course of sciatic neuropathy. Initially, the clinical presentation most often mimics peroneal neuropathy. *It has long been recognized that the peroneal fibers are preferentially affected in most sciatic nerve lesions*. Thus, it is not unusual for a patient with sciatic neuropathy to present with a footdrop and sensory disturbance over the dorsum of the foot and lateral calf. Indeed, early sciatic nerve lesions may be nearly impossible to differentiate clinically from peroneal nerve lesions at the fibular neck (Table 33–1).

On physical examination, close attention must be paid to muscles that receive non-peroneal innervation, especially ankle inversion (tibialis posterior–tibial nerve), toe flexion (flexor digitorum longus–tibial nerve), and knee flexion (hamstring muscles–sciatic nerve). Weakness in any of these muscles in a patient with a footdrop suggests dysfunction beyond the peroneal nerve distribution. Likewise, on sensory examination, any sensory disturbance over the lateral knee, lateral foot, or sole of the foot suggests a lesion of the sciatic or tibial nerves or more proximally. Isolated sciatic nerve lesions spare sensation over the medial calf and foot (saphenous nerve) and posterior thigh (posterior cutaneous nerve of the thigh). Any involvement of these

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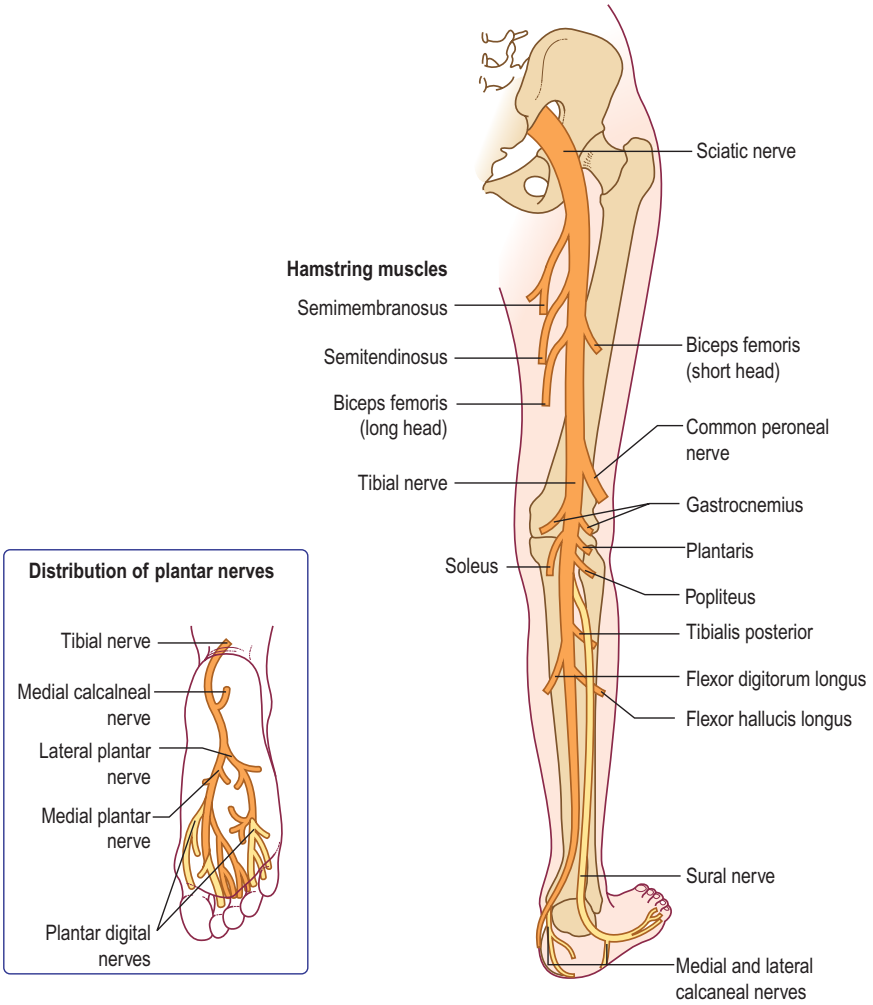

FIGURE 33–1 Sciatic nerve anatomy.
(From Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia. with permission.)

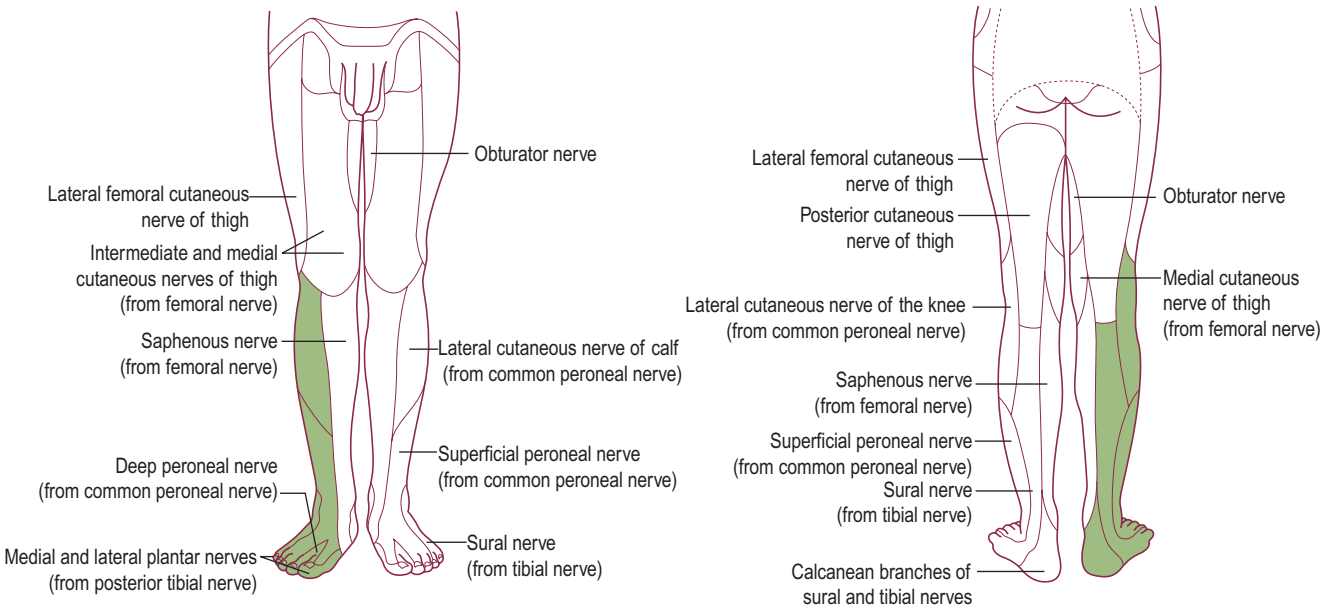

FIGURE 33–2 Sensory loss in sciatic neuropathy (in green).
(Adapted from Haymaker, W., Woodhall, B., 1953. Peripheral nerve injuries. WB Saunders, Philadelphia, with permission.)

Table 33–1. Clinical Differentiating Factors in Suspected Sciatic Neuropathy

	Deep Peroneal Nerve	Common Peroneal Nerve	Sciatic Nerve	Lumbosacral Plexus	L5
Weakness of foot dorsiflexion	X	X	X	X	X
Weakness of foot eversion		X	X	X	X
Weakness of foot inversion			X	X	X
Weakness of knee flexion			X	X	X
Weakness of glutei				X	X
Decreased ankle tendon reflex			X†	X†	X†
Sensory loss in webspace great toe	X	X	X	X	X
Sensory loss in dorsum of foot		X	X	X	X
Sensory loss in lateral calf		X	X	X	X
Sensory loss in lateral knee			X	X	X
Sensory loss in sole foot			X†	X†	X†
Sensory loss in posterior thigh				X†	X†
Tinel's sign at fibular neck	X	X			
Hip and thigh pain			X	X	X
Back pain					X
Positive straight-leg raise test					X

X = may be present; †May be present if lesion involves S1 fibers as well; CMAP = compound muscle action potential; SNAP = sensory nerve action potential.

territories in a patient with a footdrop suggests a more widespread lesion, either in the lumbosacral plexus or proximally.

It is important to remember that in addition to sciatic neuropathy and peroneal neuropathy, a footdrop with sensory disturbance over the lateral calf and dorsum of the foot may occur in lumbosacral plexopathy, radiculopathy (especially L5), or even a central lesion, such as a frontal meningioma or anterior cerebral artery infarct.

ETIOLOGY

Sciatic neuropathy is distinctly uncommon and is associated with a limited differential diagnosis (Box 33–1). As the sciatic nerve runs posterior to the hip joint, one of the most common presentations occurs following hip or femur fracture (especially posterior dislocation) or as a complication of the subsequent surgery to repair the fracture. As a complication of surgery, sciatic neuropathy may occur due to retraction or stretch, as well as a result of methylmethacrylate cement forming spurs and then eroding into the nerve months to years later, which has been well documented in several case reports.

Another common cause of sciatic neuropathy is tumor (neurofibroma, schwannoma, neurofibrosarcoma, lipoma, and lymphoma). Tumors affecting the sciatic nerve usually can be imaged quite well as a mass lesion on computed tomography or magnetic resonance imaging (MRI) scanning (Figure 33–3). Other rare mass lesions also may affect the sciatic nerve. An enlarged Baker's cyst in the popliteal fossa may compress the distal sciatic nerve as it bifurcates into the tibial and common peroneal nerves. Several unusual vascular abnormalities, including aneurysms of the inferior

Box 33–1. Etiology of Sciatic Neuropathy

- Hip (Gluteal) Region
  - Hip replacement surgery (retraction, stretch, methylmethacrylate cement)
  - Hip dislocation/fracture
  - Acute, external compression (coma, anesthesia, drug overdose, prolonged sitting)
  - Gluteal compartment syndrome
  - Gluteal contusion
  - Gluteal injection
  - Piriformis syndrome
- Thigh Region
  - Femur fracture
  - Acute, external compression
  - Posterior thigh compartment syndrome
  - Entrapment (myofascial band)
  - Laceration
  - Baker's cyst
- Hip or Thigh Region
  - Gunshot wound
  - Nerve infarction
    - Vasculitis
    - Arterial thrombosis
    - Arterial bypass surgery
    - Diabetes mellitus
    - Postradiation therapy
  - Mass Lesions
    - Benign tumors
    - Malignant cancers/lymphoma
    - Endometriosis
    - Arterial aneurysm
    - Arteriovenous malformations
    - Persistent sciatic artery
    - Myositis ossificans
    - Abscess

Modified from Yuen, E.C., So, Y.T., 1999. Sciatic neuropathy. Neurol Clin 17, 617–631.

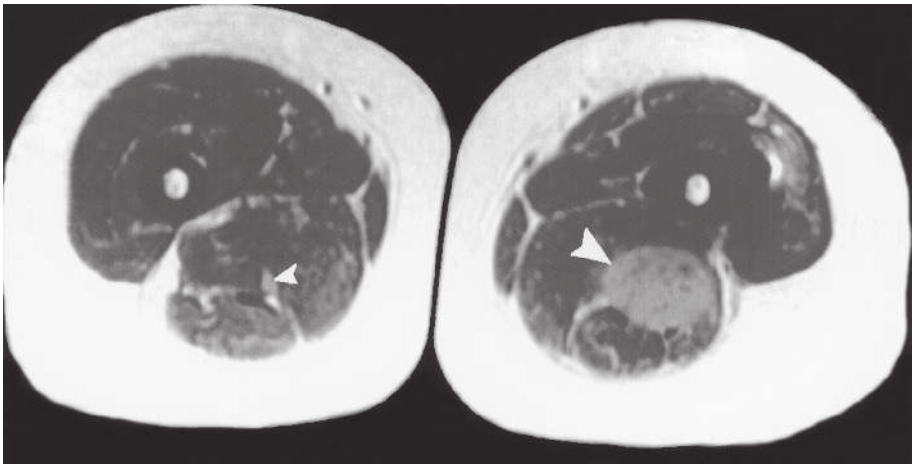

FIGURE 33–3 Mass lesion of the sciatic nerve. This patient presented with a slowly progressive, painful sciatic neuropathy over several months. Axial magnetic resonance imaging scan of the mid-thigh shows a large mass lesion in the region of the left sciatic nerve (large arrow). A normal-appearing sciatic nerve is seen on the contralateral side (small arrow). Biopsy demonstrated large cell lymphoma infiltrating and expanding the sciatic nerve. (Adapted from Preston, D.C., Shapiro, B.E., 2001. Lymphoma of the sciatic nerve. J Clin Neuromuscul Dis 2, 227–228.)

gluteal, iliac, or persistent sciatic arteries and arteriovenous malformations near the piriformis muscle, have been associated with sciatic neuropathy.

Damage to the sciatic nerve can occur from trauma or as a result of a penetrating injury, such as gunshot and knife wounds. Sciatic neuropathy also may occur as a complication of immobilization and external compression, such as during anesthesia, coma, or intoxication. In the hospital setting, damage to the sciatic nerve may occur iatrogenically from misplaced intramuscular buttock injections, especially in thin patients.

Disorders that result in a mononeuritis multiplex syndrome (see Chapter 26) may affect the sciatic nerve. For example, vasculitic neuropathy commonly results in infarction of the sciatic nerve in the proximal thigh, which is a watershed area for nerve ischemia. The neuropathy often is acute and begins with prominent pain. Until additional nerve lesions develop, recognition of the underlying mononeuritis multiplex pattern is difficult or impossible.

Piriformis Syndrome

As the sciatic nerve leaves the pelvis, it runs under or through the piriformis muscle (Figure 33–4). The piriformis muscle originates from the sacrum, the sciatic notch and the sacrotuberous ligament, and then runs through the greater sciatic foramen to attach to the greater trochanter of the femur. The main action of the piriformis is to externally rotate the hip. When the hip is in a flexed position, it also acts as a partial hip abductor. Theoretically, a hypertrophied piriformis muscle could compress the sciatic nerve (piriformis syndrome), somewhat comparable to compression of the median nerve by the pronator teres muscle in pronator teres syndrome. In the past, many cases of "sciatica" were attributed to piriformis syndrome. However, most, if not all, cases of sciatica are due to lumbosacral radiculopathy and not sciatic neuropathy from piriformis syndrome. Piriformis syndrome is considered by many to be

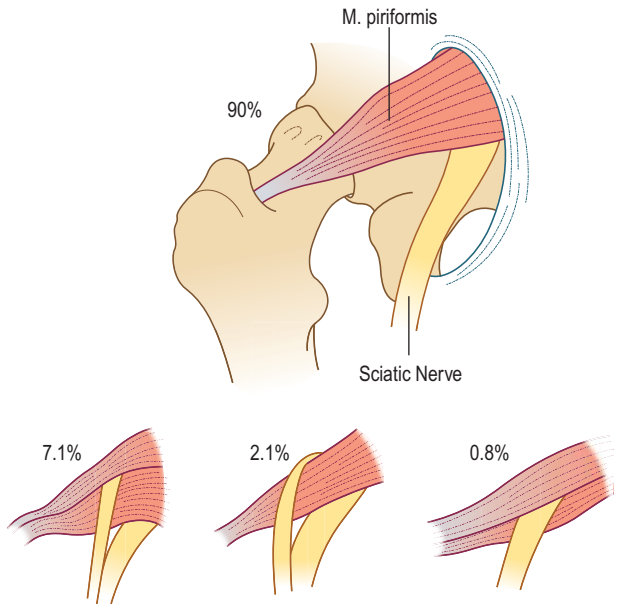

FIGURE 33–4 Anatomic relationships of the sciatic nerve to the piriformis muscle. As the sciatic nerve leaves the pelvis, it most often runs under the piriformis muscle. However, there are other less common anatomic variations. The proximity of the sciatic nerve to the piriformis muscle puts it at theoretic risk of entrapment. (Adapted from Beaton, L.E., Anson, B.J., 1938. The sciatic nerve and the piriformis muscle: their interrelation as possible cause of coccygodynia. J Bone J Surg 20, 686–688.)

a controversial entity. There are very few reported cases of patients who meet the criteria for definite piriformis syndrome, which include (1) sciatic neuropathy clinically, (2) electrophysiologic evidence of sciatic neuropathy, (3) surgical exploration showing entrapment of the sciatic nerve within a hypertrophied piriformis muscle, and (4) subsequent improvement following surgical decompression.

Clinically, piriformis syndrome should be suspected when a patient has more pain while sitting than standing; worsening of symptoms with flexion, adduction, and

Table 33–2. Electromyographic and Nerve Conduction Study Abnormalities Localizing the Lesion Site in Sciatic Neuropathy

	Deep Peroneal Nerve	Common Peroneal Nerve	Sciatic Nerve	Lumbosacral Plexus	L5
Electromyographic Findings					
Tibialis anterior	X	X	X	X	X
Extensor hallucis longus	X	X	X	X	X
Peroneus longus		X	X	X	X
Tibialis posterior			X	X	X
Flexor digitorum longus			X	X	X
Short head of biceps femoris			X	X	X
Gluteus medius				X	X
Tensor fascia latae				X	X
Paraspinal muscles					X
Nerve Conduction Study Findings					
Abnormal peroneal SNAP (if axonal)		X	X	X	
Abnormal sural SNAP (if axonal)			X	X	
Low peroneal CMAP (if axonal)	X	X	X	X	X
Low tibial CMAP (if axonal)			X†	X†	X†
Abnormal H reflex			X†	X†	X†
Conduction slowing/block at fibular neck (if demyelinating)	X	X			

X = may be abnormal; †May be abnormal if lesion involves S1 fibers as well; CMAP = compound muscle action potential; SNAP = sensory nerve action potential.

internal rotation of the hip; a history of trauma or unusual body habitus (especially very thin); and tenderness in the mid-buttock that reproduces the pain and paresthesias. Several physical examination maneuvers are reported to be useful in suspected piriformis syndrome. In each, the piriformis muscle is either stretched or voluntarily contracted. Pain from the buttock down the sciatic nerve, but without any back pain, is said to be consistent with piriformis syndrome. These maneuvers include:

- The Freiberg maneuver: with the patient lying supine, the examiner forcefully internally rotates the leg, stretching the piriformis muscle.
- The Pace maneuver: in the seated position, the patient abducts the hip against resistance, activating the piriformis muscle.
- The Beatty maneuver: lying on their side, the patient abducts the hip, activating the piriformis muscle.
- The FAIR (flexion, adduction, internal rotation) maneuver: with the patient lying supine, the examiner passively flexes, adducts, and internally rotates the hip, stretching the piriformis muscle. This maneuver is also reported to be useful in the EDX of piriformis syndrome (see below).

ELECTROPHYSIOLOGIC EVALUATION

The electrophysiologic evaluation plays a key role in the assessment of a possible sciatic neuropathy. The electrophysiologic approach is similar to the clinical approach: evaluate and exclude disorders that can mimic sciatic neuropathy, including peroneal palsy at the fibular neck, lumbosacral plexopathy, and lumbosacral radiculopathy (Table 33–2).

Nerve Conduction Studies

The nerve conduction evaluation of sciatic neuropathy is straightforward (Box 33–2). Routine peroneal and tibial motor studies should be performed bilaterally, recording the extensor digitorum brevis (EDB) and abductor hallucis brevis, respectively. Careful attention must be paid to the peroneal motor study, with the electromyographer looking for evidence of peroneal palsy at the fibular neck (either focal slowing or conduction block). In this regard, it is useful to perform peroneal motor studies recording the tibialis anterior as well as the extensor digitorum brevis. In sciatic nerve lesions with axonal loss, the amplitude of the peroneal or tibial compound muscle action potentials

Box 33–2. Recommended Nerve Conduction Study Protocol for Sciatic Neuropathy

Routine studies:

1. Tibial motor study, recording abductor hallucis brevis and stimulating medial ankle and popliteal fossa; bilateral studies
2. Peroneal motor study, recording extensor digitorum brevis and stimulating ankle, below fibular neck and lateral popliteal fossa; bilateral studies. In patients with an isolated footdrop and clinical findings limited to the distribution of the peroneal nerve, the study should be performed, recording the tibialis anterior and stimulating below fibular neck and lateral popliteal fossa, to increase the yield of demonstrating conduction block or focal slowing across the fibular neck.
3. Sural sensory study, stimulating posterior lateral calf, recording posterior ankle; bilateral studies
4. Superficial peroneal sensory study, stimulating lateral calf, recording lateral ankle; bilateral studies
5. Tibial and peroneal F responses; bilateral studies
6. H reflex; bilateral studies

Special consideration:

- In patients with suspected piriformis syndrome, consider comparing the H reflex latency between the normal anatomic and hip FAIR positions.

FAIR, flexion, adduction, and internal rotation.

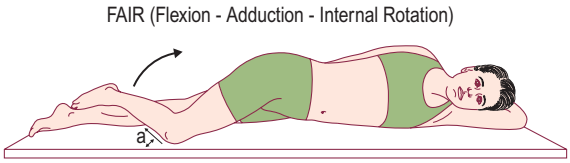

FIGURE 33–5 Flexion, adduction, and internal rotation (FAIR) position. Simultaneous downward pressure of the flexed knee and passive superolateral movement of the shin, with both acetabula oriented vertically, maximize adduction and internal rotation at the flexed thigh. The angle between the ground and flexed leg (a) should be 20 to 35 degrees.
(From Fishman, L.M., Zybert, P.A., 1992. Electrophysiological evidence of piriformis syndrome. Arch Phys Med Rehabil 73, 359–364.)

(CMAPs) may be reduced on the symptomatic side compared with normal control values or, more importantly, when compared with the contralateral asymptomatic leg. The peroneal fibers often are affected out of proportion to the tibial fibers. If there has been loss of the fastest conducting axons, there may be mild prolongation of the distal motor latency and some slowing of conduction velocity, but never into the demyelinating range.

Bilateral peroneal and tibial F responses and H reflexes should be obtained. In sciatic neuropathy, ipsilateral F wave responses may be prolonged compared with the contralateral side. In a sciatic nerve lesion, the H reflex may be prolonged or more difficult to elicit on the involved side. Although abnormal late responses place the lesion somewhere along the course of the nerve fibers being studied, the finding of prolonged or absent F and H responses cannot help in differentiating among a sciatic neuropathy, lumbosacral plexopathy, or radiculopathy. A proximal lesion is implied only if the distal conductions are normal.

Likewise, sensory nerve conduction studies must be performed bilaterally, comparing the superficial peroneal and sural sensory responses to the contralateral side. In sciatic neuropathy, both responses are expected to be abnormal, reflecting dysfunction of both the peroneal and tibial nerves. However, as noted earlier, the peroneal fibers are often the most affected.

Special Studies in Suspected Piriformis Syndrome

Most often, standard nerve conduction studies and needle EMG are normal in patients who are clinically diagnosed with piriformis syndrome. The one electrophysiologic test proposed to be of value is a modification of the H reflex. In piriformis syndrome, the H reflex is reported to be prolonged when performed with the hip in flexion, adduction, and internal rotation (FAIR test) compared to the normal anatomic position (Figure 33–5). This position stretches the piriformis muscle and theoretically may put pressure on the sciatic nerve.

In the largest reported study of this test, in patients with clinical criteria suggestive of piriformis syndrome, the mean prolongation of the H reflex in the FAIR position was 3.39 ms, which is equivalent to 5.45 standard deviations above the mean for a normal population. Compare this to the mean delay of the H reflex in 88 normal persons in the FAIR position compared to the anatomic position, which was 0.01 ms, with a standard deviation of 0.62 ms (Figure 33–6). However, the asymptomatic population was not normally distributed. Using a cutoff of 3 standard deviations (1.86) resulted in a specificity of 83% (i.e., 17% of a normal control population would be misidentified as abnormal). In addition, the contralateral, asymptomatic limbs of the patient group often demonstrated abnormalities, although they were less marked than in the symptomatic limbs.

The authors have little personal experience with the FAIR test. Other so-called dynamic nerve conduction tests generally fail to increase the yield of abnormalities in entrapment neuropathies (e.g., flexing the wrist in carpal tunnel syndrome while performing median nerve conduction studies), although this is not always true. In addition, the H reflex is well known to be affected by a variety of variables, including body and especially head position. Because the circuitry of the H reflex traverses the spinal cord, it can be modified by a variety of suprasegmental facilitatory and inhibitory inputs. For instance, the Jendrassik (reinforcement) maneuver is commonly used to "prime" the anterior horn cells and is of use in the EMG laboratory to elicit H reflexes. Presumably, head position can modify the H reflex by activating the vestibulospinal tracts. *The take-home message is the following: if the FAIR test is used in patients with suspected piriformis syndrome, ensure that other variables are held constant, especially the head and body positions; and remember the possibility of false-positive results, given the distribution of the values from a control population.*

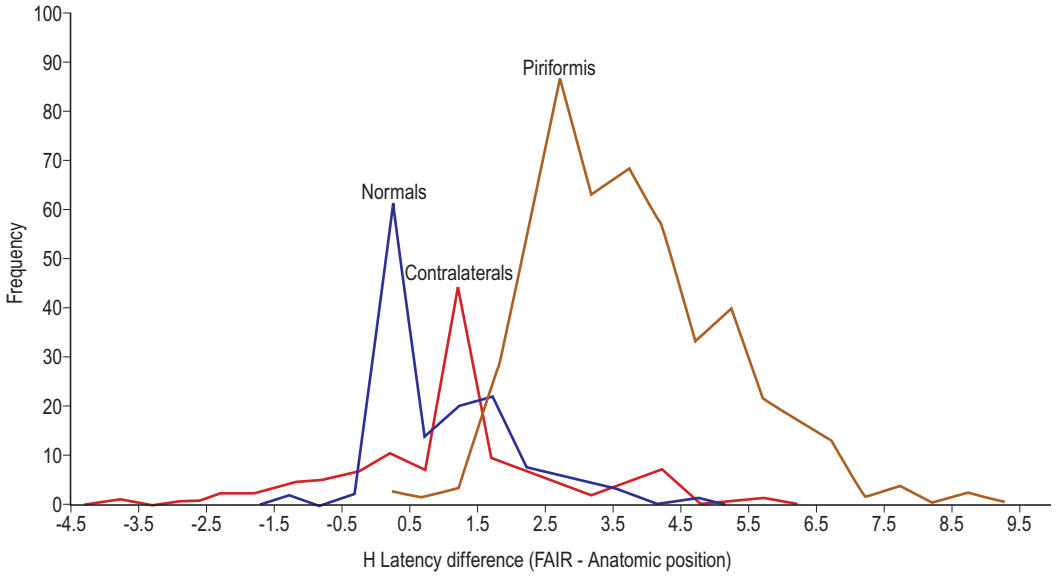

FIGURE 33–6 H latency differences (ms) between the flexion, adduction, and internal rotation (FAIR) and anatomic positions. H latency differences between the FAIR and anatomic positions in patients with clinical piriformis syndrome, in limbs contralateral to the clinical piriformis syndrome legs, and in normals are compared.
(From Fishman, L.M., Dombi, G.W., Michaelsen, C., et al., 2002. Piriformis syndrome: diagnosis, treatment, and outcome – a 10-year study. Arch Phys Med Rehabil 83, 295–301.)

Electromyographic Approach

After the nerve conduction studies are completed, EMG is used to further localize the lesion and assess its severity (Box 33–3). First, muscles innervated by the deep and superficial peroneal nerves should be sampled (e.g., tibialis anterior, extensor hallucis longus, peroneus longus). Abnormalities in these muscles are consistent with a lesion of the peroneal nerve, sciatic nerve, lumbosacral plexus, or L5–S1 nerve roots. Next, tibial-innervated muscles in the calf should be sampled, including the medial gastrocnemius and especially the tibialis posterior or flexor digitorum longus. If abnormalities are found in any of these muscles, as well as in the peroneal-innervated muscles, an isolated lesion of the peroneal nerve has been excluded. The differential at this point includes a lesion of both the tibial and peroneal nerves versus a lesion of either the sciatic nerve, lumbosacral plexus, or L5–S1 nerve roots.

Next, the hamstring muscles need to be sampled. The short head of the biceps femoris has an important role, being the only muscle supplied by the peroneal division of the sciatic nerve that originates above the fibular neck. The short head of the biceps can easily be sampled four fingerbreadths above the lateral knee, just medial to the long head of the biceps femoris tendon. Abnormalities found in the short head of the biceps femoris muscle exclude an isolated lesion of the peroneal nerve at the fibular neck and imply a more proximal lesion. After examination of the hamstring muscles, the gluteal muscles should be checked. Both the gluteus maximus (inferior gluteal nerve) and either the gluteus medius or tensor fascia latae (superior gluteal nerve) should be checked. If abnormalities are found in any of these muscles, an isolated sciatic neuropathy is excluded, and the differential diagnosis at this point is restricted to a lesion of the lumbosacral plexus or the L5–S1 nerve roots. Next, the L5 and S1 paraspinal muscles must be sampled to look for abnormalities at or proximal to the root level. Lastly, if any of the muscles studied during the needle EMG examination show borderline or equivocal abnormalities, comparison to the contralateral side is indicated.

Box 33–3. Recommended Electromyographic Protocol for Sciatic Neuropathy

Routine muscles:

1. At least two peroneal-innervated muscles (tibialis anterior, extensor hallucis longus, peroneus longus)
2. At least two tibial-innervated muscles (medial gastrocnemius, tibialis posterior, flexor digitorum longus)
3. Short and long heads of the biceps femoris
4. At least one superior gluteal-innervated muscle (gluteus medius, tensor fascia latae)
5. At least one inferior gluteal-innervated muscle (gluteus maximus)
6. L5 and S1 paraspinal muscles
7. At least two non-sciatic, non-L5–S1-innervated muscles (vastus lateralis, iliacus, thigh adductors) to exclude a more widespread lesion

Special consideration:

- If motor unit action potential abnormalities are borderline or equivocal, comparison should be made to the contralateral side.

It is important to emphasize that the EMG study can only localize a lesion at or proximal to the most proximal abnormal muscle sampled. For instance, in examining the hamstring muscles, if the semitendinosus muscle is abnormal and the semimembranosus muscle is normal, one would be tempted to assume that the sciatic nerve lesion lies between these two sites. The situation is not that simple, however. It is well known from evaluation of various compressive neuropathies that fascicles to certain muscles can be preferentially affected, whereas others are preferentially spared. Thus, in the earlier example, the lesion could even be at the level of the nerve roots, sparing fascicles to the semimembranosus. Accordingly, EMG can be used only to identify a lesion at or proximal to the most proximal muscle involved.

The classic electrophysiologic picture of sciatic neuropathy is reduced tibial and peroneal motor amplitudes compared with the contralateral side, with normal or slightly prolonged distal motor latencies and normal or slightly slowed conduction velocities. The tibial and peroneal F responses are prolonged or absent on the symptomatic side, with similar findings for the H reflex. Both the sural and superficial peroneal sensory nerves are reduced in amplitude or absent with normal potentials on the contralateral asymptomatic side. Needle EMG findings show active denervation or reinnervation with reduced recruitment of motor unit action potentials (MUAPs) in muscles supplied by (1) the sciatic nerve in the thigh, (2) the peroneal nerve, and (3) the tibial nerve, but with sparing of the gluteal, tensor fascia latae, and lumbosacral paraspinal muscles. In both the nerve conduction and needle EMG studies, the peroneal fibers are involved more often than the tibial fibers.

EXAMPLE CASE

Case 33–1

History and Physical Examination

A 52-year-old woman was referred for further evaluation of a persistent left footdrop. She described her condition as having begun slowly 6 months previously. She initially noted a sensation of numbness over the top of the foot and the lateral calf. This was followed shortly thereafter by her left foot dropping. During the last 2 months, symptoms slowly progressed to a nearly complete footdrop. More recently, she noted a sensation of tightness and pain from her hip down to her knee and into her calf.

An orthopedic consultant advised MRI scanning of the knee to evaluate the peroneal nerve. The scan was obtained and was unremarkable. She subsequently underwent MRI scanning of the lumbar spine to look for a possible L5 radiculopathy as the cause of her footdrop. The scan was obtained and was unremarkable. Past history was notable for a left hip fracture with surgical repair 3 years previously.

On examination, there was atrophy of the anterior compartment of the left leg and wasting of the left EDB muscle. In the left lower extremity there was a complete footdrop. Toe and ankle dorsiflexion were 1/5, as was ankle eversion. Ankle inversion also was weak (4/5). In addition, toe flexion was slightly but definitely weak, as was knee flexion. Knee extension was normal. Hip flexion, extension, abduction, and adduction were completely normal. Strength testing was completely normal in the right lower extremity. Deep tendon reflexes were

CASE 33–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F-wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Peroneal (m)	Ankle	EDB	5.3	2.2	≥2	5.4	5.8	≤6.5				52	55	≤56
	Below fibula	EDB	4.9	2.1		11.4	12.6		50	44	≥44			
	Lateral popliteal fossa	EDB	4.8	2.1		13.5	14.8		48	45	≥44			
Peroneal (m)	Below fibula	TA	6.7	3.1	≥3	4.5	4.7							
	Lateral popliteal fossa	TA	6.5	2.9		7.4	7.7		49	46	≥44			
Tibial (m)	Ankle	AHB	6.2	3.7	≥4	4.8	5.8	≤5.8				51	56	≤56
	Popliteal fossa	AHB	5.4	3.1		11.3	13.1		46	41	≥41			
Sural (s)	Calf	Posterior ankle	13	6	≥6	4.1	4.3	≤4.4	50	48	≥40			
Peroneal (s)	Lateral calf	Lateral ankle	9	NR	≥6	4.1	NR	≤4.4	52	NR	≥40			
H reflex	Popliteal fossa	Soleus				29.4	NR	≤34						

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; NR = no response; EDB = extensor digitorum brevis; TA = tibialis anterior; AHB = abductor hallucis brevis.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 33–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Left tibialis anterior	↑	+2	0	NL	↓↓	+2	+1	+2
Left extensor hallucis longus	↑	+2	0	NL	↓↓	+2	+2	+1
Left peroneus longus	↑	+1	0	NL	↓↓	+1	+1	+1
Left medial gastrocnemius	NL	0	0	NL	NL	NL	NL	NL
Left tibialis posterior	↑	+2	0	NL	↓↓	+2	+1	+1
Left biceps femoris (short head)	↑	+2	0	NL	↓	+2	+2	+1
Left biceps femoris (long head)	↑	0	0	NL	↓	NL/+1	NL/+1	+1
Left semitendinosus	NL	0	0	NL	NL	NL	NL	NL
Left gluteus medius	NL	0	0	NL	NL	NL	NL	NL
Left gluteus maximus	NL	0	0	NL	NL	NL	NL	NL
Left vastus lateralis	NL	0	0	NL	NL	NL	NL	NL
Left iliacus	NL	0	0	NL	NL	NL	NL	NL
Left L5 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Left S1 paraspinal	NL	0	0	NL	NL	NL	NL	NL

↑ = increased; ↓ = slightly reduced; ↓↓ = moderately reduced; NL = normal.

2+ and symmetric in the upper extremities and 2+ at the knees and right ankle. The left ankle jerk was absent. Toes were downgoing. There was a clear sensory disturbance to light touch on the top of the foot, lateral foot and calf, lateral knee, and posterior calf on the left side. Sensation over the medial calf, anterior thigh, lateral thigh, posterior thigh, and sole of the foot was intact. There was a well-healed surgical scar over the left lateral thigh.

Summary

The initial clinical presentation is that of a footdrop with numbness over the dorsum of the foot and lateral calf. Most often, this clinical picture is the result of a peroneal neuropathy at the fibular neck. However, an early sciatic neuropathy, lumbosacral plexopathy, or lumbosacral radiculopathy (especially L5) can present in a similar fashion. The slowly progressive nature of the symptoms suggests a slowly expanding or infiltrating structural lesion. As the symptoms progressed, the patient noted a sensation of tightness and pain from the hip toward the knee into the calf. These additional symptoms would be unusual for a peroneal palsy at the fibular neck and are suggestive of a more proximal lesion. MRI scanning obtained at the usual sites of compression causing a footdrop (the fibular neck and lumbar spine) did not demonstrate any abnormality and led to further evaluation and eventually an EMG study.

Neurologic examination showed severe weakness and atrophy in the distribution of the deep and superficial peroneal nerves (ankle and toe dorsiflexion, ankle eversion). Ankle inversion (tibialis posterior) and toe flexion (flexor digitorum longus), both of which are subserved by non-peroneal-innervated L5 muscles, were also weak. In addition, there was weakness of knee flexion, which is subserved by the sciatic nerve. These findings place the lesion at or proximal to the sciatic nerve. Further testing

of muscles innervated by the femoral, superior gluteal, inferior gluteal, and obturator nerves were normal. The absence of abnormalities in these muscles on clinical examination suggested that a more widespread lesion of the lumbosacral plexus or nerve roots was unlikely. Of course, early in any lesion, it may be difficult to demonstrate subtle weakness of the proximal limb muscles.

Moving on with the clinical examination, the left ankle reflex was absent, signifying a lesion somewhere along that reflex loop, in the tibial nerve, sciatic nerve, lumbosacral plexus, or lumbosacral nerve roots. Lastly, the sensory disturbance involved not only the distribution of the peroneal nerve but also the territories of the sural nerve and the lateral cutaneous nerve of the knee. Normal sensation was found in the medial calf, innervated by the saphenous nerve, the anterior thigh, innervated by the femoral nerve, the lateral thigh, innervated by the lateral cutaneous nerve of the thigh, and the posterior thigh, innervated by the posterior cutaneous nerve of the thigh. This distribution of sensory abnormalities again suggests a lesion at or proximal to the sciatic nerve. However, note that the entire sciatic sensory territory was not involved because sensation on the sole of the foot was spared (innervated by the plantar nerves).

Before proceeding to the nerve conduction study and EMG findings, the clinical history of a slowly progressive deficit, along with the neurologic examination as described, should suggest a slowly expanding or infiltrating structural lesion affecting the sciatic nerve, the lumbosacral plexus, or the lumbosacral roots. The history of prior hip surgery should suggest a likely connection between the surgery and a possible sciatic nerve palsy.

Reviewing the nerve conduction studies first, the motor nerve conduction studies in the left leg are abnormal, with borderline low CMAP amplitudes for both the peroneal and tibial motor studies. Furthermore, a clear asymmetry is seen when the potentials are compared with those from the contralateral, asymptomatic side. The tibial distal motor latency, minimum F response latency, and tibial and peroneal conduction velocities are slightly slowed. However, the amount of slowing is mild, within the range of axonal loss. Of note, there is no focal drop in amplitude or focal conduction velocity slowing in the peroneal nerve around the fibular neck. Note that for the peroneal motor studies, both the extensor digitorum brevis and tibialis anterior muscles were recorded. There are some cases of peroneal neuropathy at the fibular neck wherein conduction block and/or slowing is only seen when recording the tibialis anterior.

Moving next to the sensory nerve conduction studies, both the sural and superficial peroneal sensory studies are abnormal on the symptomatic side compared with the normal findings on the contralateral side. The superficial peroneal response is absent, whereas the sural response is only borderline low, reflecting greater involvement of peroneal, compared to tibial, nerve fibers. Finally, on the nerve conduction studies, the H reflex is absent on the ipsilateral side, corresponding to the absent ankle reflex on the clinical examination.

Thus, at the conclusion of the nerve conduction studies, there is a good clinical–electrophysiologic correlation. The muscle atrophy and weakness seen on clinical examination correspond to the low CMAP amplitudes on the peroneal and tibial motor studies. Likewise, the areas of sensory loss on clinical examination correspond to the distribution of reduced sensory nerve action potentials. Both clinical examination and electrophysiologic studies demonstrate that the peroneal nerve fibers are more involved than the tibial.

Moving next to the needle EMG study, there is marked active denervation and reinnervation in muscles innervated by the superficial and deep peroneal nerves. These prominent abnormalities correspond to the patient's clinical symptoms of footdrop. In contrast, the medial gastrocnemius (tibial nerve innervated) is normal. However, the tibialis posterior, another tibial-innervated muscle, shows fibrillation potentials and large polyphasic MUAPs with decreased recruitment. These findings provide further evidence that the abnormalities are beyond the peroneal nerve territory and must be due to either separate lesions of the tibial and peroneal nerves or a more proximal lesion.

Next, the short head of the biceps femoris is sampled. This muscle assumes special significance on the EMG examination because it is the only peroneal-innervated muscle that originates above the fibular neck. This muscle is normal in peroneal palsy at the fibular neck, but it may be abnormal in lesions at or proximal to the sciatic nerve. In this case, the short head of the biceps femoris has fibrillation potentials with reduced recruitment of large polyphasic MUAPs. Similar but less marked findings are found in the long head of the biceps femoris. The semitendinosus muscle, which is also innervated by the sciatic nerve, is normal. No abnormalities are found in the more proximal hip girdle muscles, which are innervated by the superior and inferior gluteal nerves (gluteus medius and maximus). Similarly, muscles innervated by the femoral nerve (vastus lateralis and iliacus) and the L5 and S1 paraspinal muscles are normal. At this point, we are ready to formulate our electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are consistent with a severe sciatic neuropathy at or proximal to the takeoff to the biceps femoris.*

Although the patient's initial symptoms suggested a simple peroneal palsy at the fibular neck, the subsequent clinical findings suggested a more proximal lesion, which was then confirmed with nerve conduction study and EMG findings. The abnormal sensory conduction studies mark the lesion as at or distal to the dorsal root ganglion, which is inconsistent with a disorder of the L5 or S1 nerve roots. Because both the superficial peroneal and sural sensory responses were abnormal, the lesion must be in the tibial and peroneal nerves, the sciatic nerve, or the

lumbosacral plexus. The needle EMG findings also demonstrated abnormalities outside the peroneal distribution, involving the tibial and distal sciatic nerves. Several important questions can be addressed at this point.

Can the Lesion be Localized between the Biceps Femoris and the Semitendinosus?

The most proximal abnormal muscle is the biceps femoris (short and long heads). Although one may be tempted to definitely state that the sciatic nerve lesion is between the semitendinosus, which was normal on the needle examination, and the biceps femoris, which was abnormal, such a conclusion cannot be reached. It is well known from studying other compressive neuropathies that individual fascicles to certain muscles can be preferentially affected, whereas others are spared. In this case, one cannot exclude a sciatic nerve lesion proximal to, although sparing, the fibers to the semitendinosus. Furthermore, although the present study is most consistent with a sciatic nerve lesion, one cannot definitively exclude an unusual lumbosacral plexopathy, which may spare the gluteal muscles or may not yet be severe enough to show axonal loss in the gluteal muscles.

What is the Most Likely Clinical Diagnosis

Although the prior hip surgery suggests a possible sciatic lesion adjacent to the site of the surgery, the slowly progressive nature of the clinical presentation is worrisome for an expanding or infiltrating mass lesion, such as a tumor. Of course, the possibility of methylmethacrylate cement from the hip replacement forming spurs and then slowly eroding into the nerve must be considered in this context. The combination of the clinical history, neurologic examination, and electrodiagnostic studies provides a basis for imaging studies that now can be done in a more intelligent manner. In this case, subsequent MRI scanning of the left thigh showed a large enhancing lesion of the sciatic nerve in the mid-thigh. A subsequent biopsy revealed large cell lymphoma (see Figure 33–3).

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Neuromuscular Junction Disorders 34

Disorders affecting the neuromuscular junction (NMJ) are among the most interesting and rewarding seen in the electromyography (EMG) laboratory. These disorders are generally pure motor syndromes that usually preferentially affect proximal, bulbar, or extraocular muscles. They are confused occasionally with myopathies. With knowledge of normal NMJ physiology (see Chapter 6), most of the abnormalities affecting the NMJ can be differentiated using a combination of nerve conduction studies, repetitive stimulation, exercise testing, and needle EMG.

NMJ disorders can be classified into immune-mediated, toxic or metabolic, and congenital syndromes (Box 34–1). They usually are distinguished by their clinical and electrophysiologic findings (Tables 34–1 and 34–2). All are uncommon, but among them, myasthenia gravis (MG) and Lambert–Eaton myasthenic syndrome (LEMS) are the disorders most often encountered in the EMG laboratory. Both are immune-mediated disorders. In MG the autoimmune attack is postsynaptic; in LEMS the presynaptic membrane is the target of attack. Every electromyographer must understand the electrophysiology of these disorders so that appropriate electrodiagnostic tests can be applied and the correct diagnosis not overlooked.

Box 34–1. Disorders of the Neuromuscular Junction

Immune-Mediated Disorders
- Myasthenia gravis
- Lambert–Eaton myasthenic syndrome

Toxic/Metabolic Disorders
- Botulism
- Snake venom poisoning
- Arthropod venom poisoning (e.g., from a black widow spider)
- Organophosphates, insecticide poisoning (e.g., as from malathion, parathion)
- Hypermagnesemia

Congenital Myasthenic Syndromes
- Presynaptic:
  - Defective synthesis or packaging of acetylcholine
    - Genes for choline acetyltransferase (ChAT)
    - Paucity of synaptic vesicles
    - Lambert–Eaton-like CMS
- Synaptic:
  - Deficiency of collagenic tail of acetylcholinesterase
- Postsynaptic:
  - Quantitative deficiency of acetylcholine receptors
    - Rapsyn
    - DOK-7
  - Kinetic abnormalities of acetylcholine receptors
    - Slow channel syndrome
    - Fast channel syndrome
  - Anomaly of muscle Na^+ channel
- Other
  - Myasthenic syndrome with plectin deficiency
  - No identified defect

MYASTHENIA GRAVIS

MG, the best understood of all the autoimmune diseases, is caused by an immunoglobulin G (IgG)-directed attack on the NMJ, aimed specifically at the nicotinic

Table 34–1. Clinical Characteristics of Neuromuscular Junction Disorders

Disorder	Temporal onset	Ocular Sx	Bulbar Sx	Reflexes	Autonomic Sx	Sensory Sx	GI Sx
Myasthenia gravis	Subacute	+	+	Normal*	–	–	–
Lambert–Eaton myasthenic syndrome	Subacute	+/–	+/–	Reduced	+/–	+/–	–
Botulism	Acute	+	+	Normal*	+	–	+
Congenital myasthenia	Congenital or pediatric	+	+/–	Normal*	–	–	–

Sx = symptoms/signs; GI = gastrointestinal; + = commonly present; +/– = may be seen occasionally; – = usually not present.
*May be reduced in proportion to the degree of muscle weakness.

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Table 34–2. Electrophysiologic Characteristics of Neuromuscular Junction Disorders

Disorder	Compound Muscle Action Potential Amplitude at Rest	Decrement: 3 Hz	Increment: 50 Hz	SF-EMG	Repetitive Compound Muscle Action Potential	Electromyography: Fibrillation Potentials/Positive Waves	Electromyography: Motor Unit Action Potential
Myasthenia gravis	Normal	+	–	Increased jitter/ blocking	–	–	Normal/SSP
Lambert–Eaton myasthenic syndrome	Decreased	+	+	Increased jitter/ blocking	–	–	Normal/SSP
Botulism	Decreased	+	+ (unless severe blocking)	Increased jitter/ blocking	–	+	Normal/SSP
Congenital myasthenia	Normal	+*	–	Increased jitter/ blocking	+*	–	Normal/SSP

+ = commonly seen; – = usually not present; +* = may be present in some of the syndromes; SSP small, short, polyphasic; SF-EMG, single-fiber electromyography.

acetylcholine (ACH) receptor in the vast majority of cases. The role of these anti-acetylcholine receptor antibodies as the cause of MG has been proved through a variety of experimental steps: (1) antibodies are present in the serum of most patients with MG; (2) antibodies passively transferred to animals produce experimental myasthenia; (3) removal of antibodies allows recovery; and (4) immunization of animals with ACH receptors produces antibodies and can provoke an autoimmune disease that closely resembles the naturally occurring disease.

The mechanism of antibody damage to the ACH receptor and postsynaptic membrane involves several steps. First, binding of the antibody to the receptor can directly block the binding of ACH. Second, there is a complement-directed attack, with destruction of the ACH receptor and postjunctional folds. Last, antibody binding can result in an increase in the normal removal of ACH receptors from the postsynaptic membrane (modulation). Thus, although the amount of ACH released is normal, there is reduced binding of ACH to the ACH receptor, resulting in a smaller end-plate potential and a reduced safety factor of NMJ transmission.

A subset of patients with MG clinically (approximately 8–15%) will not demonstrate antibodies to ACHR (so-called "seronegative" cases). In this subset, however, approximately 40–50% will have an antibody to muscle-specific tyrosine kinase (MuSK). MuSK is a surface receptor that is involved in the clustering of ACHRs during development.

Clinical

Patients with MG present with muscle fatigue and weakness. Because the disorder is limited to the NMJ, there is no abnormality of mental state or sensory or autonomic function. Myasthenic weakness characteristically affects the extraocular, bulbar or proximal limb muscles. Eye findings are the most common, with ptosis and extraocular muscle weakness occurring in more than 50% of patients at the time of presentation and developing in more than 90% of patients sometime during their illness. Extraocular weakness frequently begins asymmetrically, with one eye involved and the other spared. A very small degree of extraocular weakness is experienced by the patient as visual blurring or double vision. Myasthenic weakness has been known to mimic third, fourth, and sixth nerve palsies and, rarely, an intranuclear ophthalmoplegia. Unlike true third nerve palsies, however, MG never affects pupillary function. Fixed extraocular muscle weakness may occur late in the illness, especially if untreated.

Bulbar muscle weakness is next most common after extraocular weakness. This may result in difficulty swallowing, chewing, and speaking. Patients may develop fatigability and weakness of mastication, with the inability to keep the jaw closed after chewing. Myasthenic speech is nasal (from weakness of the soft palate) and slurred (from weakness of the tongue, lips, and face) but without any difficulty with fluency. Weakness of the soft palate may also result in nasal regurgitation (i.e., liquid coming out the nose when drinking). When myasthenic patients develop limb weakness, it usually is symmetric and proximal. Patients note difficulty getting up from chairs, going up and down stairs, reaching with their arms, or holding up their head. Rare patients present with an isolated limb-girdle form of MG and never develop eye movement or bulbar muscle weakness. It is these patients who are most often misdiagnosed with myopathy.

In contrast to the clinical syndrome seen in MG with anti-ACHR antibodies, the clinical characteristics of anti-MuSK MG include female predominance, prominent bulbar, neck, shoulder and respiratory involvement, and a severe presentation that occurs at a younger age than MG with anti-ACHR antibodies. Three clinical patterns are present in anti-MuSK MG: (1) severe oculobulbar

weakness along with tongue and facial atrophy, (2) marked neck, shoulder, and respiratory weakness with little or no ocular weakness, and (3) a pattern similar to anti-ACHR antibody MG. In addition, patients with anti-MuSK MG are often unresponsive or intolerant to cholinesterase inhibitors, and some have actually worsened.

The distinguishing clinical feature of MG, whether seropositive (ACHR or MuSK) or seronegative, is pathologic fatigability (i.e., muscle weakness that develops with continued use). Patients improve after rest or upon rising in the morning and worsen as the day proceeds. Although generalized fatigue is common in many neurologic and nonneurologic disorders, NMJ fatigue is limited to muscular fatigue alone, which progresses to frank muscle weakness with use. Patients with MG do not generally experience a sense of mental fatigue, tiredness, or sleepiness.

The clinical examination in a patient suspected of having MG is directed at examining muscular strength and demonstrating pathologic fatigability. To demonstrate subtle weakness, it is helpful to observe the patient performing functional tasks, such as rising from a chair or from the floor or walking, rather than relying on manual muscle strength testing alone. Pathologic fatigability may be demonstrated by having the patient look up for several minutes (to determine if ptosis or extraocular weakness is present), count aloud to 100 (to determine if nasal or slurred speech is present), or by repetitively testing the neck or the proximal limb muscles (for example, with both shoulders abducted, the examiner repetitively pushes down on both arms several times, looking for fatigable weakness). In patients with ptosis, the ice bag test can be very helpful. Ice is applied over the forehead for several minutes to cool the underlying muscles. In MG, ptosis may improve markedly with cooling. The remainder of the neurologic examination should be normal. Deep tendon reflexes are generally preserved or, if reduced, are reduced in proportion to the degree of muscle weakness.

Most patients with MG have generalized disease. However, as many as 15% of patients have the restricted ocular form of the disease. In these patients, myasthenic symptoms remain restricted to the extraocular and eyelid muscles. When a patient first presents with fluctuating extraocular weakness, it is impossible to predict from either clinical or laboratory testing which patients subsequently will generalize and which will remain with relatively benign restricted ocular symptoms. If a patient's symptoms remain restricted to the ocular muscles for one to two years, however, there is a high probability that the myasthenia will never generalize and will remain restricted to the extraocular and eyelid muscles.

Autoimmune MG may be seen in two other groups of patients aside from those with idiopathic autoimmune myasthenia. First, transient neonatal MG may occur in babies born to mothers with MG. This occurs when maternal autoantibodies pass through the placenta, resulting in the same clinical syndrome in newborn infants. The illness usually is mild and self-limited and disappears after the first few months of life as the maternal antibodies are degraded.

MG also may be seen in patients treated with penicillamine. The clinical syndrome is similar to idiopathic MG, including the presence of anti-acetylcholine receptor antibodies, except that most patients slowly improve once the penicillamine has been discontinued.

Electrophysiologic Evaluation

Like other disorders affecting the NMJ, the electrophysiologic evaluation of MG involves routine nerve conduction studies, repetitive nerve stimulation (RNS), exercise testing, routine EMG, and, in some cases, single-fiber EMG (SF-EMG) (Box 34–2).

Nerve Conduction Studies

In any patient suspected of having MG, routine motor and sensory nerve conduction studies cannot be omitted. At least one motor and sensory conduction study should be performed in an upper and lower extremity, but the number of nerves studied often depends on the clinical context. Particular attention must be paid to compound muscle action potential (CMAP) amplitudes. Normal CMAP

Box 34–2. Electrophysiologic Evaluation of Myasthenia Gravis

1. **Routine motor and sensory nerve conduction studies.** Perform routine motor and sensory nerve conduction studies, preferably a motor and sensory nerve in one upper and one lower extremity. CMAP amplitudes should be normal. If CMAP amplitudes are low or borderline, repeat distal stimulation immediately after 10 seconds of exercise to exclude a presynaptic NMJ transmission disorder (e.g., Lambert–Eaton myasthenic syndrome).
2. **Repetitive nerve stimulation (RNS) and exercise testing.** Perform slow RNS (3 Hz) on at least one proximal and one distal motor nerve. Always try to study weak muscles. If any significant decrement (>10%) is present, repeat to ensure decrement is reproducible. If there is no significant decrement at baseline, exercise the muscle for 1 minute, and repeat RNS at 1, 2, 3, and 4 minutes looking for a decrement, secondary to post-exercise exhaustion. If at any time a significant decrement is present (at baseline or following post-exercise exhaustion), exercise the muscle for 10 seconds and immediately repeat RNS, looking for post-exercise facilitation (repair of the decrement).
3. **Needle electromyography (EMG).** Perform routine needle EMG of distal and proximal muscles, especially weak muscles. Patients with moderate to severe myasthenia gravis may display unstable or short, small, polyphasic motor unit action potentials. Recruitment is normal or early. Needle EMG must exclude severe denervating disorders or myotonic disorders, which may display an abnormal decrement on RNS.
4. **Single-fiber EMG (SF-EMG).** If the above are normal or equivocal in a patient strongly suspected of having myasthenia gravis, perform SF-EMG in the extensor digitorum communis and, if necessary, one other muscle, looking for jitter and blocking. It is always best to study a weak muscle. Normal SF-EMG in a clinically weak muscle excludes an NMJ disorder.

CMAP, compound muscle action potential; NMJ, neuromuscular junction.

amplitudes are an important and expected finding in MG, in direct contrast to LEMS, where baseline CMAPs usually are diffusely low. In only a small number of patients with MG (3–15%), the baseline CMAPs at rest are below the normal range.

Routine nerve conduction studies also must be performed to ensure the integrity of any nerve that subsequently will be used for RNS. A decrement on RNS can be seen in various denervating conditions (e.g., neuropathies, motor neuron disorders, inflammatory myopathies) and myotonic disorders, in addition to primary disorders of the NMJ. For instance, a decrement on RNS of the ulnar nerve may be seen in a severe ulnar neuropathy with denervation; such a finding in this context does not imply a primary NMJ disorder.

Repetitive Nerve Stimulation

After the routine nerve conduction studies are completed, RNS studies are performed (see Chapter 6). These studies are abnormal in more than 50 to 70% of patients with generalized MG but often are normal in patients with the restricted ocular form of MG. A decremental response on RNS is the electrical correlate of clinical muscle fatigue and weakness. In normal subjects, slow RNS (3 Hz) results in little or no decrement of the CMAP, whereas in MG, a CMAP decrement of 10% or more is characteristically seen (Figure 34–1A). Both distal and proximal nerves should be tested. Although distal nerves are technically easier to study, the diagnostic yield increases with stimulation of proximal nerves (e.g., spinal accessory or facial nerves). This is not unexpected, because the proximal muscles usually are much more involved clinically than the distal ones. Facial RNS is especially important to perform in suspected anti-MuSK MG, where the yield of finding an abnormal decrement is much higher when examining a facial muscle than a limb muscle (probably reflecting the severe facial and bulbar involvement in some patients with anti-MuSK MG).

Exercise Testing

Exercise testing should be routinely used with all RNS studies (see Chapter 6). If there is no significant decrement on RNS studies at baseline (<10% decrement), the patient should perform 1 minute of exercise, followed by RNS at 1-minute intervals for the next 3 to 4 minutes, looking for a CMAP decrement secondary to post-exercise exhaustion. If at any time, either at baseline or following exercise, a significant decrement develops, the patient should perform a brief 10-second maximum isometric contraction, immediately followed by slow RNS, looking for an increment in the CMAP and "repair" of the decrement secondary to post-exercise facilitation (Figure 34–1).

Electromyography

Every patient evaluated for a possible NMJ disorder should have routine needle EMG performed, paying particular attention to weak muscles. EMG examination is done for two reasons. First, and most important, severe denervating disorders (e.g., motor neuron disease, polyneuropathy, inflammatory myopathy) and myotonic disorders need to be excluded because they also can show a decremental CMAP response on RNS. Second, the needle examination may demonstrate motor unit action potential (MUAP) abnormalities suggestive of an NMJ disorder: unstable MUAPs; small, short-duration MUAPs similar to myopathic motor unit action potentials; or both.

Unstable MUAPs (see Chapter 15) occur when individual muscle fibers are either blocked or come to action potential at varying intervals, which leads to MUAPs that change in configuration from impulse to impulse. If some

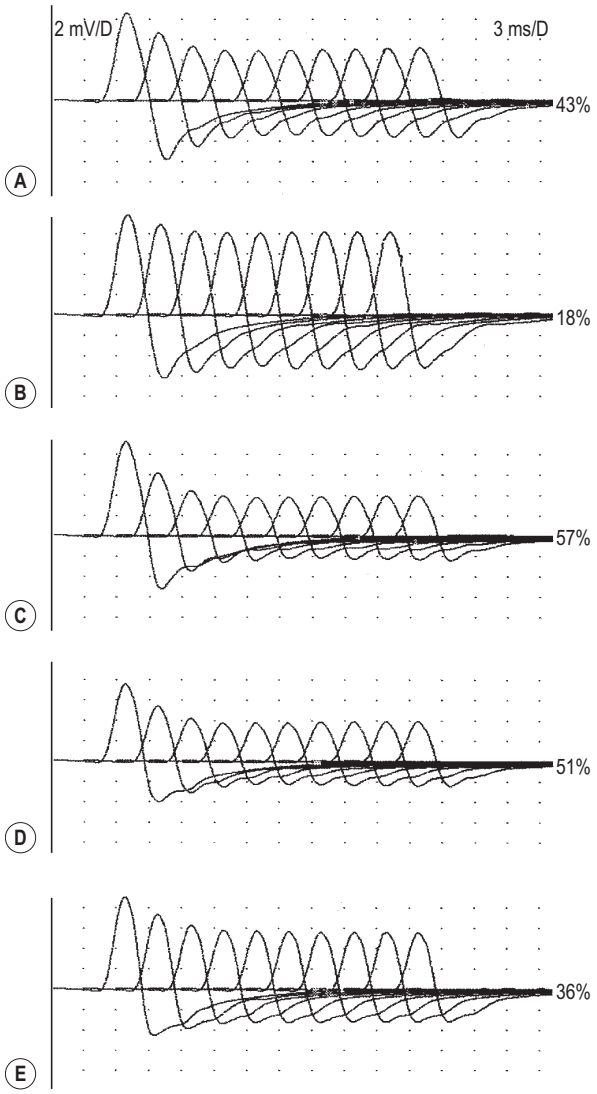

FIGURE 34–1 Repetitive nerve stimulation (3 Hz) in myasthenia gravis. Stimulating the ulnar nerve at the wrist, recording the first dorsal interosseous. Maximal decrement noted to right of traces. **A:** Baseline. **B:** Immediately after 10 seconds of exercise (post-exercise facilitation). **C, D:** Two and 3 minutes after 60 seconds of exercise (post-exercise exhaustion). **E:** Immediately after 10 seconds of exercise again (post-exercise facilitation and repair of the decrement).

muscle fibers of a motor unit are blocked and never come to action potential, the motor unit effectively loses muscle fibers, becoming short, small, and polyphasic, similar to MUAPs seen in myopathy. Otherwise, the needle EMG findings in NMJ disorders usually are normal. In general, fibrillation potentials and other abnormal spontaneous activity are not seen in NMJ disorders, with the important exception of botulism (see section on Botulism).

Single-fiber Electromyography

When a motor axon is depolarized, the action potential normally travels distally and excites all the muscle fibers within that motor unit at more or less the same time (Figure 34–2). This variation in the time interval between the firing of adjacent single muscle fibers from the same motor unit is termed jitter and primarily reflects variation in NMJ transmission time. If the NMJ is compromised, the time it takes for the endplate potential to reach threshold is prolonged, which results in greater-than-normal variation between firing of adjacent muscle fibers. If the prolongation is severe enough, the muscle fiber may never reach action potential, resulting in blocking of the muscle fiber.

SF-EMG is used to measure the relative firing of adjacent single muscle fibers from the same motor unit and can detect both prolonged jitter as well as blocking of muscle fibers. It is important to note that, whereas the clinical correlate of blocking is muscle weakness, there is no clinical correlate to increased jitter. Thus, the main advantage of SF-EMG over RNS is that the single-fiber study may be abnormal, showing increased jitter, even in patients without overt clinical weakness. In contrast, for RNS studies to be abnormal, the NMJ disorder must be sufficiently severe that blocking (the electrophysiologic correlate of weakness) also occurs, leading to a decremental response.

SF-EMG is best reserved for those electromyographers who are well trained in its use and who perform SF-EMG on a routine basis. It is a technically demanding procedure for both the patient and the electromyographer. In contrast to routine EMG, usually only one or two muscles are studied. Often, the extensor digitorum communis muscle in the forearm is selected for study. For most patients, this muscle can be steadily activated for a prolonged period and is relatively free of age-related changes. In addition, studying a clinically involved muscle is always useful. A normal single-fiber examination of a clinically weak muscle effectively rules out the diagnosis of MG.

The goal of SF-EMG is to study two adjacent single muscle fibers, known as a pair, from the same motor unit. This is accomplished by changing the filters on the EMG machine and using a specialized SF-EMG needle. The low-frequency filter (high-pass) is increased to 500 Hz (normally 10 Hz in routine EMG). By using a high-pass filter of 500 Hz, the amplitudes of distant muscle fiber potentials are attenuated while those of the nearby fibers are preserved. The SF-EMG needle is a specially constructed needle with the active electrode (G1) located in a port along the posterior shaft of the needle and with a smaller leading surface area than the conventional concentric needle electrode (Figure 34–3). The reference electrode (G2) is the needle shaft. The result of these two

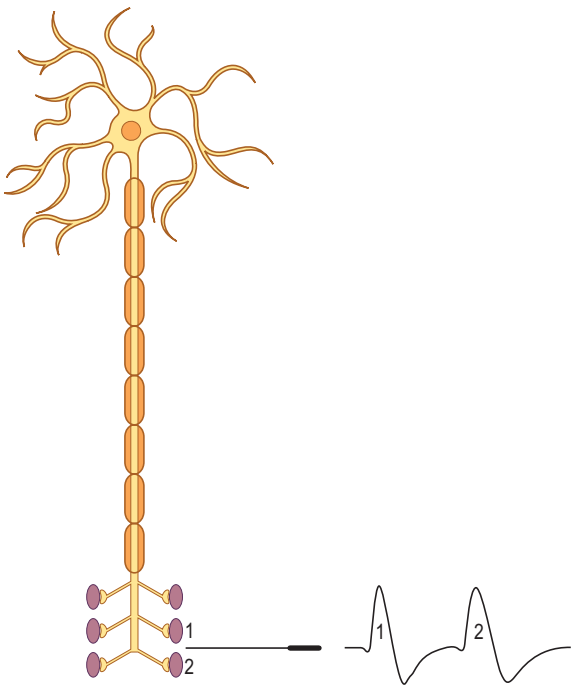

FIGURE 34–2 Single-fiber electromyography (SF-EMG). After depolarization of a neuron and its axon, all muscle fibers of the motor unit fire at approximately the same time. Variation among the firing times of individual muscle fibers occurs primarily due to different lengths of the terminal axons and neuromuscular junction transmission times. An SF-EMG needle placed between two individual muscle fibers can record the variation in firing times of two adjacent muscle fibers of the same motor unit.

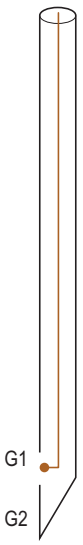

FIGURE 34–3 Single-fiber electromyography needle. The active electrode (G1) is located in a port along the posterior shaft of the needle, with a smaller leading surface area than a conventional concentric needle electrode. The reference electrode (G2) is the needle shaft.

Table 34–3. Reference Values for Jitter Measurements During Voluntary Muscle Activation

Muscle	10 Years	20 Years	30 Years	40 Years	50 Years	60 Years	70 Years	80 Years	90 Years
Frontalis	33.6/49.7	33.9/50.1	34.4/51.3	35.5/53.5	37.3/57.5	40.0/63.9	43.8/74.1		
Orbicularis oculi	39.8/54.6	39.8/54.7	40.0/54.7	40.4/54.8	40.9/55.0	41.8/55.3	43.0/55.8		
Orbicularis oris	34.7/52.5	34.7/52.7	34.9/53.2	35.3/54.1	36.0/55.7	37.0/58.2	38.3/61.8	40.2/67.0	42.5/74.2
Tongue	32.8/48.6	33.0/49.0	33.6/50.2	34.8/52.5	36.8/56.3	39.8/62.0	44.0/70.0		
Sternocleidomastoid	29.1/45.4	29.3/45.8	29.8/46.8	30.8/48.8	32.5/52.4	34.9/58.2	38.4/62.3		
Deltoid	32.9/44.4	32.9/44.5	32.9/44.5	32.9/44.6	33.0/44.8	33.0/45.1	33.1/45.6	33.2/46.1	33.3/46.9
Biceps	29.5/45.2	29.6/45.2	29.6/45.4	29.8/45.7	30.1/46.2	30.5/46.9	31.0/48.0		
Extensor digitorum communis	34.9/50.0	34.9/50.1	35.1/50.5	35.4/51.3	35.9/52.5	36.6/54.4	37.7/57.2	39.1/61.1	40.9/66.5
Abductor digiti minimi	44.4/63.5	44.7/64.0	45.2/65.5	46.4/68.6	48.2/73.9	51.0/82.7	54.8/96.6		
Quadriceps	35.9/47.9	36.0/48.0	36.5/48.2	37.5/48.5	39.0/49.1	41.3/50.0	44.6/51.2		
Tibialis anterior	49.4/80.0	49.3/79.8	49.2/79.3	48.9/78.3	48.5/76.8	47.9/74.5	47.0/71.4	45.8/67.5	44.3/62.9

95% confidence limits for upper limit of mean jitter/95% confidence limits for jitter values of individual fiber pairs (μs).

From Bromberg MB, Scott DM, Ad Hoc Committee of the AAEM single fiber special interest group. Single fiber EMG reference values: reformatted in tabular form. Muscle Nerve 1994;17:820–821. With permission.

modifications is that single-fiber muscle action potentials are recorded only if they are within 200 to 300 μm of the needle. The needle is placed in the muscle, and the patient is asked to activate the muscle in an even and constant fashion. The needle is moved until a single muscle fiber potential is located. With this single muscle fiber potential triggered on a delay line, the needle is slightly and carefully moved or rotated to look for a second potential that is time locked to the first potential (signifying that it is from the same motor unit).

More recently, the regular disposable concentric EMG needle has been used for SF-EMG studies. The standard SF-EMG needle is expensive, and needs to be surgically sanitized between patients. Thus, the cost of the standard SF-EMG needle, along with the theoretical risk of transmitting infection (including prion diseases) despite sanitizing the needle, have prompted this change. In general, the values for jitter are comparable between the traditional SF and the concentric EMG needles. Single-fiber potentials should be accepted for analysis only if the potential is at least 200 μV in amplitude with a rise time of less than 300 μs. If a time-locked second potential is located, an interpotential interval between the two potentials (i.e., the pair) can be measured. By recording multiple consecutive firings of the muscle fiber action potential pairs, the difference between consecutive interpotential intervals can be calculated. This variation between consecutive interpotential intervals is the jitter. By recording 50 to 100 subsequent potentials, the mean consecutive difference (MCD), a measure of jitter, can be calculated between the triggered potential and the time-locked second single muscle fiber potential. Most modern EMG machines have programs that automatically perform the MCD calculation. This procedure is then repeated until 20 separate single-fiber pairs are collected, to calculate a mean MCD. This value is compared with the normal mean MCD for the muscle studied and the patient's age (Table 34–3). There is also an upper limit of normal jitter for an individual pair, based on the muscle studied and the patient's age. To call the latter abnormal, more than 10% of the pairs must exceed the limit (e.g., for 20 pairs, at least two must be abnormal). To make a diagnosis of an NMJ disorder, either the mean jitter must be abnormal or the upper limit of normal jitter must be abnormal in more than 10% of individual pairs. However, in most NMJ disorders, both will be abnormal. Increased jitter is consistent with an NMJ disorder (Figure 34–4). In addition to increased jitter, blocking may be seen on SF-EMG. Two time-locked, single-fiber muscle potentials from the same motor unit normally fire together. If the triggered potential fires steadily while the second potential fires only intermittently, blocking is occurring. Blocking, which is another marker of NMJ disease, usually occurs only when the jitter is markedly prolonged (e.g., MCD > 80–100 μs).

SF-EMG is the most sensitive test to demonstrate impaired NMJ transmission (abnormal in 95–99% of patients with generalized MG). However, it must be emphasized that although SF-EMG is very sensitive, *it is not specific*. SF-EMG can be abnormal in both neuropathic and myopathic diseases. Although it might be tempting to perform SF-EMG on any patient with fatigue, this test is best reserved for patients in whom the diagnosis of MG or another NMJ disorder is strongly suspected and in whom all other diagnostic test results, including RNS, have been

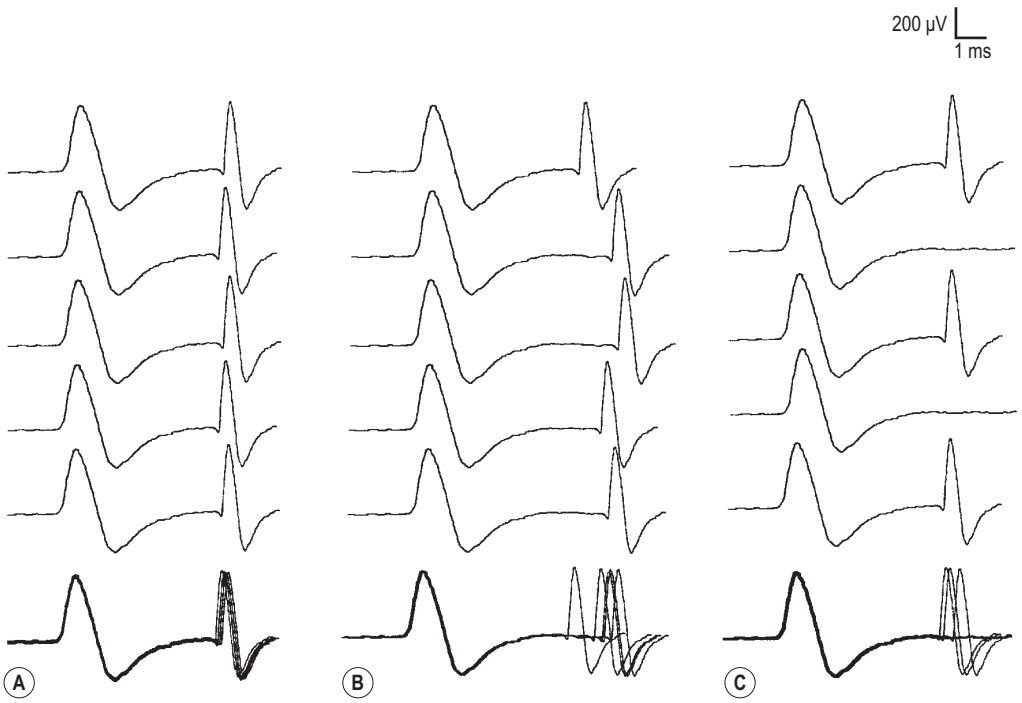

FIGURE 34–4 Single-fiber electromyography recordings. **A:** Normal. **B:** Increased jitter. **C:** Blocking. In each set, five rastered traces (top) and superimposed traces (bottom) are shown. Both increased jitter and blocking are seen in neuromuscular junction disorders.

negative or equivocal. In some patients with the restricted ocular form of MG, all study results, including SF-EMG, may be normal.

LAMBERT–EATON MYASTHENIC SYNDROME

LEMS is a disorder of NMJ transmission characterized by reduced release of ACH from the presynaptic terminal. There is now clear evidence that this disorder, like MG, is an immune-mediated disorder. The pathogenesis of LEMS is fairly well understood and in most cases involves the production of IgG antibodies directed at the presynaptic P/Q-type voltage-gated calcium channel (VGCC). These antibodies interfere with the calcium-dependent release of ACH quanta from the presynaptic membrane and subsequently cause a reduced endplate potential on the postsynaptic membrane, resulting in NMJ transmission failure. This has been shown by passively transferring IgG from LEMS patients to animals, where it produces the same physiologic and morphologic changes seen in humans.

Clinical

LEMS is quite rare. Clinically, these patients present with proximal muscle weakness (especially the lower extremities) and fatigability. In addition, deep tendon reflexes are characteristically reduced or absent, which is unusual in MG or myopathy. Autonomic complaints (especially dry mouth) and transient sensory paresthesias may be present. Bulbar symptoms (ptosis, dysarthria, dysphagia) usually, but not always, are mild, which helps to distinguish this illness from botulism and MG. The distinctive clinical finding is that of muscle facilitation. After a brief period (10 seconds) of intense exercise of a muscle, the power and the deep tendon reflex to that muscle are transiently increased. Rare patients have been diagnosed with the disorder after they have been prescribed calcium channel blockers or have failed to wean from the respirator after anesthesia.

It affects adults, generally those older than 20 years and usually older than 40 years, of whom 70% are male and 30% are female. Patients older than 40 years, usually males and smokers, are at greatest risk. Small cell lung cancer (SCLC) is eventually found in 60% of patients with LEMS. SCLCs express VGCCs, which then initiate and maintain the autoimmune process. Rarely, other tumors are associated with LEMS. The remaining patients, usually younger women, have a primary autoimmune disease without any evidence of carcinoma. Some of these patients also have antibodies to VGCCs. Commercial testing for antibodies to VGCCs is available, although the sensitivity of the test varies depending on the specific antibodies tested and whether the patient has an underlying carcinoma or primary autoimmune disease.

Electrophysiologic Evaluation

In the appropriate clinical setting, the electrophysiology of LEMS is diagnostic (Box 34–3). Single stimuli produce a reduced release of ACH quanta and a reduced endplate potential. At rest, many of the endplate potentials do not reach threshold, resulting in small-amplitude CMAPs on

Box 34–3. Electrophysiologic Evaluation of Lambert–Eaton Myasthenic Syndrome

1. **Routine motor and sensory nerve conduction studies.** Perform routine motor and sensory nerve conduction studies in at least two nerves, preferably a motor and sensory nerve in one upper and one lower extremity. CMAP amplitudes usually are diffusely low or borderline, with normal latencies and conduction velocities.
2. **Repetitive nerve stimulation (RNS) and exercise testing.** To look for facilitation, either perform high-frequency (30–50 Hz) RNS or record a CMAP with distal stimulation before and after 10 seconds of maximal voluntary exercise. Exercise testing is better tolerated by patients and is always preferable to fast RNS unless the patient cannot cooperate (e.g., sedated patient, young child). Any increment greater than 40% is abnormal (calculated by [100 × (Highest amplitude−Initial amplitude)/Initial amplitude]). Most patients with LEMS have increments greater than 100%. Increments between 40 and 100% are equivocal for presynaptic disorders.
   Perform slow RNS (3 Hz) on at least one proximal and one distal motor nerve as in MG (see Box 34–2). Decrements on slow RNS are common in LEMS but cannot differentiate this disorder from MG.
3. **Needle electromyography (EMG).** Perform routine needle EMG of distal and proximal muscles, especially weak muscles. Needle examination is usually normal. Similar to MG, motor unit action potentials may be unstable or short, small, and polyphasic with normal or early recruitment.
4. **Single-fiber EMG (usually not required in LEMS).** If performed, findings will be consistent with a neuromuscular junction disorder (increased jitter and blocking), but single-fiber EMG cannot routinely differentiate LEMS from other disorders of the neuromuscular junction.

CMAP, compound muscle action potential; LEMS, Lambert–Eaton myasthenic syndrome; MG, myasthenia gravis.

routine motor nerve conduction studies (Figure 34–5). Slow RNS (3 Hz) results in a decremental response similar to MG. However, rapid RNS (30–50 Hz) or brief (10 seconds) intense isometric exercise produces a marked increase in the CMAP amplitude (post-exercise facilitation) due to calcium accumulation in the presynaptic nerve terminal with subsequent enhancement of the release of ACH quanta (Figure 34–6). The CMAP commonly increments in amplitude by more than 100% (calculated by 100 × [(Highest amplitude−Initial amplitude)/Initial amplitude]. Brief, intense isometric exercise is preferable to rapid RNS, which can be quite painful. *Brief exercise means 10 seconds of exercise*. It has been definitely proven that the maximal increment occurs after 10 seconds. If longer exercise is used (e.g., 30 seconds), the increment may not reach the threshold criteria of a 100% increase in some patients. In the EMG laboratory, this marked post-exercise facilitation of the CMAP is the electrical correlate of the clinical facilitation of muscle strength and reflexes seen after brief exercise. Somewhat confusing in LEMS is the issue of slow RNS (3 Hz) before and after brief exercise. In both situations, there will be a decremental response. However, after brief exercise, the baseline CMAP is significantly larger (i.e., an incremental response) compared with the pre-exercise CMAP (Figure 34–7).

Needle EMG results in LEMS are similar to those in MG. Insertional activity is normal, and abnormal spontaneous activity is generally not seen. MUAPs usually are normal. Occasionally they are unstable; rarely they are short, small and polyphasic, similar to myopathic MUAPs. SF-EMG shows increased jitter or blocking, similar to MG, and cannot routinely differentiate between these two disorders.

The diagnosis of LEMS is based on the clinical findings and a diagnostic study demonstrating marked post-exercise

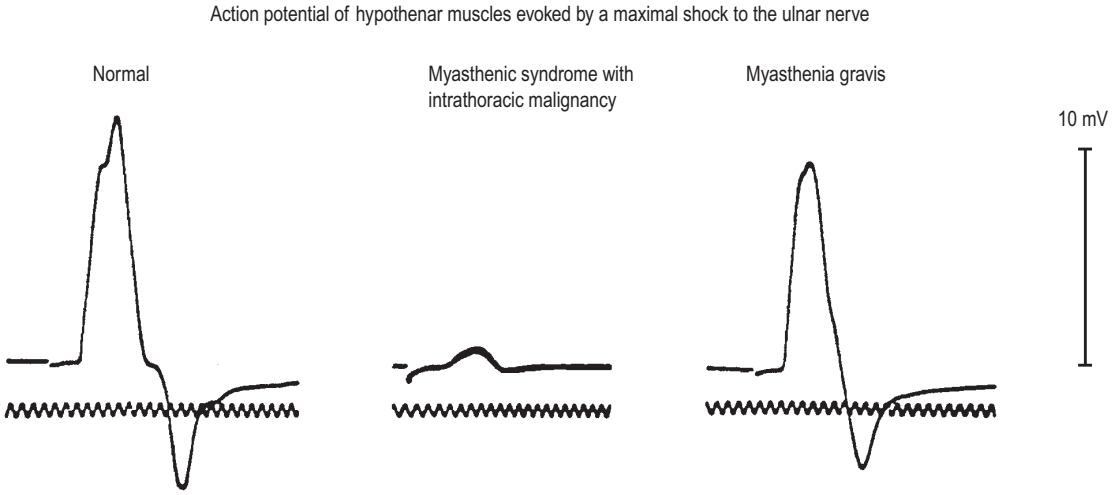

FIGURE 34–5 Compound muscle action potential amplitude in disorders of the neuromuscular junction. Note the normal amplitude in myasthenia gravis **(right)** compared with Lambert–Eaton myasthenic syndrome **(middle)**.
(Reprinted from EH Lambert, et al. Myasthenic syndrome occasionally associated with bronchial neoplasm: neurophysiologic studies. In Viets HR, ed. Myasthenia gravis: the Second International Symposium. Springfield, IL: Thomas, 1961:363. With permission.)

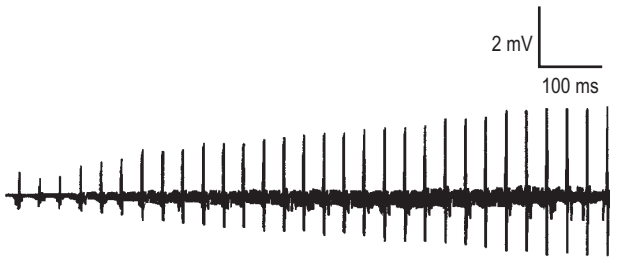

FIGURE 34–6 Rapid repetitive nerve stimulation (50 Hz) in Lambert–Eaton myasthenic syndrome. Note marked increment (>250%) in compound muscle action potential amplitude.

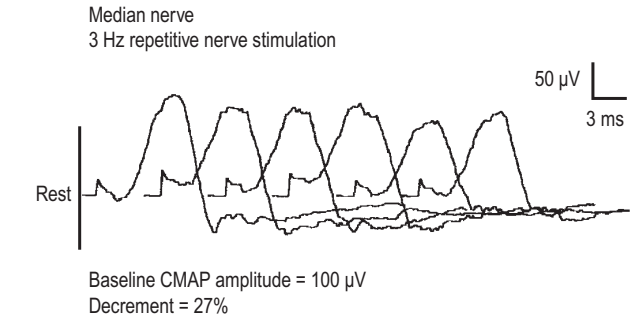

FIGURE 34–7 Slow (3 Hz) repetitive nerve stimulation in LEMS, before and after brief exercise. In both situations, there is a prominent decrement. However, after brief exercise, the baseline compound muscle action potential (CMAP) is significantly larger compared with the CMAP before exercise. In this case, the CMAP increment after brief exercise was 2000%.

facilitation. Prior history of SCLC in a patient with proximal weakness should suggest the diagnosis. The diagnosis of LEMS must be suspected in any patient whose nerve conduction studies show low or borderline low CMAP amplitudes at rest with normal sensory responses. It is not unusual for these findings to be misinterpreted as neuropathy (low amplitudes, normal conduction velocities), even though the sensory potentials are normal. If a patient with LEMS also has a superimposed neuropathy, either from an unrelated cause or as a paraneoplastic process from underlying carcinoma, the diagnosis of LEMS is missed frequently. *In any patient with low or borderline low CMAP amplitudes at rest, the distal motor stimulation should be repeated after 10 seconds of maximal exercise looking for post-exercise facilitation of the CMAP* (Figure 34–8).

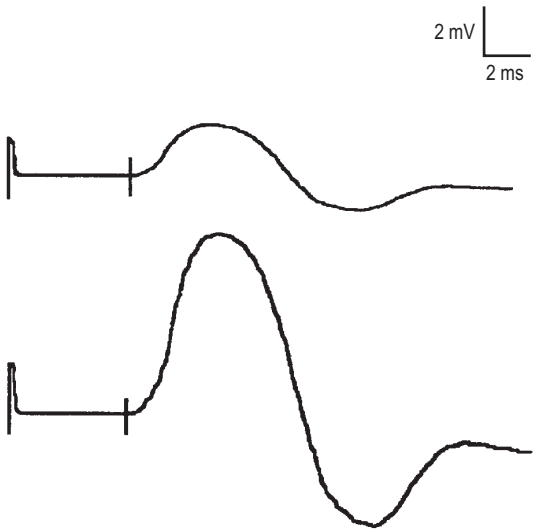

FIGURE 34–8 Exercise testing in Lambert–Eaton myasthenic syndrome, with the median nerve stimulated supramaximally at the wrist and the abductor pollicis brevis muscle recorded. **Top:** Baseline. **Bottom:** Immediately after 10 seconds of maximal voluntary exercise. Note marked increase in compound muscle action potential amplitude (post-exercise facilitation). Pre-exercise and post-exercise testing, looking for an increment, is always better tolerated by patients than is 50 Hz repetitive nerve stimulation.

Complicating the issue further is the fact that slow RNS in LEMS causes a decremental CMAP response similar to the decrement seen in MG. Many patients with LEMS initially are misdiagnosed with MG when their nerve conduction and RNS studies do not include exercise testing.

Last, patients with an overlap syndrome of both LEMS and MG have been described. Although these cases are exceptionally rare, they have been documented by the presence of ACH receptor antibodies (MG) and a diagnostic EMG with marked CMAP facilitation after exercise (LEMS). These cases tend to occur in patients with primary autoimmune disorders and have not been reported in patients with SCLC or other tumors. As mentioned earlier, many cases of LEMS are initially misdiagnosed as MG. Proximal weakness (with or without mild bulbar or ocular weakness, or both) and a decrement on slow repetitive stimulation may occur in both disorders.

BOTULISM

Botulism is caused by the potent exotoxin of *Clostridium botulinum*, which blocks presynaptic release of ACH at both somatic and autonomic synapses. The result is NMJ and parasympathetic blockade.

Clinical

Classically, botulism has been associated with ingestion of improperly prepared food which allows the exotoxin to grow, especially canned vegetables or fish. Botulism also can

occur as the result of a wound infection. In the last two decades, the most frequent setting for wound botulism has been in intravenous drug users. The most common clinical presentation of botulism, however, is infantile botulism. In infantile botulism, spores are introduced into the gastrointestinal tract that then germinate and create the toxin that is absorbed. Spores are ubiquitous in the soil and are often found in fresh produce and especially honey. Although there are eight strains of botulism, three are most commonly associated with clinical disease: types A, B, E, and F. In adult botulism, after ingestion of the exotoxin or elaboration of the toxin in a deep wound, symptoms usually occur within 2 to 72 hours. Nausea, vomiting, and abdominal pain are common initially. These symptoms are followed by blurred vision, diplopia, and dysarthria. Rapidly progressive descending weakness follows, usually resulting in a flaccid, areflexic quadriparesis, respiratory compromise, and ophthalmoplegia. The pupils are paralyzed in 50% of patients. Other manifestations of parasympathetic dysfunction include ileus, decreased salivation, and impaired accommodation (cause of initial blurred vision). The illness progresses for 1 to 2 weeks, with recovery occurring slowly over several months. The most important disorder to exclude in the differential diagnosis is MG. Clinically, MG is not usually associated with such a rapid progression, nor is there any autonomic dysfunction in MG. Guillain–Barré syndrome is included in the differential diagnosis, but sensory complaints usually are prominent.

Infantile botulism seldom presents with the dramatic findings of foodborne or wound botulism. The presenting symptoms are often decreased muscle tone and movement, a weak cry, and constipation.

Electrophysiologic Evaluation

The pathophysiology of botulism is presynaptic blocking of ACH, similar to LEMS. Likewise, the electrophysiologic evaluation and findings in botulism and LEMS are similar (Box 34–4). Sensory conduction studies are normal. CMAP amplitudes are decreased with normal latencies and conduction velocities. A decremental response may be seen with slow RNS. An incremental response characteristically occurs after brief exercise (10 seconds) or fast RNS (30–50 Hz). This finding usually is present in mild or early cases. However, the amount of increment is often not as dramatic as in LEMS, and many times it is lower than 100%. Note, in addition, that in severe botulism, if the amount of ACH release has dropped severely below threshold, even facilitation with rapid RNS or brief exercise may not result in a threshold response, and no increment occurs in the CMAP amplitude. *Thus, the lack of an incremental response to rapid RNS or brief exercise cannot completely exclude the diagnosis of botulism.*

The needle EMG of botulism is quite interesting. Fibrillation potentials and positive sharp waves, signs of denervation, are common (Figure 34–9). Botulinum toxin is such a potent NMJ blocker that the muscle fibers are effectively chemo-denervated. Similar to other NMJ disorders, MUAPs may be normal or small, short and polyphasic, similar to myopathic MUAPs. Depending on the severity, recruitment may be normal, early, or reduced. The latter may occur if every muscle fiber of a motor unit is blocked by the botulinum toxin, effectively reducing the number of motor units. Likewise, SF-EMG shows increased jitter and blocking, signifying the underlying NMJ dysfunction.

Usually, differentiating between botulism and MG is straightforward, both by clinical and electrodiagnostic

Box 34–4. Electrophysiologic Evaluation of Botulism

1. **Routine motor and sensory nerve conduction studies.** Perform routine motor and sensory nerve conduction studies in at least two nerves, preferably a motor and sensory nerve in one upper and one lower extremity. CMAP amplitudes usually are diffusely low in amplitude or absent. Latencies and conduction velocities are normal.
2. **Repetitive nerve stimulation (RNS) and exercise testing.** To look for facilitation, either perform high-frequency (30–50 Hz) RNS or record a CMAP with distal stimulation before and after 10 seconds of maximal voluntary exercise. Exercise testing is better tolerated by patients and is always preferable to fast RNS unless the patient cannot cooperate (e.g., sedated patient, young child). Any increment greater than 40% is abnormal (calculated by [100 × (Highest amplitude − Initial amplitude)/Initial amplitude]). Most patients with botulism have increments greater than 100%. Increments between 40 and 100% are equivocal for presynaptic disorders. However, in severe botulism, the neuromuscular junction may be so blocked that facilitation following exercise or rapid RNS may not be seen, and there will be no CMAP increment. The absence of an increment does not exclude the diagnosis of botulism.
   Perform slow RNS (3 Hz) on at least one proximal and one distal motor nerve as in myasthenia gravis (see Box 34–2). Decrements on slow RNS may be seen in botulism.
3. **Needle electromyography (EMG).** Perform routine needle EMG of distal and proximal muscles, especially weak muscles. Needle examination usually is markedly abnormal. After 4 to 5 days, denervating potentials (fibrillation potentials, positive sharp waves) are common. Motor unit action potentials usually are unstable or often short, small, and polyphasic, similar to myopathic motor unit action potentials. Recruitment may be normal, early, or reduced. If every muscle fiber of a motor unit is blocked by the toxin, there is an effective loss of motor units and decreased recruitment.

CMAP, compound muscle action potential.

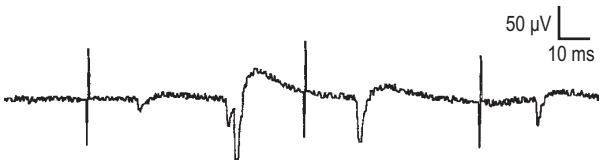

FIGURE 34–9 Spontaneous activity in botulism. Denervating potentials (fibrillation potentials and positive sharp waves) are common in botulism. Botulinum toxin is such a potent neuromuscular junction blocker that the muscle fibers are effectively chemo-denervated. Other than botulism, abnormal spontaneous activity is uncommon in neuromuscular junction transmission disorders.

findings. In contrast, the electrodiagnostic findings in botulism and LEMS may be indistinguishable (depending on the degree of denervation present in botulism), yet their clinical presentations are markedly different.

CONGENITAL MYASTHENIC SYNDROMES

The congenital myasthenic syndromes (CMS) are a group of exceptionally rare disorders caused by an inherited defect in NMJ transmission. These disorders are not immune mediated and thus are not associated with autoantibodies in the blood and do not respond to prednisone, other immunosuppressants, or plasma exchange. They are different from transient neonatal MG, which is caused by the transfer of antibodies via the placenta from a mother with MG to her baby. This latter disorder is self-limited and resolves after several months of life as the maternal antibodies are degraded.

Congenital myasthenic syndromes usually present shortly after birth or in early childhood. The range of CMS phenotypes is large, ranging from severe weakness and arthrogryposis at birth to mild weakness later in life. Similar to autoimmune MG, extraocular, bulbar, and proximal muscles often are affected. Many of the clinical manifestations are static or slowly progressive. Most are autosomal recessive in inheritance.

The CMS syndromes are classified into subgroups depending on the part of the NMJ involved: presynaptic, synaptic, and postsynaptic. Deficiency of the enzyme acetylcholinesterase was the first CMS identified. This was followed by the discovery of other defects, including presynaptic defects of ACH packaging and release, and postsynaptic defects of the ACHR itself. Several kinetic anomalies of ACHR have been demonstrated, as well as reduced numbers of receptors in other patients. In general, postsynaptic CMSs are more common than acetylcholinesterase deficiency which in turn is much more common than presynaptic CMSs.

More recently, the number of gene defects in CMS has expanded greatly, including defects in ACHR subunits and in the collagen tail of the acetylcholinesterase enzyme, as well as mutations in the genes that code for choline acetyltransferase, rapsyn, DOK-7, and the muscle sodium channel SCN4A. Of these, much attention has been focused on rapsyn and DOK-7. Rapsyn is a postsynaptic protein important in ACHR assembly and clustering. RAPSN mutations result in a reduced number and density of ACHRs, and a loss of folds on the postsynaptic membrane. DOK-7 is an activator of MuSK that is essential for formation of the neuromuscular junction (note: this is the same MuSK that is now identified with antibodies in a subset of patients with autoimmune myasthenia gravis). In CMS patients with DOK-7 mutations, the postsynaptic membrane is markedly simplified with fewer postsynaptic folds and clefts. Genetic mutations in DOK-7 and especially rapsyn now account for a sizable number of CMSs. To further complicate things, there are reports of patients with mutations of either *RAPSN* or *DOK-7* that present as young adults, and who are mistaken for seronegative MG.

Similar to the clinical presentations, the electrophysiology of these syndromes is heterogeneous. SF-EMG findings usually are abnormal. Some of the disorders display a decremental response on slow RNS, although prolonged exercise (e.g., 5 minutes) may be necessary to bring out the decrement. Those patients with either a deficiency of endplate acetylcholinesterase or an abnormality in the postsynaptic ion channel ("slow channel syndrome") may display an unusual finding on routine motor nerve conduction studies: a single impulse results in a repetitive CMAP potential.

Full characterization of these syndromes usually requires a morphologic and in vitro electrophysiologic analysis of an NMJ from a biopsied muscle, in addition to genetic analysis. Patients suspected of having a congenital myasthenic syndrome are best referred to one of the few centers where this special expertise in diagnosis is available.

EXAMPLE CASES

Case 34–1

History and Physical Examination

A 22-year-old woman was referred for fatigue and generalized weakness. Two months ago, she developed mild fatigue after exercising at the gym. Recently, she noted a change in her voice after talking for several minutes. During the last several days, she complained of intermittent double vision and drooping of the left eye late in the day.

On examination, there was a mild left ptosis that fatigued with 1 minute of upgaze. Otherwise, there was no weakness of extraocular or bulbofacial muscles. The voice was normal. Muscle bulk and tone were normal throughout. There was mild weakness of both upper and lower extremity proximal muscles, including neck extensors. The deep tendon reflexes and sensation were normal throughout.

Summary

The history is that of a young woman with muscle fatigue and weakness affecting extraocular, bulbar, and proximal muscles. Some fatigue is common in most neuromuscular syndromes, as well as in many non-neurologic conditions (e.g., hypothyroidism, anemia). However, muscle fatigue that worsens to frank muscle weakness usually is a sign of an NMJ transmission disorder. On neurologic examination there is evidence of weakness of the left levator palpebrae muscle, accounting for the left ptosis. More importantly, the left ptosis worsens after 1 minute of upgaze. Muscle bulk, tone, and reflexes are normal. This latter finding is important because the reflexes are commonly depressed in LEMS.

In addition, there is mild weakness of proximal upper and lower extremity muscles, including the neck extensors. Weakness of the neck extensors has important

CASE 34–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F-wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	12.4		≥4	3.8		≤4.4				31		≤31
	Antecubital fossa	APB	12.0			8.5			57		≥49			
Ulnar (m)	Wrist	ADM	13.2		≥6	2.8		≤3.3						≤32
	Below elbow	ADM	12.2			6.5			60		≥49	31		
	Above elbow	ADM	12.2			8.3			60		≥49			
Median (s)	Wrist	Index finger	33		≥20	3.1		≤3.5	54		≥50			
Ulnar (s)	Wrist	Little finger	27		≥17	2.9		≤3.1	55		≥50			

Repetitive nerve stimulation

Nerve stimulated	Recording site	Stimulation rate	Decrement	
Ulnar	ADM	3 Hz	4%	
Spinal accessory	Upper trapezius	3 Hz	15%	
Spinal accessory	Upper trapezius (after 10 seconds of exercise)	3 Hz	0%	Note: No change in baseline CMAP

s = sensory study; m = motor study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis; ADM = abductor digiti minimi.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 34–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right first dorsal interosseous	NL	0	0	NL	NL	NL	NL	NL
Right biceps brachii	NL	0	0	NL	NL*	NL	NL	NL
Right medial deltoid	NL	0	0	NL	NL*	NL	NL	NL
Right iliacus	NL	0	0	NL	NL*	NL	NL	NL
Right tibialis anterior	NL	0	0	NL	NL*	NL	NL	NL

NL = normal. *Unstable MUAPs.

diagnostic implications, because patients with MG often have more weakness of neck extension than neck flexion. The opposite pattern is generally seen in patients with myopathic disorders. Therefore, before proceeding to the electrodiagnostic studies, the possibility of an NMJ disorder in this young woman should be considered. Other pure motor syndromes, including myopathy, demyelinating motor neuropathies, and motor neuron disease, remain possible but appear less likely based on the clinical findings.

On nerve conduction studies, the median and ulnar motor conduction studies in the right upper extremity are performed first. Both studies are normal, including the CMAP amplitudes. This finding is important, as

CMAP amplitudes are generally preserved in patients with MG and decreased in patients with LEMS. The distal motor latencies, conduction velocities, and F responses are normal, making a demyelinating motor polyneuropathy unlikely. Next, the respective sensory conduction studies also are normal, corresponding to the clinical absence of any sensory abnormalities.

RNS is performed next. Remember that in patients with MG, slow RNS of weak muscles shows a decremental response. The ulnar nerve is selected first for study. The ulnar and other distal nerves have the major advantage of being technically easy to study. The stimulator and recording electrodes can be secured in place and the entire forearm and hand immobilized with an arm board to prevent any movement artifact. At baseline, 3 Hz RNS demonstrates a 4% decrement, which is well within the normal range of 0 to 10%. Next, a more proximal nerve, the spinal accessory, is selected. Of the proximal nerves available for routine RNS, the spinal accessory has very few technical difficulties.

The spinal accessory nerve can easily be stimulated using a low current posterior to the sternocleidomastoid muscle and recorded over the upper trapezius muscle. Although the shoulder cannot be completely immobilized, gentle pressure downward on the shoulder can prevent most movement artifact. RNS at 3 Hz shows a 15% decrement in CMAP amplitude. This amount of decrement is abnormal and is consistent with an NMJ transmission disorder. Because a decrement is seen at rest, the next logical step is to exercise the muscle for 10 seconds and immediately repeat the RNS, looking for the expected post-exercise facilitation. After brief exercise, the 15% decrement at baseline improves to 0% decrement, that is, there is a "repair" of the decrement after brief exercise.

Moving next to the needle EMG, both distal and proximal muscles are examined. Sampling proximal muscles is most important in this case, because these are the ones that are clinically weak. The EMG shows no evidence of abnormal spontaneous activity, and the MUAPs have normal morphology and a normal recruitment pattern. The standard needle EMG examination must always be performed to exclude severe denervating and myotonic disorders, because they also may show a decremental response on RNS. The only abnormality seen on the EMG study is unstable MUAPs, manifested by some variation in the morphology of MUAPs from impulse to impulse. At this time, we are ready to formulate our electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are consistent with a postsynaptic NMJ transmission disorder.*

The history, neurologic examination, and subsequent electrophysiologic studies are consistent with a postsynaptic NMJ disorder, in this case, MG. MG commonly presents in a subacute fashion predominantly affecting extraocular and bulbar muscles. Electrophysiologic studies usually show normal motor and sensory nerve conduction studies at rest. RNS at 3 Hz often shows a decremental response at baseline predominantly affecting proximal nerves, if the nerves studied subserve clinically weak muscles. If a decremental response is seen, the decrement can be improved or repaired after 10 seconds of exercise (post-exercise facilitation). If no decrement is seen at rest, 1 minute of exercise followed by RNS at 1, 2, 3, and 4 minutes often can bring out a decremental response (post-exercise exhaustion) after 2 to 3 minutes. This case raises several important questions.

Why was no Decrement Present in the Ulnar Nerve While One was Present in the Spinal Accessory Nerve?

In MG, the incidence of abnormalities on electrophysiologic testing increases as more proximal nerves are studied. This is not an unexpected finding, because patients with MG more commonly have symptoms referable to their proximal muscles. Even so, it is always preferable to begin with a distal muscle when performing RNS because the distal nerves and muscles are technically easier to study. In all cases of suspected MG, however, RNS of a proximal nerve must be performed if the distal studies are normal. A decremental response on slow RNS indicates that some of the muscle fibers are blocked, which is the electrical correlate of weakness in patients with MG. A normal RNS study would be expected in a clinically unaffected distal muscle, whereas a decremental response should be seen in a weak muscle, such as the trapezius in this case.

Could Anything have been done to Bring Out a Greater Decrement when Studying the Ulnar Nerve?

The ulnar nerve studied at 3 Hz of RNS showed a 4% decrement at baseline, which is within the normal range. To increase the yield of bringing out an abnormal decrement, one might have looked for post-exercise exhaustion by exercising the ulnar nerve for 1 minute to bring out an abnormal decrement that was not seen at baseline. In this case, the recorded ulnar muscle (i.e., abductor digiti minimi) could have been exercised maximally for 1 minute followed by RNS at 1, 2, 3, and 4 minutes. In patients with an NMJ disorder, prolonged exercise commonly brings out a decremental response after 2 to 3 minutes or worsens a decrement that is already present at baseline.

Are the Nerve Conduction Studies and Electromyography Consistent with the Diagnosis of Lambert–Eaton Myasthenic Syndrome?

LEMS is often in the differential diagnosis in a patient with suspected MG. The needle EMG examination in MG and LEMS may be identical. The major differentiation is based on nerve conduction studies and RNS. In this case, the nerve conduction studies and RNS are not consistent with the diagnosis of LEMS. First, patients

with LEMS usually have low or borderline low CMAP amplitudes at rest, whereas almost all patients with MG display normal CMAP amplitudes at rest, as did this patient. Second, patients with MG and LEMS both show an abnormal decrement with 3 Hz of RNS. After brief exercise or fast RNS, however, there is usually a marked increment in CMAP amplitude in patients with LEMS (which was not seen in this patient), whereas there typically is a small increment in patients with MG.

What is the Meaning of the Unstable Motor Unit Action Potentials?

Unstable MUAPs are the EMG correlate of unstable NMJs and are typically seen in primary NMJ transmission disorders. As the time to action potential varies among individual muscle fibers within a motor unit, the morphology of the MUAP may change from impulse to impulse. In more severe NMJ disorders, some endplate potentials may never reach threshold, in which case that particular muscle fiber action potential will not fire. Accordingly, in some unstable MUAPs, individual phases of the MUAP may drop in and out from impulse to impulse. Unstable MUAPs are seen in primary NMJ disorders (e.g., MG, LEMS, botulism) and in disorders with immature NMJ junctions such as commonly occur after denervation, as in motor neuron disease and polyneuropathy.

What would have Happened to the Decrement if the Limb was Cool?

Limb temperature must be closely monitored in the electrophysiologic examination of patients with a suspected NMJ transmission disorder. Commonly, patients with MG note that their symptoms are not as marked in cooler temperatures (note the clinical use of the ice bag test discussed earlier). Similarly, the decremental response seen on RNS is less marked if the limb is too cool. All patients undergoing RNS must have limb temperature recorded and maintained at or above 32°C.

Case 34–2

History and Physical Examination

A 59-year-old woman was referred with an 8-month history of weakness. The onset of her symptoms was abrupt, with slowly worsening weakness over 2 to 3 months, followed by stabilization. She complained of difficulty going up and down stairs and getting out of low chairs. Overall, she felt very fatigued. There was no numbness or difficulty swallowing or speaking. She had previously seen two neurologists. She had been given the diagnosis of motor neuron disease as well as old Guillain–Barré syndrome after undergoing two EMG examinations.

On neurologic examination, mental status and cranial nerves were normal. Motor testing demonstrated moderate weakness in proximal muscles of the upper and lower extremities bilaterally with normal bulk and tone. Distal strength was normal. Deep tendon reflexes were hypoactive to absent throughout. Sensory examination was normal. Gait was somewhat waddling. Coordination testing was normal. No pathologic fatigability could be demonstrated.

Summary

The history and neurologic examination are somewhat complex. This patient has a history of weakness and fatigue but no difficulty with extraocular or bulbar muscles suggesting MG. Indeed, she describes her major problems as difficulty getting out of chairs and going up and down stairs, both of which are suggestive of proximal muscle weakness. In the absence of associated pain or paresthesias, the diagnosis of myopathy seems most likely. The neurologic examination confirms that this is a pure motor problem, given the completely normal sensory examination. As expected from the history, strength testing demonstrates upper and lower extremity proximal weakness and, correspondingly, a waddling gait. No extraocular or bulbar weakness or fatigue is demonstrated. Also noted are hypoactive to absent deep tendon reflexes throughout. Areflexia typically is a neuropathic sign, associated with either severe loss of axons or demyelination.

Before proceeding to the nerve conduction and EMG studies, the differential diagnosis of pure motor weakness predominantly affecting the proximal muscles, with depressed reflexes, should be considered. The most likely diagnosis is myopathy. Next, an NMJ disorder with isolated proximal muscle weakness and depressed reflexes should be considered. Third, some cases of motor neuron disease predominantly affect the proximal muscles, such as seen in the adult-onset spinal muscular atrophies or the progressive muscular atrophy variant of amyotrophic lateral sclerosis. Finally, some rare cases of demyelinating polyneuropathy may be associated with pure muscle weakness predominantly affecting the proximal muscles.

Moving on to the nerve conduction studies, median, ulnar, tibial, and peroneal motor conduction studies, F responses, as well as median, ulnar, and sural sensory conduction studies are performed. All of the sensory conduction studies are normal, which corresponds to the patient's lack of sensory symptoms and signs. In contrast, all of the motor conduction studies are abnormal. The CMAP amplitudes are reduced in every nerve studied, with normal conduction velocities, distal motor latencies, and F responses. Although the presence of decreased CMAP amplitudes with normal conduction velocities usually implies axonal loss (i.e., from neuropathy, radiculopathy, motor neuron disease), decreased CMAP amplitudes also can be seen in myopathies that affect distal muscles and in NMJ transmission disorders associated with block.

Reviewing the needle EMG findings next, proximal and distal muscles in the right upper and lower extremity are sampled. No spontaneous activity is seen. All MUAPs are normal, with a normal activation and recruitment pattern. At this point, the differential diagnosis can be narrowed

CASE 34–2. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; sensory = μV			Latency (ms)			Conduction Velocity (m/s)			F-wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	2.5		≥4	3.4		≤4.4				30		≤31
	Antecubital fossa	APB	2.1			6.6			63		≥49			
Ulnar (m)	Wrist	ADM	2.2		≥6	3.3		≤3.3				31		≤32
	Below elbow	ADM	2.1			6.4			65		≥49			
	Above elbow	ADM	2.2			8.0			61		≥49			
Median (s)	Wrist	Index finger	23		≥20	3.5		≤3.5	50		≥50			
Ulnar (s)	Wrist	Little finger	17		≥17	3.1		≤3.1	50		≥50			
Tibial (m)	Ankle	AHB	1.5		≥4	5.4		≤5.8				54		≤56
	Popliteal fossa	AHB	1.3			11.6			48		≥41			
Peroneal (m)	Ankle	EDB	1.0		≥2	5.4		≤6.5						≤56
	Below fibula	EDB	0.9			11.8			47		≥44			
	Lateral popliteal fossa	EDB	0.9			14.0			45		≥44			
Sural (s)	Calf	Posterior ankle	10		≥6	4.1		≤4.4	48		≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis; ADM = abductor digiti minimi; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 34–2. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right first dorsal interosseous	NL	0	0	NL	NL	NL	NL	NL
Right extensor indicis proprius	NL	0	0	NL	NL	NL	NL	NL
Right biceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right pronator teres	NL	0	0	NL	NL	NL	NL	NL
Right triceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right medial deltoid	NL	0	0	NL	NL	NL	NL	NL
Right iliacus	NL	0	0	NL	NL	NL	NL	NL
Right vastus lateralis	NL	0	0	NL	NL	NL	NL	NL
Right tibialis anterior	NL	0	0	NL	NL	NL	NL	NL
Right medial gastrocnemius	NL	0	0	NL	NL	NL	NL	NL
Right L4 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right L5 paraspinal	NL	0	0	NL	NL	NL	NL	NL

NL = normal.

further. The differential diagnosis initially included the possibility of a pure motor demyelinating polyneuropathy. The normal distal motor latencies and conduction velocities, and the absence of conduction block and temporal dispersion, virtually exclude a demyelinating polyneuropathy. The possibility of motor neuron disease or a pure axonal motor neuropathy was also considered. Although the neurologic examination was consistent with these, the combination of the nerve conduction and EMG findings excludes these possibilities. It is not possible to have reduced CMAP amplitudes due to axonal loss and normal EMG findings in the muscles used to record those CMAPs. Even in the unusual situation where there has been an acute axonal loss lesion and there has not been enough time for fibrillation potentials to develop, recruitment of MUAPs should be dramatically reduced.

This leaves the possibility of either an NMJ transmission disorder or a myopathy. Myopathies only rarely result in decreased CMAP amplitudes, because most myopathies clinically affect proximal muscles, with relative sparing of the distal muscles that typically are used for recording during motor nerve conduction studies. However, there are some distal myopathies (e.g., myotonic dystrophy, myotubular myopathy, distal recessive inherited myopathy) that may show decreased CMAP amplitudes on routine nerve conduction studies. In such cases, a reduced CMAP amplitude associated with myopathy should show changes on the EMG examination consistent with myopathy, none of which were seen in this case.

Lastly, the possibility of an NMJ transmission disorder must be considered. From the clinical point of view, the possibility of MG seems unlikely because of the absence of extraocular or bulbar weakness, although rare cases of limb girdle MG do occur. In addition, the CMAP amplitudes are reduced, which would be an unusual finding in patients with MG. The other possible diagnosis is LEMS. Patients with LEMS present with proximal weakness and depressed reflexes. On nerve conduction studies, the CMAP amplitudes are characteristically reduced throughout. Note that although the electrophysiologic findings seen in botulism are similar to those in this case, the clinical history of slowly progressive weakness over months, with no ocular or bulbar symptoms, is not consistent with adult botulism.

The next logical step in this case is to perform fast RNS (30–50 Hz) or brief exercise (10 seconds) to look for facilitation. Brief exercise allows the patient to effectively activate his or her nerve at 30 to 50 Hz voluntarily and is always preferable to electrically stimulating the nerve at 50 Hz, which can be quite painful. This procedure is quite simple and straightforward to perform. A single supramaximal distal CMAP is recorded. The patient then is asked to activate his or her muscle maximally for 10 seconds and then quickly relax. A second single supramaximal shock is immediately given, and the CMAP amplitude is measured and compared with the pre-exercise potential. In the present case, the following study (brief exercise) was performed on the median nerve.

After 10 seconds of maximal exercise, the median CMAP amplitude increment is 300% [(10−2.5)/2.5× 100]. This is a dramatic increase that suggests a presynaptic NMJ transmission disorder. At this point, we are ready to formulate our electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are consistent with a presynaptic NMJ transmission disorder.*

After the exercise testing, the study is complete. Taken together, the history, neurologic examination, nerve conduction studies, EMG, and exercise testing suggest one clear diagnosis: that of LEMS. LEMS is a rare autoimmune disorder caused by decreased release of ACH. Patients commonly present with proximal muscle weakness and hyporeflexia or areflexia. The diagnosis often is suggested on routine motor nerve conduction studies, which show diffusely reduced or borderline-reduced CMAP amplitudes with normal distal motor latencies and conduction velocities. In contrast, the sensory potentials are well preserved. This pattern often is mistaken for axonal loss and probable polyneuropathy by many electromyographers. The key to not mistaking this pattern for a polyneuropathy with axonal loss is first recognizing that the sensory potentials are normal. Few axonal polyneuropathies have normal sensory potentials with reduced motor responses. Next, the needle EMG–nerve conduction correlation must be considered. If the nerve conduction studies show decreased CMAP amplitudes due to axonal loss, there should be clear findings

CASE 34–2. Follow-up Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; sensory = µV			Latency (ms)		
			RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	2.5		≥4	3.4		≤4.4
Immediately After 10 Seconds Exercise								
Median (m)	Wrist	APB	10.0		≥4	3.4		≤4.4

m = motor study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis.

of denervation and reinnervation on the needle EMG. If the needle EMG does not show denervation or reinnervation or reduced recruitment of MUAPs, the diagnosis of motor neuron disease or axonal loss of any etiology is not tenable. This case raises several important questions.

What is the Most Likely Clinical Diagnosis?

On reviewing the history further, the patient reported a 40-pack-per-year history of smoking. She also complained of a dry mouth for the past month. Although her initial chest X-ray film and chest computed tomography (CT) scan were unremarkable, a chest CT scan performed 6 months later demonstrated an abnormality. Biopsy of the lesion showed SCLC. When a patient presents with a subacute course of proximal weakness and hyporeflexia or areflexia, he or she must be evaluated carefully for the possibility of LEMS, especially if he or she is a smoker, because smokers are at risk for SCLC. Of course, some patients with LEMS produce antibodies to VGCCs as a primary autoimmune disorder, although the majority have a tumor (usually SCLC) that expresses VGCCs, which initiates the autoimmune process.

Could the Original Diagnoses of Motor Neuron Disease and Guillain–Barré Syndrome have been Correct?

One can appreciate that the proper electrophysiologic study dramatically changed the evaluation and subsequent therapy of this patient. The original diagnoses of motor neuron disease and Guillain–Barré syndrome were inaccurate. They probably were made based on a subacute, predominantly motor, syndrome associated with areflexia and low CMAP amplitudes on the original nerve conduction studies. However, the subsequent nerve conduction studies did not substantiate any type of demyelinating neuropathy. Likewise, the diagnosis of motor neuron disease, with its uniformly poor prognosis, was not substantiated based on subsequent EMG. The lack of denervation and reinnervation on the needle EMG study made the diagnosis of motor neuron disease unfeasible.

Case 34–3

History and Physical Examination

A 40-year-old woman developed dysphagia and a sore throat after eating dinner. Within a few hours, she rapidly developed diplopia and dysarthria, followed quickly by bifacial weakness, ptosis, and respiratory compromise. Neurologic examination showed marked limitation of horizontal gaze and upgaze. The pupils were poorly responsive to light and accommodation. There was marked bifacial weakness, ptosis, dysarthria, and dysphagia, and weakness of proximal greater than distal muscles. Deep tendon reflexes were absent throughout. The remainder of the neurologic examination, including mental status and sensation, were normal. There was no history of toxin exposure, recent travel, tick bite, viral illness, or vaccinations.

Laboratory studies showed unremarkable blood chemistries and normal cerebrospinal fluid examination. A diagnosis of atypical Guillain–Barré syndrome was considered. She worsened despite receiving two plasma exchanges.

Summary

The history is that of a woman presenting with the acute onset of rapidly progressive bulbofacial, extraocular, respiratory, and proximal limb muscle weakness, accompanied by poor pupillary responses and areflexia. Sensation is spared. There is no history of toxin exposure, recent travel, tick bite, flu, or vaccinations. The differential diagnosis of a rapidly progressive paralytic disorder includes Guillain–Barré syndrome, as well as MG, botulism, poliomyelitis, tick paralysis, acute intermittent porphyria, and organophosphate poisoning.

Reviewing the nerve conduction studies, the left median, ulnar, tibial, and bilateral facial CMAP amplitudes are either markedly reduced, with preserved distal motor latencies and conduction velocities, or absent. The F responses are absent. In contrast, the left median, ulnar, and sural sensory potentials are normal. Thus far, the nerve conduction studies are not unlike the previous case (diffusely low CMAPs with normal sensory potentials), although the clinical presentation is quite different: that of rapidly evolving weakness involving bulbofacial, extraocular, pupillary, and respiratory muscles.

Just as in the previous case, the combination of normal sensory conduction studies and low amplitude CMAPs with normal distal motor latencies and conduction velocities suggests a differential diagnosis of myopathy, motor neuron disease, polyradiculopathy, or NMJ transmission disorder. To evaluate the possibility of an NMJ transmission disorder, RNS and exercise testing are done next. Three-hertz RNS of the left ulnar nerve recording the abductor digiti minimi reveals a 15% decrement in the CMAP amplitude. In contrast, 30 Hz RNS results in a 250% increment, findings suggestive of a presynaptic NMJ transmission defect. Similar increments are found after 10 seconds of exercise with ulnar, median, and tibial CMAPs recorded.

Moving next to the EMG study, there is increased insertional activity in all muscles studied, with fibrillation potentials in several muscles. The MUAPs are small, short, and polyphasic, with a normal or early recruitment pattern. The findings on the needle EMG examination suggest that denervation also has taken place, with associated "myopathic" findings on the needle study. We now are ready to formulate our electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are consistent with a presynaptic NMJ transmission disorder, with denervating features.*

The findings of acute onset of bulbofacial, extraocular, respiratory, and proximal muscle weakness, in conjunction with the nerve conduction studies, RNS studies,

CASE 34–3. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F-wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB		0.20	≥4		3.2	≤4.4					NR	≤31
	Antecubital fossa	APB		0.18			6.8			58	≥49			
Ulnar (m)	Wrist	ADM		0.30	≥6		3.1	≤3.3					NR	≤32
	Below elbow	ADM		0.28			6.8			60	≥49			
Tibial (m)	Ankle	AHB		0.15	≥4		4.6	≤5.8					NR	≤56
	Popliteal fossa	AHB		0.15			13.7			42	≥41			
Facial (m)	Anterior tragus	Orbic oculi	NR	NR	≥1									
Median (s)	Wrist	Index finger		25	≥20		3.2	≤3.5		56	≥50			
Ulnar (s)	Wrist	Little finger		17	≥17		2.4	≤3.1		58	≥50			
Sural (s)	Calf	Posterior ankle		8	≥6		3.9	≤4.4		50	≥40			

Repetitive Nerve Stimulation

Nerve stimulated	Recording site	Simulation frequency/exercise	Decrement/ increment
Left ulnar nerve	ADM	3 Hz	15% decrement
		30 Hz	250% increment
		10 seconds exercise	300% increment
Left median nerve	APB	10 seconds exercise	350% increment
Left tibial nerve	AHB	10 seconds exercise	200% increment

s = sensory study; m = motor study; RT = right; LT = left; NL = normal; NR = no response; APB = abductor pollicis brevis; ADM = abductor digiti minimi; AHB = abductor hallucis brevis.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F-wave latency represents the minimum F-wave latency.

CASE 34–3. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right first dorsal interosseous	↑	0	0	NL	Early	–1	–1	NL/+1
Right biceps brachii	↑	+2	0	NL	NL	–1	–1	+1
Right medial deltoid	↑	+1	0	NL	NL	–1	NL/–1	NL/+1
Right iliacus	↑	+1	0	NL	Early	–2	NL/–1	NL/+1
Right tibialis anterior	↑	+2	0	NL	Early	–1	–1	NL/+1
Right medial gastrocnemius	↑	0	0	NL	NL	–1	NL	NL

↑ = slightly increased; NL = normal.

exercise testing, and needle EMG findings, are most consistent with a diagnosis of botulism. Subsequently, the patient revealed that she had tasted some home-preserved peaches but had discarded the canning jar because it smelled rancid. Trivalent botulinum antitoxin was administered within 24 hours, with slight clinical improvement over the next week. Clostridium toxin type B was isolated in the stool extract as well as from the residue from the canning jar, but it was not found in the serum.

This case raises several important questions.

Are the Clinical and Electrophysiologic Findings Consistent with a Diagnosis of Myasthenia Gravis or Lambert–Eaton Myasthenic Syndrome?

MG may present with rapid onset of bulbar, extraocular, respiratory, and limb weakness. However, several clinical and electrophysiologic findings are not consistent with MG. Autonomic dysfunction (i.e., poor pupillary response) is not seen in MG, as is seen in this case. Although the decremental response to slow repetitive stimulation is consistent with a diagnosis of MG, a prominent incremental response after brief exercise or rapid RNS, as well as the low baseline CMAPs, would be extremely unusual in MG. Furthermore, although MUAPs may be small and short with early recruitment, fibrillation potentials would be unusual in MG.

In LEMS, low baseline CMAP amplitudes, accompanied by incremental responses to brief exercise or rapid repetitive stimulation, are seen, as in this case. However, the needle EMG examination in LEMS usually is entirely normal, without fibrillation potentials, although occasionally small, short MUAPs can occur with early recruitment. Otherwise, it is the clinical, not the electrophysiologic, findings that differentiate LEMS from botulism. The two are distinctly different clinically. LEMS usually presents over months with proximal weakness and hyporeflexia, whereas botulism presents acutely and dramatically, with paralysis involving extraocular, bulbar, and respiratory muscles, often with prominent autonomic dysfunction.

What Other Diagnoses should be Considered?

Electrodiagnostic testing helps differentiate botulism from other paralytic disorders, including Guillain–Barré syndrome, tick paralysis, poliomyelitis, porphyria, and organophosphate poisoning. Guillain–Barré syndrome, poliomyelitis, tick paralysis, and acute intermittent porphyria all may reveal low CMAP amplitudes, but there should be no incremental response to brief exercise or fast repetitive stimulation in any of these disorders. Furthermore, Guillain–Barré syndrome usually reveals acquired demyelination on nerve conduction studies (e.g., conduction velocity slowing, prolonged late responses, conduction block), with reduced recruitment of MUAPs on needle EMG. Acute poliomyelitis generally presents as a febrile illness followed within days by focal, asymmetric paralysis. Although CMAP amplitudes may be low and fibrillation potentials noted on EMG, there is reduced recruitment of MUAPs in poliomyelitis. Tick paralysis results in rapidly ascending weakness. Although the CMAP amplitudes are low, with prolonged distal motor latencies and mild conduction velocity slowing, no incremental response is seen with brief exercise. Porphyria is generally accompanied by abdominal pain and psychiatric disturbance. Electrodiagnosis reveals an axonal neuropathy with reduced recruitment of MUAPs. Organophosphate poisoning may present with acute weakness, but miosis and fasciculations differentiate this poisoning from botulism. Nerve conduction studies may show repetitive CMAPs to a single stimulus, with no incremental response to fast repetitive stimulation or brief exercise.

Why are the F Responses Absent?

As noted earlier, Guillain–Barré syndrome is among the disorders that can result in rapidly progressive paralysis. Early on, the only abnormality on nerve conduction studies may be prolonged, dispersed, or absent F responses, reflecting demyelination of the nerve roots. It is important to remember, however, that F responses generally are not seen in nerves where the CMAP amplitude is severely reduced. As the F response is 1 to 5% of the amplitude of the CMAP, F responses often are unobtainable or very low in amplitude and difficult to measure when CMAP amplitudes are severely reduced. Therefore, absent F responses cannot be considered supportive of proximal demyelination in cases where the distal CMAP amplitudes are very low, such as in this case.

How do the Electrodiagnostic Findings in Botulism Relate to the Underlying Pathophysiology?

The unique electrophysiologic findings in botulism reflect the underlying pathophysiology of botulinum poisoning. Botulinum toxin binds to presynaptic cholinergic nerve terminals, resulting in reduced ACH quanta release from autonomic and motor nerve terminals. On nerve conduction studies, widespread low-amplitude CMAPs are seen with normal distal latencies and conduction velocities. Sensory nerve potentials are unaffected. Ten seconds of exercise or rapid RNS results in increased release of ACH quanta and higher endplate potentials. Accordingly, threshold is reached in more muscle fibers, resulting in an increment in CMAP amplitude. In severe cases of botulism, the NMJ may be so blocked that even facilitation from brief exercise or rapid RNS may not be able to raise the endplate potentials above threshold. On needle EMG, fibrillation potentials are often noted, as the NMJ is so blocked that muscle fibers are effectively chemodenervated from the botulinum toxin. Long-term recovery depends on sprouting new nerve terminals and forming new NMJs over several months.

Suggested Readings

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35 Myopathy

In the evaluation of patients with suspected myopathy, molecular genetics has supplanted the need for electrodiagnostic (EDX) studies or muscle biopsy in many patients with inherited conditions. Moreover, in patients with suspected myopathy and no evidence of an inherited condition, a muscle biopsy ultimately will be required for definitive diagnosis, regardless of EDX studies. Despite these facts, EDX studies, especially the needle electromyography (EMG) examination, continue to play an important role in the evaluation of patients with suspected myopathy (Figure 35–1). EMG can often confirm the presence of a myopathy, as well as add diagnostic information if certain types of spontaneous activity are present. For example, fibrillation potentials and positive sharp waves in a myopathy suggest the possibility of inflammation or necrosis, whereas myotonic discharges suggest one of the myotonic muscle or periodic paralysis disorders (see Chapter 36), acid maltase deficiency, myotubular myopathy, or certain

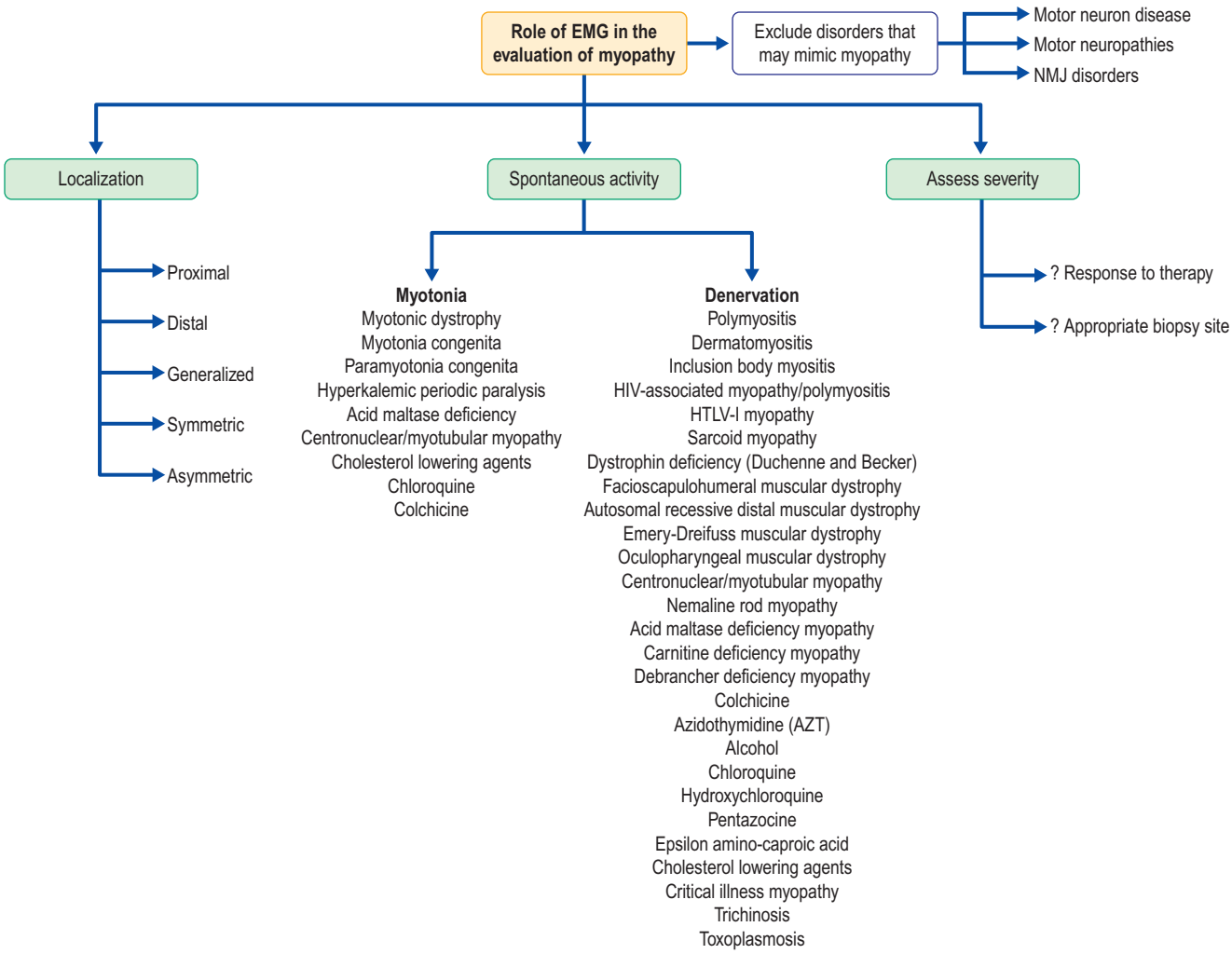

FIGURE 35–1 Role of electromyography in the evaluation of myopathy.

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toxic myopathies. Additionally, EMG may be helpful in suggesting alternate diagnoses that can mimic myopathy clinically.

EMG can also be useful in directing the site for a muscle biopsy in a patient with a myopathy. The EMG examination has the advantage that multiple muscles and sites can be sampled easily and often can suggest a suitable muscle to biopsy. It is always desirable to biopsy an unequivocally abnormal muscle yet one that is not end stage. However, biopsy is always recommended on the side contralateral to the EMG examination (see later).

Although the EMG examination may yield valuable information in the evaluation of suspected myopathy, mild cases may be especially difficult to interpret. Some myopathies, including steroid myopathy, may have minimal or no changes on EMG. In addition, some disorders of the neuromuscular junction (NMJ) may present with very similar clinical and EDX findings. Close attention to clinical detail, and often further EDX studies, including repetitive nerve stimulation and single-fiber EMG, may be required to differentiate between a myopathy and NMJ disorder.

CLINICAL

Myopathies present as pure motor syndromes without any disturbance of sensory or autonomic function. In most myopathies, symptoms tend to be bilateral and affect proximal muscles preferentially. Patients usually complain of difficulty rising from chairs, going up and down stairs, or reaching with their arms. Although most myopathies are symmetric and proximal, there are exceptions to both. For example, inclusion body myositis (IBM) and facioscapulohumeral muscular dystrophy may be very asymmetric. Myotonic dystrophy, distal hereditary myopathy, and IBM may preferentially affect distal more than proximal muscles. In some myopathies, ocular and bulbar muscles may be affected. Deep tendon reflexes are generally preserved or, if reduced, are in proportion to the degree of muscle wasting and weakness.

In evaluating a patient with suspected myopathy, it is important to determine whether symptoms are exercise induced. Such symptoms may manifest as fatigability, exercise-induced muscle cramps, or swelling. Patients who present with exercise-induced muscle cramps (see later) may develop frank weakness, swelling, and, if severe enough, myoglobulinuria. These latter symptoms suggest an inherited disorder of muscle energy metabolism. Note that although fatigability is certainly common in myopathies, frank muscle weakness that develops with exercise over a short period of time, if not accompanied by cramps, suggests a disorder of the NMJ rather than a myopathy. Additionally, patients with Lambert–Eaton myasthenic syndrome (LEMS) and some rare patients with myasthenia gravis (MG) present with isolated proximal muscle weakness mimicking a myopathy. In addition, adult onset spinal muscular atrophy, including X-linked bulbospinal muscular atrophy, usually presents with proximal muscle weakness and mimics the typical pattern of a myopathy.

Disorders of muscle can be simplified into the following categories: (1) muscular dystrophies, (2) inflammatory myopathies, (3) endocrine associated myopathies, (4) drug-induced and toxic myopathies, (5) metabolic myopathies, (6) congenital myopathies, and (7) myopathy associated with periodic paralysis.

Muscular dystrophies are inherited muscle disorders characterized by a progressive course and often an early onset, usually with a specific clinical and muscle biopsy pattern. In recent years, the chromosomal abnormality or specific gene product (e.g., dystrophin in Duchenne and Becker muscular dystrophy) has been discovered in several of these disorders. The more common muscular dystrophies include myotonic dystrophy, Duchenne muscular dystrophy, Becker muscular dystrophy, Emery–Dreifuss muscular dystrophy, facioscapulohumeral muscular dystrophy, oculopharyngeal muscular dystrophy, and limb girdle muscular dystrophies.

Inflammatory myopathies are associated most commonly with a presumed immunologic attack and include polymyositis (PM), dermatomyositis (DM), and IBM. Other types of inflammatory myopathy include those caused by muscle infection by parasites, viruses, or bacteria.

Endocrine myopathies are often seen in disorders of the thyroid and adrenal glands. In addition, myopathy can accompany some cases of acromegaly and parathyroid disease.

Drug-induced and toxic myopathies are becoming increasingly common. Examples of common drug-induced and toxic myopathies include those caused by steroids, alcohol, colchicine, azidothymidine (AZT), clofibrate, and many of the cholesterol-lowering agents.

Metabolic myopathies are disorders of muscle resulting from inherited enzyme deficiencies important in intracellular energy production. They may present in one of three ways: (1) as cramps and myoglobinuria, (2) as part of a more diffuse neurologic syndrome, often involving the central nervous system, or (3) as a typical clinical proximal myopathy. In patients with cramps and myoglobinuria, the genetic defect often is found either in the glycogen or lipid metabolism pathways. These patients may be completely normal at rest but become symptomatic during or after exercise. In patients with disorders along the lipid pathway, symptoms commonly occur after an episode of long or forced exercise (e.g., a long march or mountain climbing). In patients with disorders along the glycogen pathway, symptoms commonly occur after brief, intense isometric exercise. Muscle aches and fatigue may begin during the exercise, followed by frank myoglobinuria. Headache, nausea, and vomiting may occur. Muscles become painful and swollen. The creatine kinase (CK) level often is dramatically elevated into the thousands. The most common of these are caused by a deficiency of carnitine palmitoyltransferase (CPT) along the lipid pathway and myophosphorylase (McArdle's disease) along the glycogen pathway. Patients with defects in mitochondrial metabolism often present with a myopathy, as well as abnormalities involving other systems, including the central nervous system. Short

stature, hearing loss, seizures, cardiac abnormalities, learning disabilities, and stroke-like episodes are common. Lastly, some rare defects in metabolism (i.e., carnitine or acid maltase deficiency) may present as a typical clinical slowly progressive myopathy with proximal weakness.

Congenital myopathies are a group of myopathies in which each disorder has a fairly specific muscle biopsy finding on histochemical staining (e.g., nemaline rods, central cores, fiber type disproportion, myotubular myopathy). Typically, hematoxylin and eosin paraffin staining is normal or nonspecific. Although most patients present in the first few years of life, an occasional patient with a congenital myopathy presents in adulthood with one of these disorders. The clinical syndromes are nonspecific and tend to be slowly progressive or static. Muscle biopsy usually is needed for definitive diagnosis.

Myopathy associated with periodic paralysis occurs in the setting of hypokalemic and hyperkalemic periodic paralysis (see Chapter 36). Patients develop proximal weakness in the fifth or sixth decade. Even those patients with hypokalemic periodic paralysis who have never experienced episodic weakness, a common scenario in affected females, invariably will develop a proximal vacuolar myopathy in adulthood.

ELECTROPHYSIOLOGIC EVALUATION

Nerve Conduction Studies

Routine nerve conduction studies should always be done in patients with suspected myopathy (Box 35–1). Sensory nerve conduction studies are always normal, unless there is a coexistent neuropathy. Because most myopathies preferentially affect proximal muscles and routine motor nerve conduction studies record distal muscles, motor nerve conduction studies are also usually normal. If the myopathy is severe enough to affect distal and proximal muscles or is one of the rare myopathies that preferentially affects distal muscles, motor studies may show decreased compound muscle action potential (CMAP) amplitudes with normal latencies and conduction velocities.

The major reason nerve conduction studies must be performed is to exclude other motor disorders that may mimic myopathy (Box 35–2). Other than myopathy, pure motor disorders include motor neuron disease, rare cases of demyelinating polyneuropathy, and NMJ disorders. The nerve conduction studies in motor neuron disease and myopathies that affect distal muscles may be very similar. Differentiation is made based on the associated clinical features and needle EMG findings. Nerve conduction studies can easily differentiate demyelinating polyneuropathy from myopathy by the presence of conduction block or temporal dispersion, marked slowing of distal latencies and conduction velocity, or a combination of these findings.

Disorders of the NMJ present more of a challenge. NMJ disorders may present with proximal muscle weakness similar to myopathies. Postsynaptic disorders (e.g., MG) typically have normal CMAP amplitudes at rest. To demonstrate the NMJ abnormality, slow (3 Hz), repetitive nerve stimulation is required to demonstrate a decrement (see Chapter 34). Presynaptic disorders (e.g., LEMS) have a more characteristic nerve conduction pattern: CMAP amplitudes are low at rest with normal latencies and conduction velocities. Brief exercise (10 seconds) characteristically results in a marked increment of CMAP amplitude (typically >100% of baseline).

Box 35–1. Recommended Nerve Conduction Study Protocol for Myopathy

Routine studies:

1. At least one motor and one sensory conduction study and corresponding F responses from the upper extremity (e.g., median motor and sensory, median F responses)
2. At least one motor and one sensory conduction study and corresponding F responses from the lower extremity (e.g., tibial motor and sural sensory, tibial F responses)

Special considerations:

- If the compound muscle action potential (CMAP) amplitudes are decreased or borderline, exercise the muscle maximally for 10 seconds, then repeat a single supramaximal distal stimulation, looking for a significant CMAP increment (>100% of baseline), suggestive of the diagnosis of Lambert–Eaton myasthenic syndrome.
- If there is a clinical history of fatigability, repetitive nerve stimulation (3 Hz) of one distal muscle (e.g., ulnar nerve recording abductor digiti minimi) and one proximal muscle (e.g., the spinal accessory nerve recording the upper trapezius) should be performed. If a significant decrement is found with 3 Hz repetitive nerve stimulation of any muscle, then proceed with further testing, looking for a disorder of the neuromuscular junction (see Chapter 34, Box 34–2).

Electromyographic Approach

For the patient with suspected myopathy, the needle EMG examination must be individualized based on the distribution of the patient's symptoms (Box 35–3). Overall,

Box 35–2. Disorders that May Mimic Myopathy

- Motor neuron disease
  - Especially late-onset spinal muscular atrophy
  - X-linked bulbospinal muscular atrophy (Kennedy's disease)
  - Some cases of the progressive muscular atrophy variant of amyotrophic lateral sclerosis
- Neuromuscular junction disorders
  - Especially Lambert–Eaton myasthenic syndrome
  - Rare cases of restricted limb girdle myasthenia gravis
- Motor neuropathies
  - Usually demyelinating peripheral neuropathy (motor variants of chronic inflammatory demyelinating polyneuropathy; multifocal motor neuropathy with conduction block)
  - Rare cases of porphyric neuropathy preferentially affect proximal motor fibers
  - Diabetic amyotrophy (often affects proximal motor fibers, but usually with prominent pain)
- Central nervous system lesions
  - Bilateral middle cerebral artery–anterior cerebral artery watershed strokes

Box 35–3. Recommended Electromyographic Approach to Myopathy

Routine studies:

1. At least two distal and two proximal muscles in the lower extremity (e.g., tibialis anterior, gastrocnemius, vastus lateralis, iliacus)
2. At least two distal and two proximal muscles in the upper extremity (e.g., first dorsal interosseous, extensor indicis proprius, biceps brachii, medial deltoid)
3. At least one paraspinal muscle

Special considerations:

- Always try to study weak muscles. The number and distribution of muscles studied depend on the pattern of weakness.
- Try to study muscles that can easily be biopsied on the contralateral side (deltoid, biceps, vastus lateralis, gastrocnemius).
- If the motor unit action potential (MUAP) parameters are indeterminate, consider the following:
  Quantitative MUAP analysis: Accumulate 20 MUAPs from different locations within each muscle. Calculate the mean amplitude and duration and compare with age-matched controls for the muscle sampled.
  Single-fiber electromyography: If MUAP parameters, recruitment and activation pattern are normal when examined in weak muscles, then a neuromuscular junction disorder should be considered. Repetitive nerve stimulation should be performed first; if normal, single-fiber electromyography should be considered.

examining distal and proximal muscles in both the upper and lower extremities is indicated. Sampling the paraspinal muscles (the most proximal muscles) often is very useful. As most myopathies affect proximal muscles, the yield of finding abnormalities increases as progressively more proximal muscles are sampled. In adult-onset acid maltase deficiency myopathy, for instance, prominent changes may be seen only in the paraspinal muscles.

There are two other issues to keep in mind when performing EMG studies. First, measuring the serum CK immediately after the EMG examination probably is not wise. The CK level may rise slightly as a consequence of the EMG examination (typically 1.5× normal). The second issue is that of which muscle to biopsy, because patients with suspected myopathy often go on to muscle biopsy. The EMG can be very helpful in identifying an appropriate muscle to biopsy. One should biopsy a muscle that is abnormal but not at end stage. It usually is advisable to biopsy a muscle *contralateral* to the side sampled by the EMG needle. Because the EMG needle may induce transient inflammatory changes on the muscle biopsy, it is best not to biopsy muscles that have been sampled by the EMG needle. One would not like to diagnose an inflammatory myopathy and inappropriately place a patient on high-dose steroids based on spurious inflammation on a biopsy caused by the EMG needle.

Spontaneous Activity in Myopathies

Fibrillation potentials and positive sharp waves usually are associated with neuropathic disorders (i.e., neuropathy, radiculopathy, motor neuron disease). *However, denervating potentials occur frequently in many myopathic disorders*. They are thought to most likely occur as a consequence of segmental inflammation or necrosis of muscle fibers, separating a distal, healthy portion of the muscle fiber from the part attached to the endplate (Figure 35–2). Infarction of small intramuscular nerve twigs by surrounding interstitial inflammation also is speculated to be a possible cause of denervation in inflammatory myopathies. Although the presence of denervating potentials in a patient with myopathy often suggests the diagnosis of an inflammatory myopathy, denervating potentials can occur in a variety of myopathies (Box 35–4). In chronic myopathies, complex repetitive discharges may also be seen.

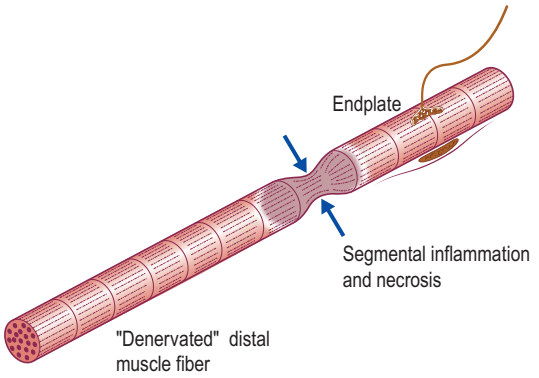

FIGURE 35–2 Generation of fibrillation potentials in inflammatory myopathies. Active denervation usually is associated with neuropathic disorders. However, active denervation also occurs frequently in many myopathies, especially those associated with inflammation or necrosis. Denervation is believed to occur as a consequence of segmental inflammation or necrosis of muscle fibers, separating a distal, healthy portion of the muscle fiber from the part attached to the endplate.

The presence of myotonic discharges yields additional information. A myotonic discharge is the spontaneous firing of a muscle fiber that waxes and wanes in both amplitude and frequency. The morphology of a myotonic discharge is either a positive wave or a brief spike potential. This morphology is the same as that of acute denervating potentials (i.e., fibrillation potentials and positive sharp waves). This should not be surprising because myotonic discharges are generated by muscle fibers as well. Myotonic discharges can be differentiated from fibrillation potentials and positive sharp waves by the waxing and waning of both firing frequency and amplitude. Remember that fibrillation potentials and positive sharp waves, in contrast, fire at a very regular rate. Myotonic discharges may be seen in myotonic dystrophy (types 1 and 2), myotonia congenita, paramyotonia congenita and hyperkalemic periodic paralysis. They can also be seen in other myopathies, including acid maltase deficiency (especially in the paraspinal muscles), myotubular (centronuclear) myopathy, some drug-induced myopathies (e.g., chloroquine, colchicine, cholesterol-lowering agents), and, occasionally, in PM.

Box 35–4. Myopathies with Denervating Features

- Inflammatory myopathies
  - Polymyositis
  - Dermatomyositis
  - Inclusion body myositis
  - Human immunodeficiency virus-associated myopathy/polymyositis
  - Human T-cell lymphotropic virus-1 myopathy
  - Sarcoid myopathy
- Dystrophies
  - Dystrophin deficiency (Duchenne and Becker)
  - Facioscapulohumeral muscular dystrophy
  - Autosomal recessive distal muscular dystrophy
  - Emery–Dreifuss muscular dystrophy
  - Oculopharyngeal muscular dystrophy
- Congenital myopathies
  - Centronuclear/myotubular myopathy
  - Nemaline rod myopathy
- Metabolic myopathies
  - Acid maltase deficiency myopathy
  - Carnitine deficiency myopathy
  - Debrancher deficiency myopathy
- Toxic myopathies
  - Colchicine, azidothymidine (AZT), alcohol, chloroquine, hydroxychloroquine, pentazocine, clofibrate, ε-aminocaproic acid, cholesterol-lowering agents, critical illness myopathy
- Necrotizing myopathy (non-inflammatory, immune-mediated)
- Amyloid myopathy
- Infectious myopathies
  - Trichinosis
  - Toxoplasmosis

The last type of "spontaneous activity" to recognize is a *contracture*, which is the complete absence of any EMG activity in a muscle while it is in the contracted state. Superficially, a muscle cramp and a contracture may appear similar clinically – the painful involuntary contraction of a muscle. However, during muscle cramps, which are neuropathic in origin, the EMG shows involuntary firing of motor unit action potentials (MUAPs) at a high frequency, whereas during a contracture, there is electrical silence. Contractures are seen only in rare metabolic myopathies (e.g., McArdle's disease, CPT deficiency) and occur as a result of insufficient energy available to break the actin–myosin bonds and return the muscle to a relaxed state. The "cramps" experienced by patients with metabolic myopathies such as McArdle's disease or CPT deficiency are, in fact, contractures.

Motor Unit Action Potential Analysis in Myopathies

Differentiating between myopathic and neuropathic disorders usually is primarily based on analysis of MUAP parameters (Figure 35–3). In most myopathies, there is dropout or dysfunction of individual muscle fibers that effectively decreases the size of the motor unit (Figure 35–4). In this situation, the actual number of motor units (i.e., anterior horn cells and axons) does not change. Only in the rare case of a very severe myopathy where every muscle fiber in a motor unit drops out does the effective number of motor units decrease.

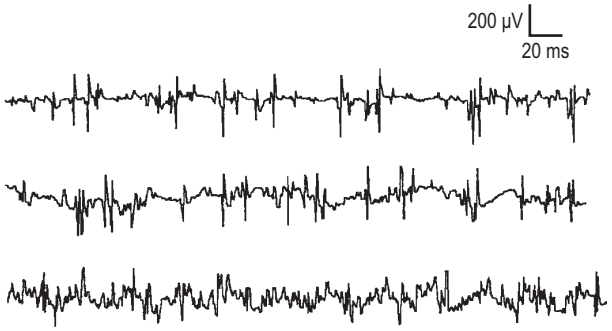

FIGURE 35–3 Myopathic motor unit action potentials. Short-duration, small-amplitude, polyphasic MUAPs with early recruitment are characteristic of myopathy. With little movement, many small, polyphasic MUAPs fill the screen and cannot be differentiated from each other **(lower trace).**

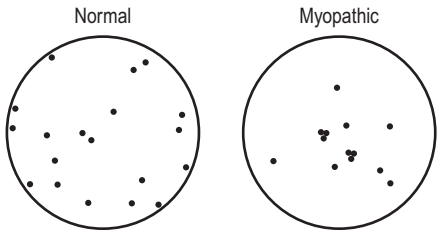

FIGURE 35–4 Motor unit territory in myopathy. In myopathy, motor unit territory typically decreases in size as individual muscle fibers drop out. Sometimes muscle fibers from the same motor unit are in close contact, either from muscle fiber splitting or after reinnervation in those myopathies associated with denervating features.
(Modified from Brown, W.F., 1984. The physiological and technical basis of electromyography. Butterworth, Boston, with permission).

Remember that there is a large normal variation in MUAP parameters. In borderline cases, it is advisable to measure at least 20 MUAPs and compare them with age-matched controls for the muscle sampled. Analysis of MUAPs, either subjectively or, more ideally, quantitatively, commonly allows a diagnosis of myopathy by noting specific changes in MUAP duration, amplitude, phases, and recruitment pattern.

MUAP duration is the most important parameter to measure in myopathy. Duration most closely reflects the total number of muscle fibers in a motor unit, including those muscle fibers at a distance from the recording electrode. The measurement of duration usually does not include linked potentials. In myopathy, duration characteristically decreases. The reduction in duration is best explained by the random dropout of muscle fibers (Figure 35–5). Of course, the finding of one brief MUAP does not make the electrodiagnosis of myopathy. Because there is a normal range of MUAP duration that varies depending on age and the muscle studied, one must sample several MUAPs to determine the *mean* duration. In myopathy, although the mean duration decreases, some of the MUAPs may be normal or possibly of long duration (Figure 35–6). In mild or equivocal cases, quantitative EMG of 10 to 20 MUAPs should be performed. In addition, it is important

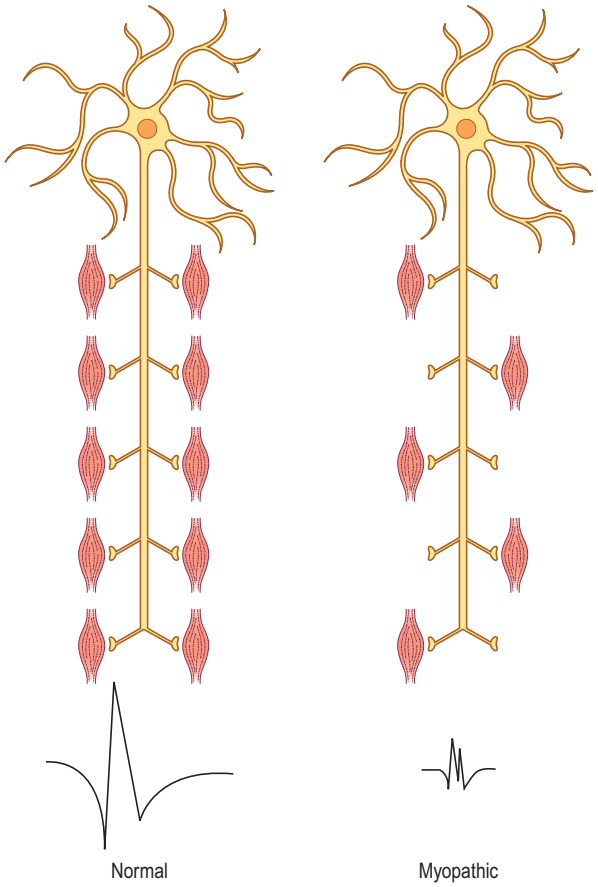

FIGURE 35–5 Model of the myopathic motor unit action potential. The MUAP in myopathy becomes short in duration, low in amplitude, and polyphasic from dropout and dysfunction of individual muscle fibers, whereas the motor neuron and its axon remain intact.

to remember that brief-duration MUAPs may be seen in conditions other than myopathy. Any disorder that effectively causes loss or dysfunction of individual muscle fibers (e.g., myopathy, NMJ disorders with block, disorders of the terminal axon) without affecting the motor neuron and its main axon can result in short-duration MUAPs (Box 35–5). A similar situation occurs in early reinnervation after severe denervation, when only a few fibers have successfully reinnervated, resulting in nascent (early reinnervated) motor unit potentials, which are also short and small. This point again emphasizes that the entire EMG examination must be taken as a whole and interpreted in light of the nerve conduction studies, as well as the history and examination, before a diagnosis is reached.

Somewhat surprisingly, chronic myopathies may have very long MUAP durations or frequently have linked or satellite potentials. These findings likely are secondary to fiber splitting or collateral sprouting from reinnervation in those myopathies associated with necrosis and subsequent denervation. In the chronic or late stage of a myopathy, it may be very difficult to distinguish a myopathic from a neuropathic disorder based on the duration of the MUAPs alone.

Box 35–5. Conditions Associated with Small, Short, Polyphasic Motor Unit Action Potentials

Myopathy
Neuromuscular junction disorders (myasthenia gravis, Lambert–Eaton myasthenic syndrome)
Early reinnervation after severe denervation (i.e., nascent motor unit potentials)
Periodic paralysis (during attack)
Disorders that selectively affect terminal axons (? paraneoplastic)

MUAP amplitude depends on just the few muscle fibers that are very close to the needle electrode. In myopathy, the amplitude commonly is decreased, but it can also be normal or increased if the needle electrode is placed near split or reinnervated fibers.

MUAP phases often are increased (>4 phases) in myopathy, but this is a nonspecific finding. The number of phases is primarily a measure of synchrony, and polyphasia may be seen in both myopathic and neuropathic disorders. Presumably, many of the remaining muscle fibers are dysfunctional and do not fire as synchronously as normal.

One of the most important findings in a myopathy is the presence of an early recruitment pattern. In myopathies in which there is dropout of individual muscle fibers from a motor unit, the motor unit becomes smaller and subsequently can generate less force. *Early recruitment refers to the inappropriate firing of many MUAPs to generate a small amount of force. In general, only the electromyographer performing the study can assess early recruitment.* Assessing early recruitment requires knowledge of how much force is being generated for the number of MUAPs that are firing. In myopathy, the number of MUAPs firing (recruitment) is appropriate for the firing frequency (activation); what is inappropriate is the number of MUAPs firing for the degree of force generated.

Only very rarely is the recruitment of MUAPs actually reduced in myopathy. This occurs only in the setting of end-stage muscle disease if all the muscle fibers of a single motor unit are lost, thereby causing an actual reduction in the number of motor units. This results in a reduced recruitment pattern on EMG. This situation is extremely uncommon but may arise in some very chronic myopathies that involve certain muscles severely, such as the quadriceps in IBM.

Single-fiber Electromyography in Myopathy

Single-fiber EMG (see Chapter 34) in patients with myopathy is commonly associated with increased jitter and blocking, especially in those myopathies associated with abnormal spontaneous activity. This finding emphasizes that increased jitter and blocking, although very sensitive to disorders of the NMJ, are not specific to these disorders. Any neuropathic or myopathic condition that involves any degree of denervation and reinnervation results in newly formed or dying NMJs, which in turn lead to abnormalities on single-fiber EMG. In differentiating a myopathy from a disorder

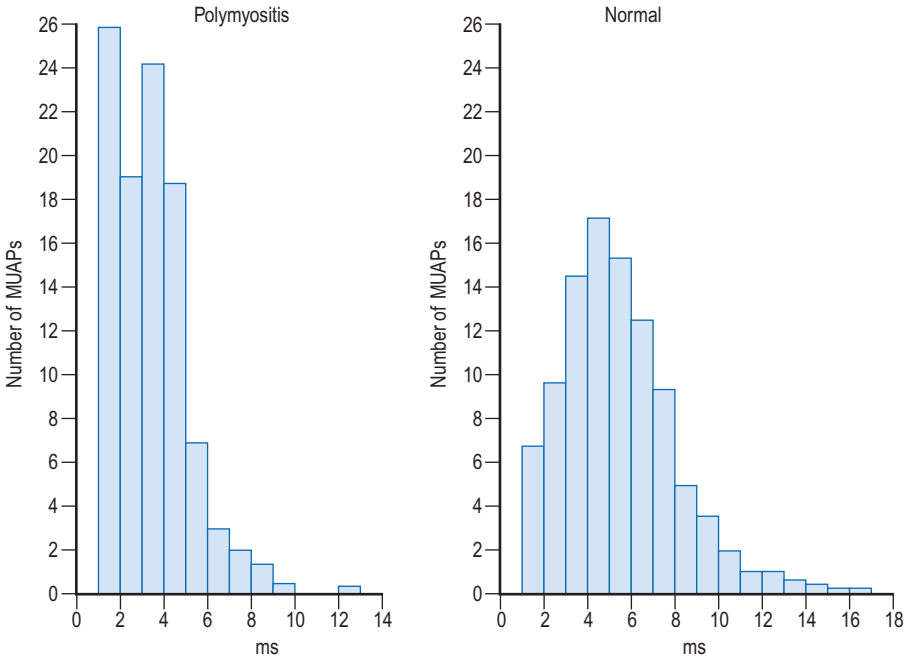

FIGURE 35–6 Motor unit action potential (MUAP) durations in myopathy. Patient with polymyositis **(left)** and a normal control **(right)** are shown. In the patient with polymyositis, there is a shift in mean duration to shorter MUAPs, although some medium and longer duration MUAPs are still present.
(Adapted from Buchthal, F., Pinelli, P., 1953. Muscle action potentials in polymyositis. Neurology 3, 424, with permission.)

of NMJ transmission, single-fiber EMG is most helpful in those cases where both nerve conduction and routine needle EMG findings are normal. In this setting, if the single-fiber EMG is abnormal, a disorder of NMJ transmission is more likely than a primary muscle disorder.

CLINICAL AND ELECTROPHYSIOLOGIC PATTERNS IN SELECTED MYOPATHIES

Polymyositis and Dermatomyositis

PM and DM are idiopathic inflammatory myopathies. Although they likely are autoimmune in nature, the disease mechanisms are not as clearly defined as in MG and LEMS, and at present the evidence is indirect. Muscle weakness may develop alone, which is the usual case. However, less commonly it may occur with a skin rash (DM), in association with one of a number of connective tissue diseases, or in the presence of a malignancy (usually occult). Approximately 20% of patients have an associated autoimmune or connective tissue disease (e.g., systemic lupus erythematosus, scleroderma, rheumatoid arthritis, Sjögren's disease, mixed connective tissue disease, polyarteritis nodosa).

The weakness in PM and DM usually develops subacutely but may be chronic and present over many months. Proximal muscles are predominantly affected in a symmetric fashion. The patient has difficulty getting out of chairs, the car, and bath; climbing stairs; and reaching above the head. In some cases, dysphagia occurs. Deep tendon reflexes are preserved unless the muscles are very weak, and atrophy is generally mild or does not occur. The neck muscles, especially the neck flexors, are commonly involved. However, the facial and extraocular muscles are generally spared, allowing fairly easy differentiation from MG. In a minority of patients, muscle swelling, tenderness, and myalgias occur. Also, arthralgias, joint stiffness, and Raynaud's phenomenon may occur, but true erosive arthritis is rare unless the patient has an associated connective tissue disorder. Cardiac involvement may occur in up to 40% of patients. This may range from minor electrocardiographic abnormalities to arrhythmias, pericarditis, and severe cardiomyopathy.

In DM, in addition to muscle weakness, the patient has a characteristic skin rash. This consists of a lilac-colored, reticulated, heliotrope-appearing rash on the upper eyelids. In addition, there is often erythema on the cheeks and over the shoulders and exposed upper chest. Erythematous, hyperkeratotic, scaly patches occur symmetrically on the extensor surfaces of the elbows, knuckles, and knees and over the medial malleoli. Periungual hyperemia and telangiectasias are common. In chronic DM, subcutaneous calcium deposits can occur and then rupture and drain.

Motor and sensory nerve conduction studies typically are normal. EMG typically shows prominent spontaneous activity (fibrillation potentials, positive sharp waves, and complex repetitive discharges). In acute and subacute cases, MUAPs are small, short, and polyphasic with early recruitment. In several studies of patients with biopsy-proven PM or DM, EMG abnormalities were seen in 89% of patients, with

fibrillation potentials present in 45 to 74% of patients. The diagnostic yield increased as more muscles were sampled. Of patients with fibrillation potentials, these were most commonly seen in the paraspinal muscles (94%), followed by the proximal shoulder and hip muscles (64–76%). With treatment, fibrillation potentials decrease or disappear. In chronic PM and DM (> one year), MUAPs become large and long in up to 50% of patients. They may occur in combination with small, short polyphasic MUAPs or rarely appear alone. The finding of large MUAPs, which most commonly are associated with neuropathic disorders, often creates confusion. In this case, assessment of the recruitment pattern is key. The finding of relatively preserved recruitment associated with large, long MUAPs must always suggest the possibility of a chronic myopathy.

Inclusion Body Myositis

IBM is an idiopathic inflammatory disorder of muscle that often is confused both clinically and on muscle biopsy with PM. IBM is now the most common inflammatory myopathy in individuals older than 50 years. Muscle biopsy shows inflammation and rimmed vacuoles, as well as intranuclear and cytoplasmic inclusions. Clinically, IBM presents as slowly progressive weakness. It is more common in men than in women (3 : 1). The age of presentation is commonly in the sixth decade. It is not unusual for patients to remain undiagnosed for many years after the onset of the first symptoms. Along with proximal muscle weakness, distal muscles are commonly involved. In some patients, the distal muscles actually are weaker than the proximal ones. Although the distribution of weakness is most commonly symmetric, asymmetric presentations also occur. *The disease has a predilection for certain muscles, especially the quadriceps and long finger flexors*. In addition, the iliopsoas, tibialis anterior, biceps, and triceps are commonly affected. Prominent muscle atrophy, especially of the quadriceps, is common. Facial and ocular weakness do not occur. The deep tendon reflexes tend to be depressed or absent early in the course, especially the quadriceps reflex. Fifteen percent of patients have other autoimmune diseases. A rare subset of patients has a familial form of IBM that spares the quadriceps muscles, and some forms are associated with Paget disease and frontotemporal dementia.

The initial diagnosis of IBM commonly is missed. It is not unusual for patients to be diagnosed initially with PM, which then fails to respond to immunosuppressive therapy. In addition, some patients with IBM and severe distal and proximal weakness and wasting, with depressed reflexes, initially are misdiagnosed with motor neuron disease. Rare patients with IBM present with dysphagia (in some patients, years before the onset of generalized weakness). Some patients present with dysphagia to solids and some also with dysphagia to liquids and nasal regurgitation. In these cases, the diagnosis of myopathy is rarely considered. The mechanism of the dysphagia in such patients has been shown to be paresis of the pharyngeal wall that precludes timely emptying of the pharynx before the upper esophageal sphincter closes, resulting in repetitive swallowing and choking.

Unfortunately, the electrophysiology often complicates the diagnosis of IBM. A distinct subset of patients demonstrates a mild sensory or sensorimotor polyneuropathy on nerve conduction studies (33–50% of patients). In addition, the needle EMG examination often is confusing. Prominent denervating potentials (fibrillation potentials and positive sharp waves) are common. The associated MUAP findings fall into one of three separate groups:

Group I	Small short MUAPs with polyphasia
Group II	Small short and large long MUAPs with polyphasia
Group III	Normal or large long MUAPs with polyphasia

As noted earlier, although large, long-duration MUAPs classically are associated with neuropathic disorders, they also are seen in myopathy, especially in chronic cases. In addition, patients with IBM can have an early, normal, or slightly reduced MUAP recruitment pattern, the latter finding usually associated with neuropathic processes. In group II, the small short and large long MUAPs may be found in the same muscle. The distribution of clinical weakness is most often proximal in group I and distal in groups II and III. Group III, although rare, is commonly mistaken for motor neuron disease (diffuse fibrillation potentials, large long-duration MUAPs with decreased recruitment). The heterogeneous profile of IBM makes the electrophysiologic diagnosis difficult. Many have commented that the combination of neuropathic and myopathic findings on EMG should suggest the diagnosis of IBM, although, in reality, this finding is simply consistent with a very chronic myopathy, as is usually the case in IBM.

Steroid Myopathy

Among drug-induced myopathies, steroids probably are the most common. The risk of steroid myopathy increases with the dose and duration of use. It typically is a proximal myopathy, preferentially affecting the hip girdle muscles. Motor and sensory nerve conduction studies are normal. The needle EMG typically is normal unless the myopathy is severe. In this situation, low-amplitude, short-duration MUAPs may be seen in the proximal muscles. *Of note, abnormal spontaneous activity is not seen*. This point is often very useful in differentiating PM from steroid myopathy. It is not uncommon for patients with PM to be treated with steroids, respond well initially, and then note a progression of weakness. In this case, it may be very difficult to differentiate recurrent or undertreated PM from steroid myopathy on clinical grounds. *The presence of abundant abnormal spontaneous activity strongly suggests PM, rather than steroid myopathy, as the cause of the weakness*.

Critical Illness Myopathy

Critical illness myopathy (CIM) is now a well-recognized and fairly common condition encountered in the intensive

care unit setting. It was first reported in patients who developed profound weakness after receiving intravenous steroids, usually high dose, after intubation. Nearly all of these patients were concurrently treated with NMJ-blocking agents. Patients with status asthmaticus have most often been reported. Typically, these are patients who are intubated and treated with several days of pharmacologic paralysis and high-dose intravenous steroids. After these measures are withdrawn, profound weakness is recognized or the patient fails to wean off the respirator. Often patients are flaccid and areflexic. Distal and proximal muscles are affected, and atrophy shortly ensues. Neck flexor weakness is common. Bifacial weakness can occur; however, extraocular weakness is unusual. Sensation usually is completely spared, an important finding that differentiates this condition from critical illness polyneuropathy and acute inflammatory demyelinating polyneuropathy. Laboratory testing frequently shows an elevated CK level, especially if the patient is tested early in the course of the weakness. Later CK levels may be slightly elevated or normal.

Nerve conduction studies demonstrate low CMAP amplitudes without any evidence of demyelination, *although in some patients the CMAPs are long in duration*. Conduction velocities and distal latencies are normal. Sensory studies are normal, unless there is a coexistent condition resulting in abnormal sensory potentials, such as critical illness polyneuropathy. Repetitive nerve stimulation studies are also normal. Needle EMG shows short-duration, low-amplitude MUAPs, often with denervation potentials, especially early in the course. Recruitment is normal or early, despite the profound weakness. On muscle biopsy, there is a characteristic loss of the thick (myosin) filaments on electron microscopy. In general, long-term prognosis is good, although most patients require not weeks, but usually several months, of rehabilitation to recover.

The pathophysiology of this disorder is not completely understood but most likely results primarily from toxicity of high-dose steroids in combination with NMJ blockers. In the majority of cases, patients have been exposed to both. Rarely, the myopathy develops with the use of steroids alone. The types of NMJ blockers vary, as do the type and dose of steroids. In general, patients treated with longer NMJ blockade (>24–48 hours) and longer- and higher-dose steroids appear to be more likely to develop this complication. The total dose of intravenous methylprednisolone usually is more than 1000 mg.

In recent years, there is growing evidence that CIM also occurs following the systemic inflammatory response syndrome (SIRS) that often accompanies sepsis, multi-organ failure, burns, trauma, and/or major procedures in the ICU. SIRS is felt to be present in the majority of patients hospitalized in the ICU for more than a week. In addition, many of the patients who develop CIM in the ICU also develop critical illness polyneuropathy as well, further complicating the clinical assessment, as well as the electrophysiologic evaluation (see Chapter 37).

EXAMPLE CASES

Case 35–1

History and Physical Examination

A 42-year-old woman was referred for progressive weakness of several months' duration. She had a long history of asthma treated with low-dose oral prednisone. Her initial symptoms were difficulty going up and down stairs and getting out of chairs. In addition, she developed mild difficulty with swallowing. The process was symmetric and progressive with little pain.

Neurologic examination showed mild proximal weakness in both upper and lower extremities. There was mild weakness of neck flexion with preserved neck extension. Muscle bulk and tone were normal. No facial or bulbar weakness was noted. Deep tendon reflexes and sensation were normal.

Summary

The history in this case suggests proximal muscle weakness. Difficulty going up and down stairs and difficulty getting out of low chairs are symptoms characteristic of proximal lower extremity weakness. On examination, proximal weakness in both upper and lower extremities, as well as mild weakness in the neck flexors, was found. Weakness of neck flexion is a key finding that indicates abnormalities above the cervical area. In some patients it may be difficult to differentiate whether upper extremity proximal weakness is due to myopathy or radiculopathy affecting the C5 and C6 roots. In such cases, examination of the neck flexors can be very helpful because they frequently are abnormal in myopathy.

The differential diagnosis of proximal weakness includes myopathy, polyradiculopathy, motor neuron disorders, NMJ transmission disorders, and unusual primarily motor demyelinating neuropathies. The absence of any sensory symptoms along with the intact reflexes argues against the possibility of a polyradiculopathy or demyelinating motor neuropathy. The absence of fatigability or weakness of the extraocular muscles makes the diagnosis of MG unlikely, although MG, along with LEMS, must still be considered. The history of long-term prednisone use may be important, because steroids are a common cause of myopathy.

Reviewing the nerve conduction findings, the right median, ulnar, tibial, and peroneal motor studies and F response studies are normal. All of the CMAP amplitudes, conduction velocities, and latencies are normal. Likewise, the median, ulnar, and sural sensory responses are intact. These normal motor, sensory, and F response studies effectively exclude a demyelinating polyneuropathy. In addition, the normal CMAP amplitudes at rest make the diagnosis of LEMS unlikely.

The EMG findings are very abnormal, with diffuse fibrillation potentials, especially in the proximal muscles. In addition, many of the MUAPs in the proximal muscles are of brief duration, low amplitude, and polyphasic with

CASE 35–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	9.4		≥4	4.2		≤4.4				28		≤31
	Antecubital fossa	APB	8.9			8.5			64		≥49			
Ulnar (m)	Wrist	ADM	8.2		≥6	2.9		≤3.3				29		≤32
	Below elbow	ADM	8.2			6.5			60		≥49			
	Above elbow	ADM	8.2			8.2			60		≥49			
Median (s)	Wrist	Index finger	34		≥20	3.4		≤3.5	55		≥50			
Ulnar (s)	Wrist	Little finger	25		≥17	2.9		≤3.1	64		≥50			
Tibial (m)	Ankle	AHB	7.4		≥4	4.7		≤5.8				52		≤56
	Popliteal fossa	AHB	7.0			12.3			44		≥41			
Peroneal (m)	Ankle	EDB	4.2		≥2	4.8		≤6.5				51		≤56
	Below fibula	EDB	4.0			8.4			45		≥44			
	Lateral popliteal fossa	EDB	4.0			11.2			44		≥44			
Sural (s)	Calf	Posterior ankle	24		≥6	4.2		≤4.4	47		≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis; ADM = abductor digiti minimi; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 35–1. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right first dorsal interosseous	NL	0	0	NL	NL	NL	NL	NL
Right abductor pollicis brevis	NL	0	0	NL	NL	NL	NL	NL
Right extensor indicis proprius	NL	0	0	NL	NL	NL	NL	NL
Right biceps brachii	↑	+2	0	NL	Early	–2	–2	+2
Right pronator teres	↑	+1	0	NL	Early	–2	–2	+2
Right iliacus	↑	+1	0	NL	Early	–2	–2	+2
Right vastus lateralis	↑	+1	0	NL	Early	–1	–1	+1
Right tibialis anterior	↑	+1	0	NL	Early	–1	–1	+1
Right L5 paraspinal	↑	+2	0	NL	Early	–2	–2	+2
Right T6 paraspinal	↑	+2	0	NL	Early	–2	–2	+2

↑ = increased; NL = normal.

an early recruitment pattern. This MUAP profile of brief-duration, low-amplitude polyphasic MUAPs with early recruitment is characteristic of myopathic MUAPs. The prominent fibrillation potentials yield additional important diagnostic information, suggesting an inflammatory or necrotic muscle disease. Note that fibrillation potentials are not seen in steroid myopathy or in most cases of MG or LEMS.

When the nerve conduction studies and EMG examination are complete, the electrophysiologic impression can be formulated.

IMPRESSION: *There is electrophysiologic evidence consistent with a proximal myopathy with active denervating features.*

This case raises several important questions.

Does the Electromyography–Nerve Conduction–Clinical Correlation Make Sense?

There are several important correlations to note among the electrophysiologic study, the clinical history, and the neurologic examination. Looking first at the correlation between the motor nerve conduction studies and the needle EMG, the motor nerve conduction studies are quite normal, whereas the needle EMG findings are very abnormal. This paradox occurs because motor nerve conduction studies routinely record distal muscles, which are normal in most myopathies, whereas the needle EMG also can sample proximal muscles, which are abnormal in most myopathies. If CMAPs had been recorded from proximal muscles, where denervation is seen on the needle EMG, these would likely be abnormal with low amplitudes. It is not unusual for the routine motor conduction studies to be normal in typical proximal myopathies.

The next point to consider is the presence of the prominent fibrillation potentials, in light of the patient's history of steroid use. Although the patient takes steroids, her myopathy cannot be attributed to steroid use because of the active denervation. This EMG pattern is much more suggestive of an inflammatory myopathy such as PM.

The presence of brief-duration, low-amplitude, polyphasic MUAPs with early recruitment also eliminates the neuropathic disorders from the differential diagnosis, including amyotrophic lateral sclerosis, adult-onset spinal muscular atrophy, motor neuropathies, and polyradiculopathy. Early recruitment is characteristic of myopathic disorders. Because there is dropout or dysfunction of individual muscle fibers, each motor unit can generate less force. Therefore, more motor units than usual are needed to create a small amount of force. The EMG correlate of this underlying pathophysiology is the finding that the EMG screen fills very easily with many brief-duration, low-amplitude polyphasic MUAPs with a very small amount of force. To judge recruitment requires knowledge of how much force is being generated. Only the electromyographer can clearly assess early recruitment.

Which Muscle Should be Biopsied?

Muscle biopsy was performed on the contralateral vastus lateralis muscle. The contralateral side was chosen to avoid the possibility that minor inflammation caused by the EMG needle would be misinterpreted. Pathologic examination subsequently showed muscle fiber necrosis, with prominent mononuclear inflammatory infiltrates consistent with the diagnosis of PM. The patient was treated with high-dose prednisone and responded well.

Case 35–2

History and Physical Examination

A 75-year-old man developed progressive difficulty walking over a 2-year period. Initially, he noted that his gait was slightly unsteady. Later, he developed difficulty walking up stairs. His symptoms slowly worsened to the point that he would trip frequently when he walked quickly or walked on uneven ground. He noted no pain, numbness, or paresthesias in his legs and no bowel or bladder difficulties. He complained of no arm weakness, visual difficulties, or speech or swallowing problems.

Neurologic examination revealed normal cranial nerves and full strength in the neck flexors and extensors. He had 4/5 strength in the deltoids bilaterally and full strength in the biceps and triceps. More distally, the wrist extensors were 4/5, finger flexors were 3/5, and median and ulnar hand intrinsics were 4/5 bilaterally. Muscle bulk was near normal in the upper extremities, except for mild wasting of the proximal volar forearms. In his lower extremities, hip flexion was mildly weak bilaterally. There was prominent weakness of left knee extension (2/5) and bilateral foot dorsiflexion (3/5). Prominent wasting was noted in the left thigh and distally in both anterior calves. Deep tendon reflexes were 1+ in the upper extremities and at the right knee but were otherwise absent at the ankles and the left knee. Plantar responses were flexor bilaterally. Sensory examination, including vibration sense, light touch, position sense, and temperature sensation, was normal in the distal upper and lower extremities. Coordination was normal. He walked with a marked steppage gait.

Summary

The history and examination in this case suggest slowly progressive asymmetric weakness, predominantly affecting the lower extremities. There are no sensory complaints or sensory findings suggesting a radiculopathy or polyneuropathy. Examination shows asymmetric weakness and wasting, involving both proximal and distal muscles, but with a predilection for the left knee extensors and bilateral finger flexors. The diminished reflexes at the ankles and the left knee suggest a possible neuropathic process, although reduced reflexes may be seen with severe weakness from any cause.

CASE 35–2. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB		9.9	≥4		4.0	≤4.4					27	≤31
	Antecubital fossa	APB		9.8			7.9			51	≥49			
Ulnar (m)	Wrist	ADM		9.5	≥6		3.3	≤3.3					29	≤32
	Below elbow	ADM		8.9			6.9			55	≥49			
	Above elbow	ADM		8.8			8.9			50	≥49			
Median (s)	Wrist	Index finger		25	≥20		3.4	≤3.5		54	≥50			
Ulnar (s)	Wrist	Little finger		17	≥17		2.9	≤3.1		50	≥50			
Tibial (m)	Ankle	AHB		2.6	≥4		5.3	≤5.8					60	≤56
	Popliteal fossa	AHB		2.3			14.1			40	≥41			
Peroneal (m)	Ankle	EDB		1.1	≥2		5.1	≤6.5					56	≤56
	Below fibula	EDB		0.9			14.1			38	≥44			
	Lateral popliteal fossa	EDB		0.9			16.6			40	≥44			
Sural (s)	Calf	Posterior ankle		16	≥6		3.7	≤4.4		45	≥40			

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis; ADM = abductor digiti minimi; AHB = abductor hallucis brevis; EDB = extensor digitorum brevis.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 35–2. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Left tibialis anterior	CRD	+1	0	NL	Early	–1	NL	+2
Left medial gastrocnemius	CRD	+2	0	NL	Early	–1	NL	+1
Left vastus lateralis	CRD	+2	0	NL	↓	–1/+1	NL	+1
Left iliacus	CRD	+2	0	NL	Early	–1	NL	+1
Left L5 paraspinal	CRD	+1	0	NL	NL	–1	NL	+1
Left first dorsal interosseous	CRD	+2	0	NL	Early	–1	NL	+1
Left pronator teres	CRD	+1	0	NL	Early	–1	NL	NL
Left triceps	↑	0	0	NL	Early	–1	NL	+1
Left biceps brachii	↑	+1	0	NL	Early	–1	NL	+1
Left medial deltoid	CRD	+1	0	NL	Early	–1	NL	+1

CRD = complex repetitive discharge; ↑ = increased; ↓= slightly reduced; NL = normal.

Given the history and neurologic examination, the differential diagnosis includes motor neuron disease, a demyelinating motor neuropathy, or an unusual myopathy that is asymmetric and affects proximal and distal muscles. The prominent asymmetry and muscle wasting are not consistent with a disorder of the NMJ.

Moving on to the electrophysiology, the left median and ulnar motor and sensory nerve conduction studies and F responses are normal. In the left lower extremity, however, the peroneal and tibial CMAP amplitudes are decreased, with normal distal motor latencies and slightly slowed conduction velocities. The tibial F response latency is also slightly prolonged. The left sural sensory response is intact. The low motor responses with normal sensory responses in the lower extremity again suggest a predominant motor problem. The absence of markedly prolonged distal motor latencies or conduction velocity slowing, with no evidence of conduction block or temporal dispersion, effectively excludes a demyelinating motor polyneuropathy. After reviewing the nerve conduction studies, the possibility of motor neuron disease or an unusual disorder of muscle must still be considered.

The EMG shows prominent spontaneous activity, with frequent complex repetitive discharges and fibrillation potentials in most muscles tested. Most of the MUAPs, however, are short duration and polyphasic with early recruitment, consistent with a myopathy. The only exception is the left vastus lateralis, which has both long- and short-duration polyphasic MUAPs with slightly reduced recruitment.

After the nerve conduction and EMG studies, the electrophysiologic impression can be formulated.

IMPRESSION: *There is electrophysiologic evidence consistent with a chronic, asymmetric myopathy with denervating features.*

Several important questions can be addressed.

What is the Significance of the Complex Repetitive Discharges?

The presence of the complex repetitive discharges implies that the process is chronic. In addition, the finding of both long- and short-duration MUAPs in the vastus lateralis suggests a chronic process and, in the setting of small, short-duration MUAPs with early recruitment in other muscles, a chronic myopathy. Although myopathy is characteristically associated with small, short MUAPs, large, prolonged MUAPs also can be seen in chronic myopathies associated with denervating features (inflammatory and necrotic myopathies) in which reinnervation occurs as well.

What is the Most Likely Clinical Diagnosis?

This patient eventually had a biopsy of the right medial deltoid, a muscle that was clinically involved but had not been studied with the EMG needle. Pathologic examination showed marked variation in fiber size, marked mononuclear inflammatory infiltrates, numerous rimmed vacuoles, and intracytoplasmic inclusions. The pathologic diagnosis was IBM.

IBM usually presents in older men as a very slowly progressive muscle disorder often affecting both upper and lower extremity muscles. Many patients develop distal as well as proximal weakness. In some patients, weakness may be limited to the distal muscles. IBM often involves certain muscles preferentially, including the quadriceps, iliopsoas, tibialis anterior, biceps, triceps and the forearm, and long finger flexors. Focal atrophy of one of these muscles suggests the possibility of IBM. Occasional patients develop isolated dysphagia from IBM.

Electrophysiology often shows normal motor and sensory nerve conduction studies, although approximately one third of patients have mild slowing of motor and sensory conduction velocities. If distal muscles have been affected by the myopathy, the CMAP amplitudes also may be low. Fibrillation potentials are quite common, as are complex repetitive discharges, especially in long-standing cases. MUAPs may be brief or of long duration. A combination of large and small MUAPs may be present within the same muscle. In muscles that are severely affected by the myopathy, recruitment may actually be reduced. This occurs if every muscle fiber within a motor unit is lost, effectively leading to loss of the motor unit.

In end-stage muscle secondary to myopathy, it is not unusual to see fibrillation potentials, with large, prolonged MUAPs and a decreased recruitment pattern. These findings often incorrectly suggest a neuropathic illness, such as motor neuron disease. However, any EMG examination showing large, prolonged polyphasic MUAPs with a relatively normal or just slightly reduced recruitment pattern should suggest the possibility of a chronic myopathy. The only electromyographic clue that the disorder is myopathic in these cases is that the magnitude of the MUAP abnormalities appears too great for the mild degree of decreased recruitment. Indeed, there are occasional patients with chronic IBM in whom it is very difficult to differentiate IBM both clinically and electromyographically from the progressive muscular atrophy form of motor neuron disease.

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Myotonic Muscle Disorders and Periodic Paralysis Syndromes

36

The myotonic muscle disorders and periodic paralysis syndromes compose a group of disorders characterized by muscle stiffness, pain, and sometimes weakness, which may be intermittent or constant. Evaluation of these disorders in the electromyography (EMG) laboratory is particularly gratifying, as the EMG accompaniment of myotonia is easily recognized by the experienced electromyographer. Clinically, myotonia is characterized by delayed muscle contraction after activation. Myotonia can also be demonstrated after percussion of the muscle. On EMG, myotonic discharges produce a distinctive revving engine sound. This results from the spontaneous firing of muscle fibers that wax and wane in frequency and amplitude, producing this unmistakable sound (Figure 36–1). The myotonic potential may take the form of either a positive wave or a brief spike potential, thus identifying the source generator as a muscle fiber. Myotonia can be induced by mechanical stimulation, such as percussion of the muscle or movement of the EMG needle, or may follow voluntary muscle contraction. Clinically, myotonia is noted most frequently in the myotonic muscle disorders and in some of the periodic paralysis syndromes (Box 36–1). Patients describe an inability to relax their muscles after contraction, such as during hand grip. In addition, myotonia may be experienced by the patient as muscle stiffness.

Traditionally, the myotonic muscle disorders have been classified into those with dystrophic changes on muscle biopsy, such as the myotonic dystrophies, resulting in weakness, and those without dystrophic changes, such as myotonia congenita and paramyotonia congenita, where weakness is generally not a feature. Myotonia also occurs in several of the periodic paralysis syndromes, both inherited and acquired, as well as on the EMG examination in some metabolic, inflammatory, congenital, and toxic myopathies, although clinical myotonia is generally not apparent. Myotonia can be unmasked or precipitated by various drugs. Very rarely, myotonic discharges are noted on EMG examination in disorders of nerve associated with severe denervation. Although a single, brief run of myotonia may be seen in denervating disorders, it is never the predominant waveform. Neuromyotonia, a rare phenomenon associated with peripheral nerve as opposed to muscle disorders, may result in a delay in muscle relaxation. However, this can be distinguished from myotonia in the EMG laboratory by the spontaneous firing of *motor unit action potentials* (MUAPs) as opposed to *muscle fiber action potentials*.

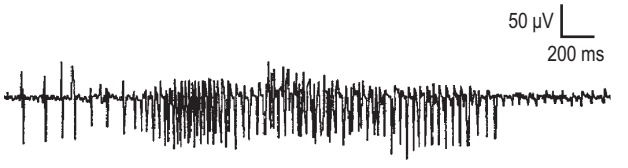

FIGURE 36–1 Myotonic discharge. A myotonic discharge is the spontaneous discharge of a muscle fiber that waxes and wanes in both amplitude and frequency. An individual myotonic potential may have either a positive wave or a brief spike morphology (identifying the source generator as a muscle fiber). Myotonic discharges are characteristically seen in myotonic dystrophy, myotonia congenita, paramyotonia congenital, and in some patients with hyperkalemic periodic paralysis. They also may occur in some myopathies, e.g., acid maltase deficiency, polymyositis, myotubular myopathy, hyperkalemic periodic paralysis.

Genetic linkage and mutational analyses have identified the molecular basis for several of the myotonic muscle disorders and periodic paralysis syndromes, resulting in the classification of these disorders based on a specific ion channel or protein kinase defect. Classification of these disorders now can be accomplished based on clinical, electrophysiologic, and molecular findings (Table 36–1). Once myotonia is identified on clinical or needle EMG examination, the electrophysiologic evaluation is directed toward answering several key questions to arrive at the correct diagnosis. To answer these questions, a variety of tests can be performed in the EMG laboratory to distinguish among the dystrophic and nondystrophic myotonic muscle disorders, the periodic paralysis syndromes, and other disorders of muscle with accompanying EMG myotonia. In addition to routine nerve conduction studies and needle EMG, muscle cooling, exercise testing, and repetitive nerve stimulation often are very helpful in differentiating among these disorders (Box 36–2).

MUSCLE COOLING

In some of the myotonic disorders, muscle cooling can be used to enhance myotonic discharges or bring out other characteristic abnormalities (see sections on Myotonia Congenita and Paramyotonia Congenita). Muscle cooling is best accomplished by wrapping the limb in a plastic bag

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Box 36–1. Classification of Myotonic and Periodic Paralysis Disorders

I. Inherited myotonic muscle/periodic paralysis disorders
  A. Dystrophic myotonic muscle disorders
    1. Myotonic dystrophy, types 1 and 2
  B. Nondystrophic myotonic muscle disorders/periodic paralysis syndromes
    1. Chloride channel disorders
      a. Autosomal dominant myotonia congenita (Thomsen)
      b. Autosomal recessive myotonia congenita (Becker)
    2. Sodium channel disorders
      a. Paramyotonia congenita (Eulenburg)
      b. Hyperkalemic periodic paralysis (±myotonia)
      c. Sodium channel myotonia congenita
      d. Hypokalemic periodic paralysis type 2 (rare form)
  C. Andersen–Tawil syndrome (no myotonia)
  D. Hypokalemic periodic paralysis, type 1 (calcium channel, no myotonia)
  E. Schwartz–Jampel syndrome (note: there is evidence that the abnormal discharges on EMG are more likely neuromyotonic and not myotonic)

II. Acquired periodic paralysis disorders
  A. Secondary hyperkalemic periodic paralysis (may be associated with myotonia) may be seen in association with the following:
    1. Renal failure
    2. Adrenal failure
    3. Hypoaldosteronism
    4. Metabolic acidosis
  B. Secondary hypokalemic periodic paralysis (not associated with myotonia) may be seen in association with:
    1. Hyperthyroidism, especially in Asian adults
    2. Primary hyperaldosteronism
    3. Diuretics
    4. Inadequate potassium intake
    5. Chronic licorice ingestion
    6. Excessive potassium loss through sweat
    7. Gastrointestinal or renal potassium wasting
    8. Steroid use

III. Muscle disorders associated with electromyographic myotonia
  A. Metabolic: acid maltase deficiency
  B. Inflammatory: polymyositis
  C. Congenital: myotubular myopathy
  D. Associated with systemic disorders: malignant hyperpyrexia
  E. Drug-induced hypothyroidism

IV. Drugs that unmask or precipitate myotonia either clinically or on electromyographic examination
  A. Clofibrate
  B. Propranolol
  C. Fenoterol
  D. Terbutaline
  E. Colchicine
  F. Penicillamine
  G. Cyclosporin
  H. Hydroxymethylglutaryl coenzyme A (HMG-CoA) reductase inhibitors (lipid-lowering agents)

and submerging it in ice water for 10 to 20 minutes. After the skin temperature is brought down to 20°C, needle EMG of the extremity is performed, with the electromyographer looking for abnormalities. Note that the limb should always be removed from the ice water if weakness develops.

EXERCISE TESTING

Exercise testing can play an important role in the periodic paralysis and myotonic syndromes. Both short and prolonged exercise tests can be performed. In both, a routine distal compound muscle action potential (CMAP) is evoked with supramaximal stimulation (e.g., stimulating the ulnar nerve at the wrist, recording the abductor digiti minimi [ADM]). The nerve then is stimulated at 1-minute intervals for several minutes to ensure a stable baseline, before exercise is begun.

Short Exercise Test

For the short exercise test, the patient is asked to rest for about 5 minutes while a CMAP is recorded every minute, to ensure that the baseline is stable and does not decrease at rest. The patient is then asked to perform maximal voluntary contraction for 5 to 10 seconds. Immediately afterward, a CMAP is recorded. If a decrement in amplitude is seen, then a CMAP is recorded every 10 seconds until the CMAP recovers to baseline (typically 1–2 minutes) (Figure 36–2). If a decrement occurs after brief exercise and then recovers, the same procedure is repeated several times to see if the decrement continues to occur or habituates, which can help differentiate among some of the myotonic syndromes (discussed later).

Prolonged Exercise Test

For the prolonged exercise test, the recording procedure is the same. The patient is asked to rest for about 5 minutes while a CMAP is recorded every minute, to ensure the baseline is stable and does not decrease at rest. After ensuring a stable baseline, the patient is asked to voluntarily contract his or her muscle maximally for 5 minutes, resting every 15 seconds for a few seconds. After the 5 minutes of exercise are complete, the patient relaxes completely. A CMAP is recorded immediately and then every 1 to 2 minutes for the next 40 to 60 minutes. In the periodic paralysis syndromes, both inherited and acquired, the CMAP amplitude may be unchanged or slightly larger immediately after prolonged exercise and then decline substantially over the next 20 to 60 minutes (Figure 36–3).

Table 36–1. Clinical Features of Myotonic and Periodic Paralysis Disorders

	Myotonic Dystrophy, Type 1	Myotonic Dystrophy, Type 2	Myotonia Congenita: Dominant	Myotonia Congenita: Recessive	Sodium Channel Myotonia	Paramyotonia Congenita	Hyperkalemic Periodic Paralysis	Hypokalemic Periodic Paralysis	Andersen–Tawil Syndrome
Age at onset	Teens to early adult	Teens to mid-adult	Infancy	Early childhood	Childhood to early teens	Infancy	Infancy to early childhood	Early teens	Childhood or early teens
Inheritance	Autosomal dominant	Autosomal dominant	Autosomal dominant	Autosomal recessive	Autosomal dominant	Autosomal dominant	Autosomal dominant	Autosomal dominant	Autosomal dominant
Gene defect	Protein kinase, chromosome 19q (*DMPK* gene)	Zinc finger protein-9, chromosome 3q (*ZNF9* gene)	Chloride channel, chromosome 7q (*CLCN* gene)	Chloride channel, chromosome 7q (*CLCN* gene)	Sodium channel, chromosome 17q (*SCN4A* gene)	Sodium channel, chromosome 17q (*SCN4A* gene)	Sodium channel, chromosome 17q (*SCN4A* gene)	Calcium channel, chromosome 1q (type 1) (*CACNA1S* gene) Sodium channel chromosome 17q (type 2) (*SCN4A* gene)	Potassium channel, chromosome 17q (*KCNJ2* gene)
Myotonia	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Distribution of myotonia	Distal more than proximal	Proximal and distal	Generalized	Generalized	Proximal more than distal	Face, hands, thighs	Generalized, if present	None	None
Periodic weakness	No	No	No	Yes, in some patients	No	Yes	Yes	Yes	Yes, in some patients
Duration of weakness	N/A	N/A	N/A	N/A	N/A	Minutes to days	Minutes to days	Hours to days	
Progressive weakness	Yes	Yes	No	Rarely	No	No	Variable	Yes	Yes
Extramuscular involvement	Yes	Yes	No	No	No	No	No	No	Yes
Provocative factors	None	None	Cold	Cold	Potassium, delay after exercise	Cold, exercise, fasting	Cold, rest after exercise, emotional stress, fasting, potassium loading	Cold, rest after exercise, emotional stress, carbohydrates, alcohol	Rest after exercise, alcohol
Alleviating factors	None	None	Exercise	Exercise	Unknown	Warming	Carbohydrates, mild exercise	Potassium, mild exercise	Mild exercise

Box 36–2. Protocol for Evaluation of Myotonic and Periodic Paralysis Disorders

1. Routine motor and sensory nerve conduction studies should be done first. Generally one or two motor and sensory conduction studies and corresponding F responses in an upper and lower extremity should be performed. Distal CMAPs may be low in the dystrophic myopathies. Proceed to needle EMG.
2. Needle EMG study is carried out after standard conduction studies are completed. The study should include proximal and distal muscles of one upper and lower extremity, as well as facial and paraspinal muscles. Careful note should be made of abnormal spontaneous activity, including myotonic discharges, complex repetitive discharges, fibrillation potentials and positive waves, and MUAP potential configuration and recruitment pattern.
3. Muscle cooling is carried out if there is a clinical suspicion of paramyotonia congenita.
   A. Wrap the limb in a plastic bag, submerge in ice water for about 10 to 20 minutes to bring skin temperature to 20°C. Remove the patient's hand from water. The hand should always be removed from the ice water if weakness develops.
   B. Needle EMG of a distal forearm or hand muscle is performed, noting the presence of abnormal spontaneous activity (e.g., fibrillation potentials, myotonic bursts) and MUAPs with voluntary contraction.
   C. Allow muscle to rewarm to precooling temperature and continue to record EMG activity (may take >1 hour).
4. Short exercise test is performed if steps 1, 2, and 3 do not yield a definitive diagnosis.
   A. Immobilize hand. Record supramaximal CMAP at abductor digiti minimi stimulating ulnar nerve at the wrist.
   B. Record the CMAP once per minute for 5 minutes with muscle at rest to ensure no decrease in the baseline CMAP.
   C. Have the patient perform maximum voluntary contraction for 5 to 10 seconds.
   D. Record the CMAP immediately. If a decrement in amplitude is seen, continue to record the CMAP every 10 seconds until it recovers to baseline (typically 1–2 minutes).
   E. In cases where a decrement is seen after exercise, repeat the same procedure several times to see if a decrement in the CMAP continues to occur or habituates.
5. Prolonged exercise test is performed if steps 1, 2, 3, and 4 do not yield a definitive diagnosis.
   A. Immobilize hand. Record supramaximal CMAP at abductor digiti minimi, stimulating ulnar nerve at the wrist.
   B. Record the CMAP once per minute for 5 minutes with muscle at rest to ensure a stable baseline.
   C. Have the patient perform maximal voluntary muscle contraction for 2 to 5 minutes, resting every 15 seconds for 3 to 4 seconds.
   D. After the 5 minutes of exercise are complete, have the patient relax completely.
   E. Record the CMAP immediately, then every 1 to 2 minutes for 40 to 60 minutes afterward or until there is no further decline observed in the CMAP (this can go on for >1 hour). Decrement is calculated as follows: (Highest CMAP amplitude after exercise − Smallest CMAP amplitude after exercise)/(Highest CMAP amplitude after exercise ×100). Any decrement >40% definitely is abnormal.
   F. Note that immediately after exercise, the CMAP may be larger, before the slow decline in amplitude takes place. This finding is more common when the pre-exercise rest produces a drop in CMAP, as seen in the periodic paralyses.
6. Repetitive nerve stimulation at 10 Hz.

CMAP, compound muscle action potential; EMG, electromyography; MUAP, motor unit action potential.

REPETITIVE NERVE STIMULATION

Many of the same findings on exercise testing can also be found with repetitive nerve stimulation (RNS). Decrements are not uncommon with RNS in the myotonic syndromes. Although decrements may be seen with slow repetitive stimulation (3 Hz), they are more common with faster frequencies, typically 10 Hz. Abnormalities are not seen in all patients; when present, they are not specific to any individual syndrome.

When all the available electrophysiologic techniques are used, the correct diagnosis usually can be determined by answering several key questions (Table 36–2):

1. Are routine nerve conduction studies normal?
2. On concentric needle EMG:
   A. Are myotonic discharges present on needle EMG, and, if present, are they widespread or focal? If focal, what is the distribution, proximal or distal?
   B. Are the MUAPs and recruitment pattern on EMG examination normal or abnormal? If the MUAPs and recruitment pattern are abnormal, are they myopathic or neurogenic?
3. Is there an effect of muscle cooling on the needle examination?
4. What does the short exercise testing show?
5. What does the prolonged exercise testing show?
6. What does the repetitive nerve stimulation show?

DYSTROPHIC MYOTONIC MUSCLE DISORDERS

Myotonic Dystrophy

The myotonic dystrophies are among the most common of the myotonic muscle disorders. They are an autosomal dominant inherited, multisystem disorder characterized by progressive facial and limb muscle weakness, myotonia, and involvement of several organ systems outside of skeletal muscle. Myotonic dystrophy type 1 (DM1) is the most common; it is due to a defect in the protein kinase

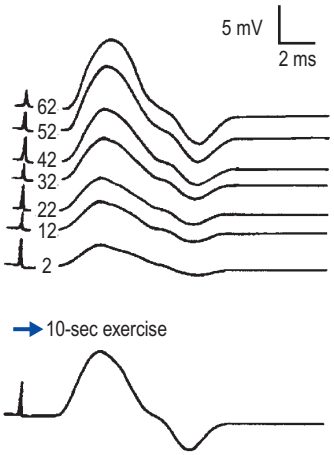

FIGURE 36–2 Short exercise test in the myotonic syndromes. After a brief maximal voluntary contraction, the compound muscle action potential (CMAP) immediately decrements in the myotonic syndromes. If subsequent CMAPs are evoked every 10 seconds, the decrement recovers to baseline in 1 to 2 minutes in myotonic dystrophy and myotonia congenita **(top)**. Numbers on the left refer to the time in seconds measured after the exercise. In paramyotonia congenita, the recovery may be quite delayed, in the range of 10 to 60 minutes.
(From Streib, E.W., 1987. AAEE minimonograph, no. 27: differential diagnosis of myotonic syndromes. Muscle Nerve 10, 606, with permission.)

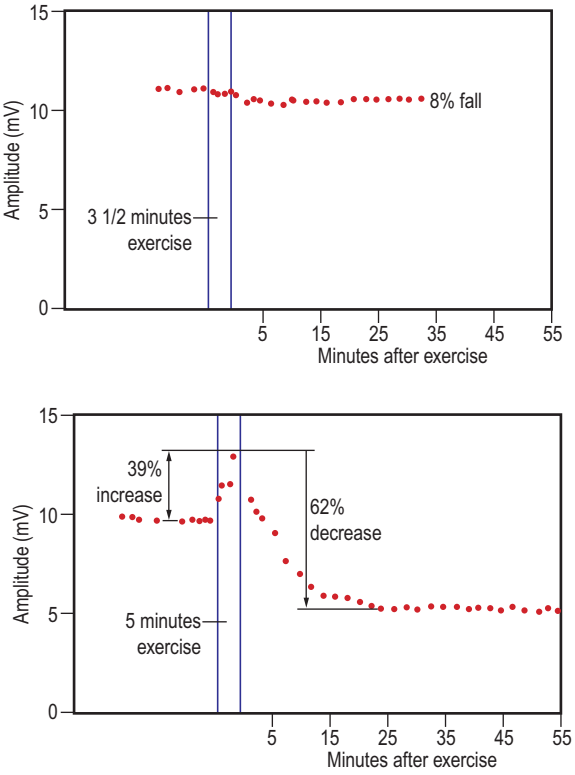

FIGURE 36–3 Typical pattern of response on prolonged exercise test in periodic paralysis. After 3 to 5 minutes of prolonged exercise, the compound muscle action potential (CMAP) amplitude recorded every 1 to 2 minutes shows little change in normal controls **(top)**. In the periodic paralysis syndromes, there is frequently an increment immediately after exercise, followed by a slow decrement over the next 30 to 40 minutes **(bottom)**. Decrements of more than 40% definitely are abnormal.
(Reprinted from McManis, P.G., Lambert, E.H., Daube, J.R., 1986. The exercise test in periodic paralysis. Muscle Nerve 9, 704, with permission.)

myotonin [dystrophia myotonica-protein kinase (*DMPK*)] gene on chromosome 19q. The gene defect itself is an unstable expansion of a CTG trinucleotide repeat in the untranslated region of the myotonin gene. Age of onset and severity of symptoms are variable and proportional to the size of the abnormal CTG trinucleotide repeats, which expands over subsequent generations. This phenomenon of "anticipation" results in an earlier onset and more severe course in subsequent generations. Myotonic dystrophy type 2 (DM2), also known as *proximal myotonic myopathy* (PROMM syndrome) and proximal myotonic dystrophy (PDM), is due to a defect in the zinc-finger protein-9 (*ZNF9*) gene on chromosome 3q. The gene defect itself is an unstable expansion of a CCTG repeat in intron 1 of the zinc-finger protein-9 gene.

Myotonic Dystrophy Type 1

Clinical

Patients with DM1 generally present in their late teens with mild distal weakness and delayed muscle relaxation, such as difficulty releasing their hand grip. This disorder is distinguished from other muscle disorders by the distal rather than proximal predominance of weakness, as well as the myotonia. The myotonia is less marked than in the myotonia congenitas. In classic myotonic dystrophy, patients experience stiffness that improves with repeated contractions. Thus, patients often report that repeated opening and closing of the hand results in a faster relaxation time with each grip. As the weakness progresses over years, the myotonic symptoms generally recede.

There is a distinctive clinical appearance characterized by bifacial weakness, temporal wasting, and frontal balding, resulting in a narrow, elongated face and horizontal smile, with ptosis, and distal muscle wasting and weakness (Figure 36–4). Patients with a smaller CTG repeat may not have the typical facial appearance. Weakness of neck flexion is also an early sign, and patients may notice difficulty lifting their head off the pillow or a tendency for the head to fall backwards during acceleration. DM1 is distinguished from many of the other myotonic disorders by the progressive distal weakness as well as involvement of several organ systems outside of skeletal muscle resulting in cataracts, cardiac conduction and pulmonary defects, endocrine dysfunction, testicular atrophy, hypersomnia, gynecologic problems, and, in some patients, mild to moderate cognitive impairment. As in the other myotonic and periodic paralysis syndromes, patients with myotonic dystrophy should be warned against potential anesthetic complications of succinylcholine and anticholinesterase agents.

The clinical examination in a patient suspected of having myotonic dystrophy is directed at recognition of the typical facies, i.e., demonstration of bifacial, neck flexor, and distal wasting and weakness, and demonstration of grip and percussion myotonia. Percussion myotonia can generally be

Table 36–2. Electrophysiologic Testing in Myotonic and Periodic Paralysis Disorders

Test	Myotonic Dystrophy, Type 1	Myotonic Dystrophy, Type 2	Myotonia Congenita: Dominant	Myotonia Congenita: Recessive	Sodium Channel Myotonia	Paramyotonia Congenita	Hyperkalemic Periodic Paralysis	Hypokalemic Periodic Paralysis	Andersen–Tawil Syndrome
Nerve conduction studies	Normal or decreased distal CMAPs	Normal	Normal	Normal	Normal	Normal	Normal between attacks; decreased CMAP amplitude during attack of weakness	Normal between attacks; decreased CMAP amplitude during attack of weakness	Normal
EMG Myotonia MUAPs	++D >P Myopathic D	++D >P (upper extremity); D = P (lower extremity) Occasional CRDs Myopathic P	+++P and D Normal	+++P and D Usually NL, ±Myopathic	++P and D Normal	++P and D Normal	++P and D, especially during attack Myopathic late in course	No myotonia Myopathic late in course	No myotonia Normal
Muscle cooling (20°C) on electromyography	No effect	Unknown	May lead to increased duration of myotonic bursts; easier to elicit	No effect	Unknown	Transient dense fibrillation potentials that disappear below 28°C; myotonic bursts disappear below 20°C electrical silence, long lasting muscle contracture at 20°C	No effect	No effect	No effect
Short exercise	Drop in CMAP amplitude; quick recovery over 2 minutes; drop is smaller or does not persist on subsequent trials	Not well documented	Variable drop in CMAP amplitude; quick recovery over 2 minutes	Large drop in CMAP amplitude; delay in recovery may become progressive over time	Unknown	Normal or small increment in a warm muscle; marked drop in CMAP amplitude and very slow recovery over 1 hour in cooled muscle	No effect or transient increase in CMAP amplitude during an attack of weakness	No effect or transient increase in CMAP amplitude during an attack of weakness	No effect
Prolonged exercise	Small decrement immediately after exercise, with recovery over 3 minutes	Unknown	Unknown	Small decrement immediately after exercise, with recovery over 3 minutes	Unknown	Moderate decrement immediately after exercise, maximal at 3 minutes, with slow recovery over 1 hour in cooled muscle	Most with initial increase in CMAP amplitude (~35%); progressive drop in CMAP amplitude (~50%) over 20 to 40 minutes with slow recovery over 1 hour	Most with initial increase in CMAP amplitude (~35%); progressive drop in CMAP amplitude (~50%) over 20 to 40 minutes with slow recovery over 1 hour	Most with initial increase in CMAP amplitude (~35%); progressive drop in CMAP amplitude (~50%) over 20 to 40 minutes with slow recovery over 1 hour
10 Hz RNS	Decrement	Not well documented	Decrement	Large decrement	Not documented	Normal	Normal	Normal	Normal

CMAP, compound muscle action potential; CRD, complex repetitive discharge; D, distal; EMG, electromyogram; MUAP, motor unit action potential; NL, normal; P, proximal; RNS, repetitive nerve stimulation.

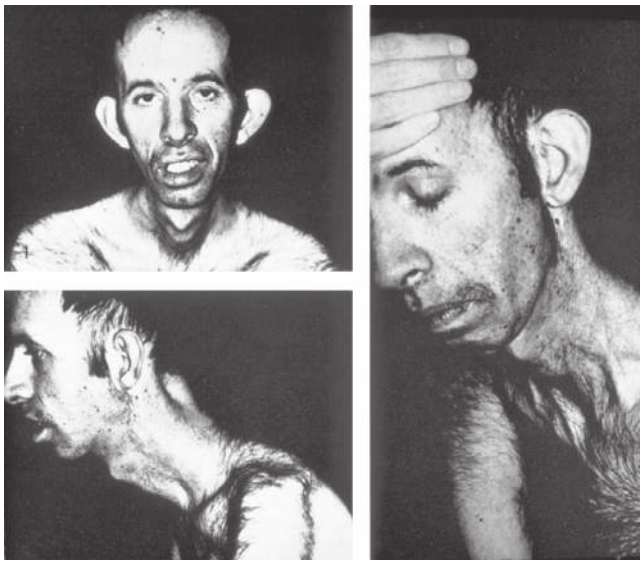

FIGURE 36–4 Typical facies in myotonic dystrophy. Note frontal balding, ptosis, temporal wasting, elongated face, horizontal smile. (Reprinted from Brooke, M.H., 1986. A clinician's view of neuromuscular disease. Williams & Wilkins, Baltimore, with permission.)

elicited most easily over the thenar muscles and long finger extensors. Eyelid myotonia is not seen. Deep tendon reflexes often are reduced or absent in the lower extremities as the disease progresses. Slit lamp examination reveals posterior capsular cataracts, which early on have a characteristic multicolored pattern. Approximately 10% of cases are congenital, characterized by severe weakness and hypotonia at birth and mental retardation. Children with the congenital form are floppy at birth, have a typical tented upper lip with poor sucking and swallowing, and often have contractures. Surprisingly, clinical myotonia is not present the first year of life. The congenital form nearly always is maternally inherited. In many cases, the mother may be so minimally affected that her diagnosis is not made until the infant is born with severe hypotonia and a myopathic facies.

Creatine kinase (CK) levels may be mildly to moderately elevated. Muscle biopsy typically reveals a mild increase in connective tissue, increased variation in fiber size, atrophy of type I muscle fibers, increase in central nuclei, ring fibers, and occasional small angulated fibers.

The clinical severity of DM1 is directly related to the number of CTG repeats. In normals, the number varies between 5 and 37, whereas in patients with DM1 the number of CTG repeats may range into the thousands. In patients with a very small increase in the number of repeats (50–100), less than a half of these patients are symptomatic, and most of these patients have cataracts only. More typically symptoms and signs of DM1 are present in patients with over 100 repeats.

Electrophysiologic Evaluation

The electrophysiologic evaluation of DM1 (Table 36–2) consists of routine nerve conduction studies, electromyography, muscle cooling, and exercise testing.

1. Routine motor and sensory nerve conduction studies are normal as a rule. Generally, one motor and sensory nerve conduction study and F responses in an upper and lower extremity will suffice. A mild neuropathy has been described, perhaps secondary to the accompanying endocrine changes. Low CMAP amplitudes may be noted secondary to the distal myopathy in patients with severe disease.
2. Concentric needle EMG of at least one upper and one lower extremity should be performed, in addition to sampling facial and paraspinal muscles. Most but not all patients with DM1 will demonstrate myotonic discharges on EMG. In very mild cases (e.g., in patients with a small increase in the number of repeats), myotonic discharges may be difficult to find. Otherwise, myotonic discharges are generally most prominent in the distal hand, forearm extensor, foot dorsiflexor (tibialis anterior), and facial muscles but usually are not found in proximal muscles. The distribution of myotonic discharges follows the same pattern as the weakness. Myotonic discharges in DM1 are the classic waxing and waning muscle fiber action potentials (Figure 36–5A). MUAP analysis may be difficult because of the myotonic discharges provoked by needle insertion or muscle contraction. However, careful examination reveals myopathic (low amplitude, short duration, polyphasic) MUAPs with early recruitment, which are generally noted in the forearm extensor and tibialis anterior muscles, consistent with the distal predominant weakness on clinical examination.
3. Muscle cooling to 20°C has no appreciable effect on the EMG examination.
4. The short exercise test produces a drop in the CMAP amplitude immediately after exercise. If the CMAP then is recorded every 10 seconds up to 2 minutes, it recovers to baseline. If short exercise is repeated, the decremental response habituates after one or two cycles, with no further decrement in the CMAP occurring immediately after exercise.
5. Repetitive nerve stimulation at 10 Hz produces a decrement, similar to the short exercise test.

When electrophysiologic testing is completed, one has established the presence of myotonia with myopathic MUAPs on the needle examination, with a distal and facial muscle predominance. There is no effect of muscle cooling. The short exercise test demonstrates a decrement that recovers over 1 to 2 minutes and habituates with further cycles. This pattern of abnormalities strongly suggests the diagnosis of myotonic dystrophy type 1. Note that when a patient presents with typical signs and symptoms of myotonic muscular dystrophy, muscle cooling, exercise testing, and repetitive nerve stimulation are not necessarily done on a routine basis, but may be helpful in some clinical situations, when the diagnosis is still in question after standard nerve conduction studies and EMG needle examination are completed.

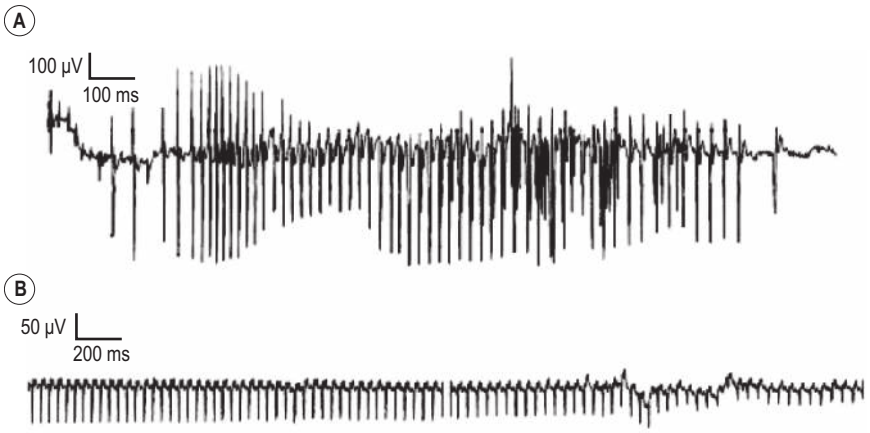

FIGURE 36–5 Myotonic discharges. **A:** Two-second myotonic discharge in a patient with DM1 showing typical waxing and waning frequency and amplitude; maximal frequency about 60 Hz, minimal frequency about 8 Hz. **B:** Four-second myotonic discharge (two successive oscilloscope sweeps) in a patient with DM2 in which frequency and amplitude gradually decline with no waxing component; maximal frequency toward onset about 23 Hz, minimal frequency toward termination about 19 Hz.
(With permission from Logigian, E.L., Ciafaloni, E., Quinn, L.C., et al., 2007. Severity, type, and distribution of myotonic discharges are different in type 1 and type 2 myotonic dystrophy. Muscle Nerve 35, 479–485.)

Myotonic Dystrophy Type 2

Clinical

DM2 has many features in common with DM1. Like DM1, it is an autosomal dominant inherited muscle disorder recognized by a constellation of signs, including bifacial weakness, ptosis, progressive weakness, myotonia, and involvement of several organ systems outside of skeletal muscle. Patients typically present after the age of 40 with progressive weakness. Unlike myotonic dystrophy, however, the weakness involves predominantly proximal, as opposed to distal, muscles. The pattern of weakness typically involves the hip flexors and extensors, neck flexors, elbow extensors, and finger and thumb flexors. Anticipation is generally not seen between generations of affected family members. Like DM1, the multisystem involvement may include posterior capsular cataracts, frontal balding, testicular atrophy, and cardiac conduction defects. However, CNS involvement does not occur or is much less common.

Patients are recognized by their presentation of proximal greater than distal weakness, with mild bifacial weakness and ptosis in the setting of grip and percussion myotonia. Many patients have a peculiar intermittent pain syndrome in the thighs, arms, or back. CK may be mildly to moderately elevated, and the muscle biopsy reveals a nonspecific myopathic pattern, including increased variation in fiber size, small angulated fibers, pyknotic nuclear clumps, predominant atrophy of type II fibers, and increased central nuclei. Rare cases of isolated elevated CK ("hyper-CKemia") without other clinical or electrical abnormalities have been reported in DM2.

Electrophysiologic Evaluation

See Table 36–2.

1. Routine motor and sensory nerve conduction studies are normal as a rule. Generally, one motor and sensory nerve conduction study and F responses in an upper and lower extremity will suffice.
2. Concentric needle EMG of at least one upper and one lower extremity and paraspinal muscles should be performed. In contrast to DM1, the myotonic discharges tend to be predominantly waning potentials (Figure 36–5B). These potentials are less specific than the classic waxing and waning discharges typically associated with myotonia. The distribution of the myotonic discharges in the upper extremities in DM2 is surprisingly more prominent in the distal than in the proximal muscles, similar to DM1. The leg, however, is different. Although myotonic discharges are present in distal muscles (e.g., the tibialis anterior), the number of myotonic discharges is not significantly greater in distal than in proximal muscles (e.g., tensor fascia lata). Thus, the presence of myotonic discharges in the proximal lower extremity muscles is much more common in DM2 than DM1. Similar to DM1, the absence of myotonic discharges does not exclude the diagnosis of DM2. Complex repetitive discharges are noted occasionally. MUAP analysis reveals myopathic (low amplitude, short duration, polyphasic) MUAPs with early recruitment, which are generally noted in the proximal lower extremity muscles.

   Once the nerve conduction studies and EMG are completed, the presence of myotonia with myopathic MUAPs has been established on needle examination, present primarily in proximal muscles of the lower extremity, and distal muscles of both the upper and lower extremities. Few disorders associated with myotonia have a proximal predominance with myopathic MUAPs. Rarely, prominent myotonic discharges, complex repetitive discharges, and myopathic MUAPs in the very proximal muscles are noted in patients with adult-onset acid maltase deficiency. In this disorder, however, the myotonic discharges are generally restricted to the paraspinal muscles. Myotonic discharges also may be seen in some cases of

polymyositis, where abnormal spontaneous activity and MUAP changes are more prominent proximally. However, myotonic discharges are only infrequently seen in polymyositis. In the myotonia congenitas, myotonic discharges are noted mostly in proximal muscles as well, but with rare exception (i.e., some cases of recessive generalized myotonia congenita), there are no myopathic MUAP changes.

3. The effects of muscle cooling and the short and prolonged exercise tests have not been well described for this disorder. Short exercise testing in one patient personally examined by the authors revealed no drop in the CMAP amplitude recording from a distal hand muscle. This negative finding may reflect the proximal predominance of weakness.

NONDYSTROPHIC MYOTONIC MUSCLE DISORDERS AND PERIODIC PARALYSIS SYNDROMES

Myotonia Congenita

Myotonia congenita is distinguished from the dystrophic muscle disorders by the lack of weakness in most patients and by the absence of extramuscular abnormalities. Two forms of myotonia congenita have classically been recognized. An autosomal dominant form, Thomsen disease, was first described in 1876 by Julius Thomsen, who was himself affected. Thomsen noted the great variability among his own affected family members; it was barely apparent in his mother and uncle, but very severe in his younger brother and sister. An autosomal recessive form of generalized myotonia congenita was first described by Becker. The recessive form is characterized by later onset, marked myotonia, and moderate muscular hypertrophy. Late in the course, there may be minor weakness and atrophy of the forearm and neck muscles, though it is still considered a nondystrophic syndrome. Some patients with recessive myotonia congenita also experience transient attacks of weakness that are relieved with exercise. Both the recessive and dominant forms of myotonia congenita arise from a skeletal muscle chloride channel-1 (*CLCN*) gene defect on chromosome 7q.

Other myotonia congenita phenotypes have also seen described, but with mutations on the muscle sodium α-subunit (*SCN4A*) gene on chromosome 17. These atypical myotonia congenitas include potassium aggravated myotonia (PAM), myotonia permanens, myotonia fluctuans, and acetazolamide responsive myotonia. This is the same sodium channel gene with mutations that result in hyperkalemic periodic paralysis, paramyotonia congenita, and rare cases of hypokalemic periodic paralysis. These atypical myotonia congenitas are discussed with the periodic paralyses and paramyotonia congenita disorders below to which they are more closely related.

Clinical

Onset of the dominant form is generally in infancy or early childhood; onset of the recessive form is usually later in childhood. Patients generally present with painless myotonia resulting in muscle stiffness that is nonprogressive. Muscle hypertrophy is common, secondary to the almost constant state of muscle contraction. The stiffness worsens after rest or with cold and diminishes with exercise. The myotonia may also be exacerbated during pregnancy, from hunger, and secondary to emotional upset. Patients typically describe a warm-up period, during which they can work through the muscle stiffness. For example, it is not uncommon for a patient to describe difficulty rising from a chair after sitting for a few minutes or difficulty climbing up the first few steps of a stairway, which then improves. In the autosomal dominant form, muscle hypertrophy is often noted in the proximal arms, thighs, and calves. Grip and percussion myotonia are easily elicited. CK levels may be slightly elevated in the dominant form and moderately elevated in the recessive form. Muscle biopsy may show a lack of type IIB fibers.

Electrophysiologic Examination

See Table 36–2.

1. Routine motor and sensory nerve conduction studies are normal as a rule. Generally, one motor and sensory nerve conduction study and F responses in an upper and lower extremity will suffice.
2. Concentric needle EMG of at least one upper and one lower extremity and paraspinal muscles generally shows widespread myotonic discharges, which are easily elicited with minimal needle movement or muscle contraction in proximal and distal muscles. In the dominant form, the MUAPs and recruitment pattern are normal. In the recessive form, there may be mildly myopathic MUAPs with early recruitment.
3. Muscle cooling to 20°C in the dominant form may produce myotonic bursts of longer duration that may be more easily elicited than at room temperature.
4. The short exercise test produces a drop in CMAP amplitude immediately after exercise, which recovers over 1 to 2 minutes with repeated recording of the CMAP every 10 seconds (Figure 36–2). Muscle cooling has no appreciable effect on the exercise test. This is unlike paramyotonia congenita (see section on Paramyotonia Congenita), in which a decremental response recovers very slowly over many minutes, if the muscle is cooled. In the recessive form of myotonia congenita, the initial drop in amplitude often is profound with a delay in recovery that may become progressive over time. In the dominant form, the decrement is variable with a quick recovery.
5. Repetitive nerve stimulation at 10 Hz may result in large decrements (often greater than 40%) in two thirds of patients with recessive myotonia congenita, in contrast to only one third that demonstrate a decrement using the short exercise test. Thus, RNS may be a useful adjunct in the evaluation of patients with recessive myotonia congenita.

The electrodiagnosis of myotonia congenita is based on the presence of widespread myotonic discharges with normal MUAPs and recruitment pattern on needle examination. The responses to muscle cooling, the short exercise test and RNS can then be used to differentiate it from paramyotonia congenita.

Paramyotonia Congenita, Hyperkalemic Periodic Paralysis, and Sodium Channel Myotonia Congenita

Paramyotonia congenita, hyperkalemic periodic paralysis, and sodium channel myotonia are associated with distinct mutations of the voltage-gated sodium channel α-subunit (*SCN4A*) gene on chromosome 17q. Each of these conditions is inherited in an autosomal dominant fashion.

Clinical

Patients with paramyotonia congenita and hyperkalemic periodic paralysis experience attacks of weakness; patients with sodium channel myotonia congenita do not experience weakness.

Paramyotonia Congenita

Paramyotonia congenita was first described by Eulenburg in 1886. Patients present in infancy with muscle stiffness that primarily affects the bulbofacial, neck, and hand muscles. In paramyotonia, muscle stiffness is brought on by repeated muscle contraction or exercise, as opposed to myotonia, in which a warm-up period of repeated muscle contraction alleviates the muscle stiffness. Thus, the designation is *paradoxical*, or *paramyotonia*. Muscle stiffness also is triggered by exposure to cold. In most patients, cold induces attacks of stiffness followed by true weakness, especially during prolonged exercise in cold temperatures. It may take hours to regain strength despite warming. The first signs often occur when the infant is noted to have prolonged eye closure after crying or sleeping near a fan or after having his or her face washed with cool water. Patients often are very muscular.

Hyperkalemic Periodic Paralysis

Patients with hyperkalemic periodic paralysis present in early childhood with attacks of periodic weakness that are provoked by rest after exercise, fasting, emotional stress, cold, and potassium loading. Weakness commonly occurs in the morning after awakening from sleep. Some patients can forestall an impending attack with mild exercise. Attacks of weakness usually are brief, lasting from minutes to hours, and generally are accompanied by hyporeflexia. Rare patients experience prolonged attacks of weakness. Weakness usually is generalized but spares the facial and respiratory muscles. The potassium level usually is elevated during attacks, although in some patients it is normal. Symptoms are relieved by ingesting carbohydrates or inhaling a β-adrenergic agent. Myotonia, if present, can be variable. In some patients, the myotonia is detected only on EMG testing, whereas in others myotonia is elicited on physical examination. The frequency of attacks generally lessens in middle age, and some patients develop fixed progressive proximal weakness in adulthood.

Sodium Channel Myotonia Congenita

Patients with sodium channel myotonia congenita, also known as *potassium-aggravated myotonia* (PAM), present with episodes of generalized stiffness secondary to myotonia. The disorder is quite potassium sensitive, with worsening of symptoms by potassium ingestion but in most patients no worsening with cold. These patients do not experience true episodic weakness. The myotonia may be painful and has a peculiar feature in that it is exercise induced, with a delay in the onset of the myotonia for several minutes after exercise. Several variants with various names, depending on the severity and quality of the fluctuating stiffness and its response to treatment, have been described. All are inherited in an autosomal dominant fashion. These variants include myotonia fluctuans, myotonia permanens, and acetazolamide-responsive myotonia. Myotonia permanens is the most severe, often associated with continuous myotonic discharges on EMG. In some reported cases, retarded growth and dysmorphic facial features have been noted.

Electrophysiologic Examination

See Table 36–2.

Paramyotonia Congenita

1. Routine motor and sensory nerve conduction studies are normal as a rule. Generally, one motor and sensory nerve conduction study and F responses in an upper and lower extremity will suffice.
2. Concentric needle EMG of at least one upper and one lower extremity and paraspinal muscles generally shows easily elicited myotonic discharges in proximal and distal muscles, although not as easily elicited as in the myotonia congenitas. The myotonia may be more prominent in distal muscles. The MUAPs are normal in amplitude and duration with a normal pattern of recruitment.

   Once the presence of myotonia has been established on needle examination, with normal MUAPs and recruitment pattern, muscle cooling and exercise testing may be helpful.
3. Muscle cooling to 20°C may have a profound effect on the needle EMG, which is pathognomonic for this disorder. Transient dense fibrillation potentials appear with cooling and eventually disappear below 28°C. As the muscle cools down further, all myotonic discharges completely disappear below 20°C, giving way to paralysis of the muscle. At this point the muscle is inexcitable to electrical or mechanical stimulation as the muscle goes into a long-lasting, electrically silent contracture. This state may last over an hour after the muscle is warmed to room temperature. Note that the hand should always be removed from the ice water if weakness develops.
4. Repetitive nerve stimulation at 10 Hz results in no decrement.
5. The short exercise test results in no decrement and in some cases a slight increment when the muscle is warm at room temperature. However, with the

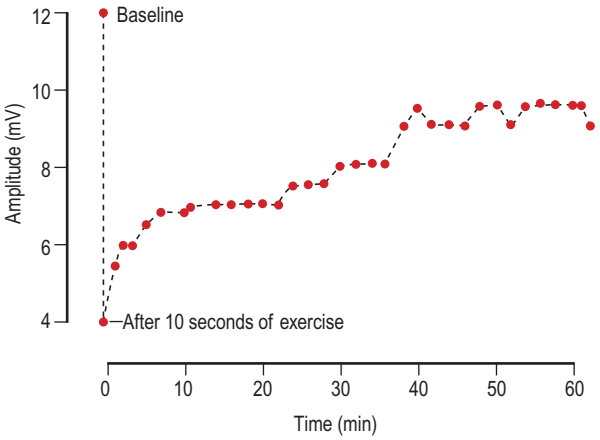

FIGURE 36–6 Typical response on the short exercise test in paramyotonia congenita. After a brief maximal voluntary contraction, the compound muscle action potential immediately decrements in the myotonic syndromes. In paramyotonia congenita, the recovery may be quite delayed, in the range of 10 to 60 minutes, especially if the muscle is cooled, compared with myotonic dystrophy or myotonia congenita, in which the repair occurs over 1 to 2 minutes.
(From Streib, E.W., 1987. AAEE minimonograph, no. 27: differential diagnosis of myotonic syndromes. Muscle Nerve 10, 603, with permission.)

muscle cooled, the short exercise may produce a large drop in CMAP amplitude that shows a marked delay in recovery to the baseline CMAP amplitude with repeated recording of the CMAP up to 1 hour (Figure 36–6). This is unlike myotonic dystrophy or the chloride channel myotonia congenitas, in which the drop in CMAP amplitude recovers to baseline over 1 to 2 minutes, although in recessive myotonia congenita the delay in recovery may become progressive over time.

Hyperkalemic Periodic Paralysis

1. As a rule, routine motor and sensory nerve conduction studies are normal if performed between attacks of weakness. Generally, one motor and sensory nerve conduction study and F responses in an upper and lower extremity suffice. During an attack of weakness, the CMAP amplitudes may decline proportionally to the degree of weakness.
2. Concentric needle EMG of at least one upper and one lower extremity and paraspinal muscles between attacks may be normal in amplitude and duration with a normal pattern of recruitment, but in some patients myopathic MUAPs may be found. In patients with hyperkalemic periodic paralysis with myotonia, myotonic discharges may either increase or appear for the first time during an attack of weakness in patients whose baseline EMG does not show myotonic discharges. Myotonic discharges are seen early in the attack but then disappear as weakness progresses. During an attack of weakness, there is a reduction in the size and number of MUAPs recruited in weak muscles.
3. Muscle cooling has no appreciable effect on the needle EMG findings.

   Once the presence of myotonia has been established on needle examination, with normal or myopathic MUAPs, the next step is exercise testing.
4. The short exercise test produces no decrement.
5. The prolonged exercise test often produces an immediate increase in the CMAP amplitude, especially if the initial amplitude is low. This is followed, however, by a progressive drop in the CMAP amplitude by about 50% over 20 to 40 minutes, with most of the decline occurring in the first 20 minutes (Figure 36–3). It should be noted that a similar decline in the CMAP may be noted by simply immobilizing the muscle without exercise. If there is a decline in the CMAP with rest, then exercise may produce a brief increment in the CMAP.

Sodium Channel Myotonia Congenita

1. Routine motor and sensory nerve conduction studies are normal as a rule. Generally, one motor and sensory nerve conduction study and F responses in an upper and lower extremity will suffice.
2. Concentric needle EMG examination of at least one upper and one lower extremity and paraspinal muscles generally shows myotonic discharges, which are elicited in proximal and distal muscles. The MUAPs are normal in amplitude and duration with normal recruitment.
3. The effects of muscle cooling, short and prolonged exercise testing, and repetitive stimulation are not well documented.

Hypokalemic Periodic Paralysis

Hypokalemic periodic paralysis is not a myotonic disorder. However, the clinical features of periodic attacks of flaccid weakness and the development of fixed proximal weakness later in life resemble the sodium channel disorders discussed earlier. This is an autosomal dominant inherited disorder associated with a defect in the α subunit of a voltage-sensitive muscle calcium channel (*CACNA1S*) gene on chromosome 1q (hypokalemic periodic paralysis type 1). More recently, mutations were identified in the α subunit of the sodium channel gene (*SCN4A*) on chromosome 17q, and the term hypokalemic periodic paralysis type 2 was used to designate this small group of patients, who are clinically indistinguishable from those with hypokalemic periodic paralysis type 1. Both types result from missense mutations in the voltage-sensor domains of their respective channel. This similarity suggests a common functional defect produced by these voltage-sensor mutations, and may explain why different mutations on two different channels result in hypokalemic periodic paralysis.

At least 20% of cases remain genetically undetermined.

Clinical

Patients with hypokalemic periodic paralysis present in their teenage years with attacks of periodic weakness.

Attacks are provoked by cold, carbohydrate ingestion, alcohol, emotional stress, and rest after exercise. Some patients can forestall an impending attack with mild exercise. Attacks of weakness may be quite prolonged, generally occurring on awakening from sleep and rarely involving respiratory muscles. Weakness often is accompanied by hyporeflexia. The potassium level usually is low during attacks, although in some cases it is normal. Myotonia is not present either clinically or with EMG testing, with the exception of eyelid myotonia in some patients. Attacks are more frequent in males than females. It is not uncommon for females to be so minimally affected or completely unaffected by periodic weakness that they are unaware that they have the disorder. All patients, however, invariably develop progressive proximal weakness during adulthood, whether or not they have had attacks of periodic paralysis. Muscle biopsy shows a vacuolar myopathy.

Electrophysiologic Examination

See Table 36–2.

1. Routine motor and sensory nerve conduction studies are normal as a rule. Generally, one motor and sensory nerve conduction study and F responses in an upper and lower extremity will suffice. During an attack of weakness, the CMAP amplitudes generally decline proportionally to the degree of weakness.
2. Concentric needle EMG findings of at least one upper and one lower extremity and paraspinal muscles should show no myotonic discharges. The MUAPs and recruitment pattern are generally normal in the early stages of the disorder. As in hyperkalemic periodic paralysis, however, there is a reduction in the size and number of MUAPs recruited in weak muscles during a paralytic attack. As patients develop fixed proximal weakness, myopathic MUAPs with early recruitment are noted in proximal muscles. We studied one elderly female patient in the later stages of the disorder with fixed proximal weakness who had large, prolonged MUAPs with reduced recruitment in proximal more than distal muscles. Thus, in very chronic myopathies, the EMG changes may resemble those of chronic neurogenic disorders.
3. Muscle cooling has no appreciable effect on the needle EMG findings.
4. The short exercise test produces no decrement.
5. The prolonged exercise test often produces an immediate increase in the CMAP amplitude, especially if the initial amplitude is low. This is followed, however, by a progressive drop in the CMAP amplitude by about 50% over 20 to 40 minutes, with most of the decline occurring in the first 20 minutes. It should be noted that a similar decline in the CMAP may be noted just by immobilizing the muscle without exercise. If there is a decline in the CMAP with rest, exercise may produce a brief increment in the CMAP.

Andersen–Tawil Syndrome

Andersen–Tawil syndrome (ATS) is characterized by a clinical triad of periodic paralysis, ventricular arrhythmias, and dysmorphic facial features. This is an autosomal dominant inherited disorder associated in most families with mutations in the Kir2.1 subunit of the inward rectifying potassium channel (*KCNJ2*) gene on chromosome 17q, resulting in dysfunctional inward rectifier potassium channels. Genetic heterogeneity is likely, as no mutations in Kir2.1 have been found in some families with Andersen–Tawil syndrome. These families may have mutations in other genes that regulate Kir2.1.

Clinical

Patients present in childhood or adolescence, with some or all features of the clinical triad of periodic paralysis, prolonged QT interval and ventricular arrhythmias, and distinctive physical features. Characteristic physical features include short stature, high arched palate, low-set ears, broad nose, micrognathia, hypertelorism, clinodactyly of the fingers, short index finger, and syndactyly of the toes (Figure 36–7). Some patients may have minor neurocognitive deficits, among them, difficulties with complex problem-solving, attention and concentration, and solving abstract problems. Scoliosis may be present. Neurologic examination between paralytic attacks may reveal generalized limb and neck flexor weakness. There is no associated grip or percussion myotonia. Paralytic attacks may occur spontaneously or may be triggered by rest after exercise or alcohol. Some patients report intermittent muscle pain without attacks of weakness.

As with other types of periodic paralysis, some patients can work through the muscle pain by continuing with mild exercise. The periodic paralysis may be associated with hypo-, hyper-, or normal potassium levels. Prolonged QT interval is the most consistent cardiac manifestation, present in about 80% of patients, and may be the only finding in some individuals from a family with typical ATS syndrome. In some patients, the long QT interval may be asymptomatic. However, patients may present in childhood with cardiac arrest, with no history of periodic paralysis, although they may experience periodic paralysis in later years. Some patients with periodic paralysis and characteristic facial features do not have a prolonged QT interval at rest, although other electrocardiographic findings may be seen, such as a prominent U wave in the chest leads.

Electrophysiologic Examination

See Table 36–2.

1. Routine motor and sensory nerve conduction studies are normal as a rule. Generally, one motor and sensory nerve conduction study and F responses in an upper and lower extremity will suffice. During an attack of weakness, the CMAP amplitudes generally decline proportionally to the degree of weakness.

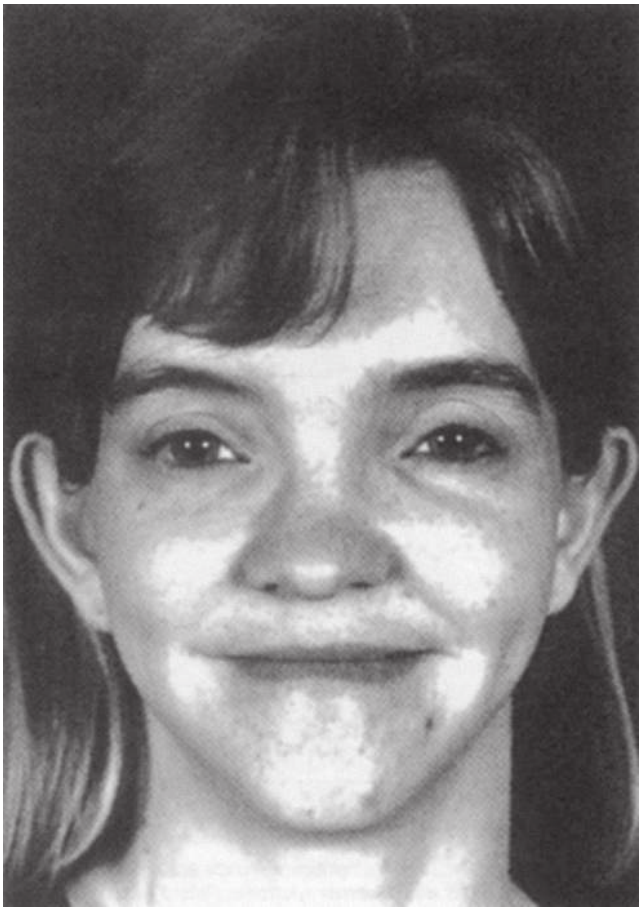

FIGURE 36–7 Characteristic facial features in Andersen–Tawil syndrome. Note low-set ears, broad nose, and hypertelorism. (Reprinted from Sansone, V., Griggs, R.C., Meola, G., et al., 1997. Andersen's syndrome: a distinct periodic paralysis. Ann Neurol 42, 305–312, with permission.)

2. Concentric needle EMG findings of at least one upper and one lower extremity and paraspinal muscles should show no myotonic discharges. The MUAPs and recruitment pattern are generally normal. As with the other periodic paralyses, there may be a reduction in the size and number of MUAPs recruited in weak muscles during a paralytic attack.
3. Muscle cooling has no appreciable effect on the needle EMG findings.
4. The short exercise test produces no decrement.
5. The prolonged exercise test often produces an immediate increase in the CMAP amplitude, especially if the initial amplitude is low. This is followed, however, by a progressive drop in the CMAP amplitude by about 50% over 20 to 40 minutes, with most of the decline occurring in the first 20 minutes. It should be noted that a similar decline in the CMAP may be noted just by immobilizing the muscle without exercise. If there is a decline in the CMAP with rest, exercise may produce a brief increment in the CMAP.

Schwartz–Jampel Syndrome (Chondrodystrophic Myotonia)

Schwartz–Jampel syndrome (SJS) is a rare, inherited myotonic-like disorder characterized by distinctive physical features, skeletal deformities, and muscle stiffness. The syndrome usually is inherited as an autosomal recessive condition, but in occasional families, the inheritance pattern suggests an autosomal dominant disorder. SJS is linked to chromosome 1q, 1p, or 5p in different families. SJS type 1 is associated with mutations in the gene encoding perlecan (*HSPG2*) on chromosome 1p. Perlecan is a heparan sulfate proteoglycan present in all basement membranes and is involved in cell adhesion and growth factor signaling. SJS type 2 is associated with mutations in the leukemia inhibitory factor receptor (*LIFR*) gene on chromosome 5p. The variability in severity of SJS within and between families suggests that the phenotype may be modified by several genes.

Clinical

The clinical manifestations of SJS may vary among affected members of the same family. In general, patients have muscle stiffness and chondrodysplasia. There is often predominantly distal weakness and atrophy, which may be accompanied by prominent proximal upper and lower extremity muscle hypertrophy. In contrast to the pseudohypertrophy seen in dystrophinopathies, proximal limb muscles in SJS are genuinely enlarged. Characteristic facial and physical appearance include short stature, short neck, and multiple facial anomalies (micrognathia, low-set ears, pursed lips, prominent eyebrows, upward slanting eyes, blepharophimosis, exotropia, and microcornea) (Figure 36–8). Approximately 20% of patients have some degree of cognitive impairment. SJS type 1 manifests at birth or during early childhood with moderate bone dysplasia, muscle hypertrophy, stiffness, and dysmorphic facial features. SJS type 2 is the more severe, manifesting at birth with contractures, severe long bone bowing, prominent stiffness, and severe facial and pharyngeal deformities that preclude normal feeding, usually leading to infantile death. Other features include malignant hyperthermia and susceptibility to carpal tunnel syndrome.

SJS had been initially described as a myotonic disorder. However, on EMG, there is increasing evidence that the abnormal discharges are not myotonic discharges, but rather neuromyotonic discharges. The discharges can be abolished by curare, which strongly implies that the abnormal discharges are of peripheral nerve origin. The discharges also persist immediately after nerve transection but completely disappear when wallerian degeneration has been completed, which strongly suggests a distal axonal localization of the spontaneous discharges.

Electrophysiologic Examination

1. Routine motor and sensory nerve conduction studies are normal as a rule. Generally, one motor and

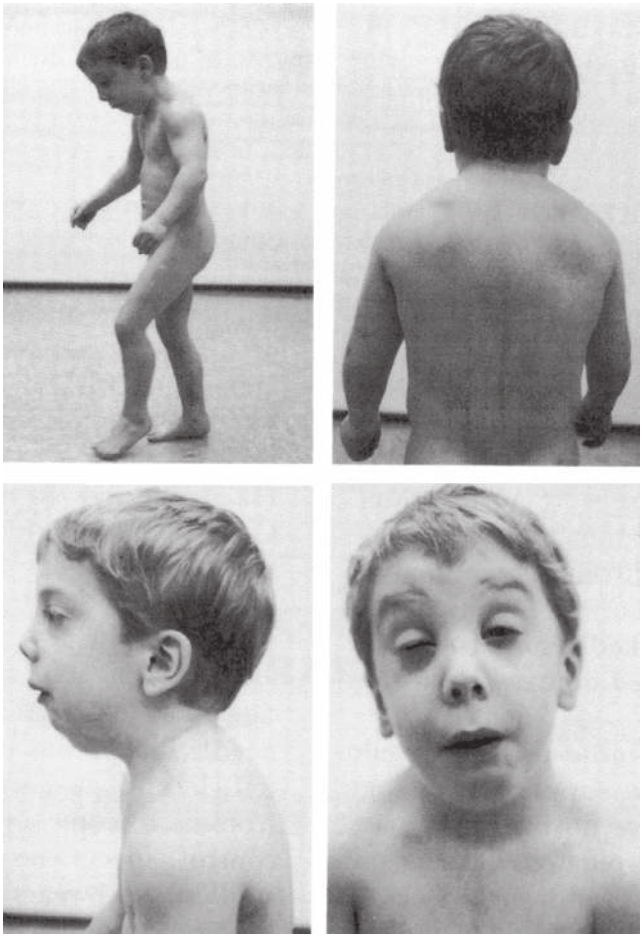

FIGURE 36–8 Typical appearance of Schwartz-Jampel syndrome. Note skeletal and facial anomalies including short neck, small mouth, micrognathia, pursed lips, upward slanting eyes, blepharophimosis, low-set ears, and prominent eyebrows. Proximal upper and lower extremity muscle hypertrophy and distal predominant generalized weakness and atrophy also are noted.
(Reprinted from Spaans, F., Theunissen, P., Reekers, A.D., et al., 1990. Schwartz–Jampel syndrome: I. Clinical, electromyographic, and histologic studies. Muscle Nerve 13, 516–527, with permission.)

sensory nerve conduction study and F responses in an upper and lower extremity will suffice.

2. Concentric needle EMG findings of at least one upper and one lower extremity and paraspinal muscles generally show continuous discharges. As noted above, these discharges have a myotonic quality, but close inspection reveals that they are more likely neuromyotonic discharges (with a motor unit action potential morphology, waning amplitude and frequency, and very high initial firing rates). In some cases, complex repetitive discharges are seen. In others, myokymic discharges have been described.
3. The effects of muscle cooling, short exercise, and prolonged exercise testing are unknown.

The clinical presentation of SJS is so characteristic that the differential diagnosis is quite limited. The diagnosis is usually established by the combination of characteristic physical features, dwarfism, and stiffness accompanied by muscle enlargement.

OTHER CONDITIONS ASSOCIATED WITH MYOTONIA

Occasionally, myotonia and periodic paralysis are noted in the clinical and EMG examinations of various other disease states (Table 36–1), including acquired periodic paralyses; various metabolic, inflammatory, and congenital myopathies; and some disorders associated with systemic diseases. Furthermore, certain drugs can either unmask or precipitate myotonia.

EXAMPLE CASES

Case 36–1

History and Physical Examination

A 29-year-old man was referred for mild distal weakness and difficulty releasing his hand grip. He first noted difficulty with releasing his grip approximately 10 years ago, especially while shaking hands, driving his car, or using a hammer. Symptoms were not worse in the cold. Family history was notable for the following: his mother had early cataracts, several miscarriages, and very mild distal weakness that began in her late 40s; a maternal aunt had mild diabetes; and a younger sister had similar complaints of occasional muscle stiffness.

On examination, the patient's mental status was unremarkable. On cranial nerve examination, the face was narrow and elongated, with mild bilateral ptosis, bifacial weakness with wasting of the temporalis muscles, and mild frontal balding. Extraocular movements were full. Early cataracts were noted bilaterally. Neck flexors and distal hand and foot muscles were slightly weak. Marked percussion myotonia of the tongue and thenar muscles was noted, with marked hand grip myotonia that improved with repeated contractions. Deep tendon reflexes were depressed in the lower extremities bilaterally, with plantar flexor responses. Sensation and coordination were normal throughout. Laboratory studies were notable for a mildly elevated CK level (three times normal), normal electrolyte levels and thyroid function studies, and normal electrocardiographic findings.

Summary

The history is that of a young man in his late 20s with mild distal weakness and difficulty releasing his hand grip. Neurologic examination is notable for a normal mental status; a long, narrow face with bilateral ptosis, bifacial weakness, temporal wasting, frontal balding, early cataracts, mild neck flexion, and distal weakness; hypoactive reflexes in the lower extremities; and percussion and grip myotonia of distal muscles. The myotonia improves with repeated contractions. In summary, there is clinical evidence of a dystrophic muscle disorder with key

CASE 36–1. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	10.2		≥4	3.6		≤4.4				28		≤31
	Antecubital fossa	APB	10.1			8.2			56		≥49			
Ulnar (m)	Wrist	ADM	12.6		≥6	2.9		≤3.3				31		≤32
	Below elbow	ADM	12.2			6.9			58		≥49			
	Above elbow	ADM	12.1			8.4			62		≥49			
Median (s)	Wrist	Index finger	28		≥20	3.2		≤3.5	53		≥50			
Ulnar (s)	Wrist	Little finger	24		≥17	2.8		≤3.1	51		≥50			
Tibial (m)	Ankle	AHB	6.2		≥4	5.2		≤5.8						
	Popliteal fossa	AHB	5.6			12.6			46		≥41			
Sural (s)	Calf	Posterior ankle	9		≥6	3.9		≤4.4	47		≥40			
Short exercise test:														
Ulnar (m)	Wrist	ADM	Immediate drop in baseline CMAP amplitude by 50% on first trial of exercise, which recovers over 2 minutes. Next trial produces similar results. Third and fourth trials produce no drop in CMAP amplitude after short exercise.											

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis; ADM = abductor digiti minimi; AHB = abductor hallucis brevis; CMAP = compound muscle action potential.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 36–1. Electromyography Needle Examination

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right first dorsal interosseous	Myo	0	0	NL	Early	–1	–1	+1
Right abductor pollicis brevis	Myo	0	0	NL	Early	–1	–1	+1
Right extensor digitorum communis	Myo	0	0	NL	NL	NL	NL	NL
Right biceps brachii	NL	0	0	NL	NL	NL	NL	NL
Right medial deltoid	NL	0	0	NL	NL	NL	NL	NL
Right C7 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right C8 paraspinal	NL	0	0	NL	NL	NL	NL	NL
Right tibialis anterior	Myo	0	0	NL	Early	–1	–1	NL
Right medial gastrocnemius	NL	0	0	NL	NL	NL	NL	NL
Right vastus lateralis	NL	0	0	NL	NL	NL	NL	NL
Muscle cooling to 20°C: No effect on needle EMG.								

Myo = myotonic discharges; NL = normal.

features of distal weakness, myotonia, and extramuscular manifestations including cataracts. Family history is notable for maternal diabetes and cataracts. The CK level is mildly elevated. Before proceeding to electrodiagnostic testing, the possibility of a dystrophic myotonic muscle disorder (the most likely diagnosis being DM1, given the distal weakness) should be considered.

On nerve conduction studies, the right median, ulnar, and tibial motor and F response studies reveal normal CMAP amplitudes, distal motor latencies, and conduction velocities. The right median, ulnar, and sural sensory studies are normal, which is expected given the normal sensation on clinical examination. The short exercise test, stimulating the wrist and recording from ADM, shows a drop in the CMAP amplitude immediately after exercise that recovers after 2 minutes. After the third trial of short exercise, the immediate drop in amplitude is no longer noted. This pattern is different from paramyotonia congenita, in which the drop in CMAP amplitude may persist but recovers slowly over 1 hour, especially in a cooled muscle.

On needle EMG study, myotonic discharges are noted in the right distal hand, extensor forearm, and tibialis anterior muscles but not in the more proximal and paraspinal muscles. MUAPs in distal muscles are brief in duration and low in amplitude, with an early recruitment pattern. These findings are characteristic of a dystrophic myotonic muscle disorder. No effect of muscle cooling is seen. We now are ready to formulate our electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are consistent with a myopathy with myotonic features and a distal predominance, as seen in myotonic dystrophy type 1.*

The history, physical examination, and laboratory studies are consistent with myotonic dystrophy. The electrodiagnostic studies show the presence of myotonic discharges with a distal predominance, in the context of myopathic MUAPs and early recruitment, consistent with DM1. This patient was seen in consultation with an ophthalmologist, who confirmed the presence of posterior subcapsular cataracts. DNA testing confirmed the presence of an abnormal expansion of the CTG repeat in the *DMPK* gene on chromosome 19q in the patient, his sister, and his mother. The repeat expansion was slightly larger in the patient than in his mother, likely accounting for the earlier onset and greater severity of symptoms.

Case 36–2

History and Physical Examination

A 35-year-old woman was referred for generalized muscle stiffness first noted around age 5 years. The stiffness was worse after rest or in the cold and improved with activity such as after walking a few steps. Family history was notable for her father and one brother having similar symptoms. A paternal aunt and several first cousins had similar symptoms.

On examination, her mental status was unremarkable. On cranial nerve examination, the face was notable for fairly prominent masseter muscles. There was no bulbofacial weakness or ptosis. Forceful eye closure produced a lid lag. The muscles were very well developed throughout, especially in the proximal arms, thighs, and calves, with good muscle strength in the neck and upper and lower extremities bilaterally. Marked percussion and hand grip myotonia were apparent but diminished after a few contractions. Deep tendon reflexes were normal throughout, with flexor plantar responses. Sensation and coordination were normal throughout.

Laboratory study findings were notable for a normal CK level, electrolyte levels, and thyroid function studies.

Summary

The history is that of a woman who presents with generalized muscle stiffness exacerbated by cold and relieved with repeated muscle contractions, dating back to early childhood. The neurologic examination reveals no weakness, but eyelid, percussion, and grip myotonia and well-developed musculature are obvious. There is a strong family history of similarly affected family members, with an autosomal dominant pattern of inheritance. In summary, there is evidence of myotonia and large muscles in the absence of weakness or extramuscular manifestations. Therefore, before proceeding to electrodiagnostic testing, the possibility of a myotonic muscle disorder without dystrophic changes should be considered.

On nerve conduction studies, the left median, ulnar, and tibial motor and F response studies reveal normal CMAP amplitudes, distal motor latencies, and conduction velocities. The left median, ulnar, and sural sensory studies are normal, which is expected given the clinical examination. The short exercise test, stimulating the wrist and recording from ADM, shows a drop in the CMAP amplitude immediately after exercise that recovers after 1 to 2 minutes. This pattern is seen in myotonic dystrophy and myotonia congenita, although some cases of recessive myotonia congenita may show a delay in recovery that becomes progressive over time. In paramyotonia congenita, the drop in amplitude recovers slowly over an hour, especially in a cooled muscle.

On needle EMG, myotonic discharges are noted diffusely in the proximal and distal muscles of the left upper and lower extremities, including paraspinal muscles. MUAPs are normal throughout, and recruitment pattern is normal. Muscle cooling to 20°C has no appreciable effect on the needle examination. We now are ready to formulate our electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are consistent with a myotonic muscle disorder with no evidence of dystrophic features. The response on the short exercise test and lack of effect of muscle cooling are consistent with myotonia congenita.*

CASE 36–2. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB		9.6	≥4		3.4	≤4.4					27	≤31
	Antecubital fossa	APB		9.4			8.1			54	≥49			
Ulnar (m)	Wrist	ADM		11.3	≥6		2.6	≤3.3					31	≤32
	Below elbow	ADM		11.1			6.6			57	≥49			
	Above elbow	ADM		10.8			8.2			64	≥49			
Median (s)	Wrist	Index finger		24	≥20		3.1	≤3.5		54	≥50			
Ulnar (s)	Wrist	Little finger		21	≥17		2.8	≤3.1		52	≥50			
Tibial (m)	Ankle	AHB		6.8	≥4		4.9	≤5.8						
	Popliteal fossa	AHB		5.9			11.2			50	≥41			
Sural (s)	Calf	Posterior ankle		14	≥6		3.6	≤4.4		48	≥40			
Short exercise test:														
Ulnar (m)	Wrist	ADM	Immediate drop in CMAP amplitude by 40% on first trial of exercise, which recovers over 2 minutes. After several trials, the CMAP drop is no longer seen.											

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis; ADM = abductor digiti minimi; AHB = abductor hallucis brevis; CMAP = compound muscle action potential.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 36–2. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Left first dorsal interosseous	Myo	0	0	NL	NL	NL	NL	NL
Left abductor pollicis brevis	Myo	0	0	NL	NL	NL	NL	NL
Left pronator teres	Myo	0	0	NL	NL	NL	NL	NL
Left extensor indicis proprius	Myo	0	0	NL	NL	NL	NL	NL
Left biceps brachii	Myo	0	0	NL	NL	NL	NL	NL
Left medial deltoid	Myo	0	0	NL	NL	NL	NL	NL
Left C7 paraspinal	Myo	0	0	NL	NL	NL	NL	NL
Left tibialis anterior	Myo	0	0	NL	NL	NL	NL	NL
Left medial gastrocnemius	Myo	0	0	NL	NL	NL	NL	NL
Left vastus lateralis	Myo	0	0	NL	NL	NL	NL	NL
Muscle cooling to 20°C: No effect on needle EMG.								

Myo = myotonic discharges; NL = normal.

The history, physical examination, and laboratory studies are consistent with myotonia congenita. The electrodiagnostic studies show the presence of myotonic discharges, which are widespread and easily elicited throughout. No myopathic MUAPs suggesting a dystrophic process are noted. There is no effect of muscle cooling. Therefore, the electrophysiologic findings are consistent with a myotonic muscle disorder without dystrophic changes, suggesting a diagnosis of myotonia congenita. Although the clinical history may suggest paramyotonia congenita, the lack of effect of muscle cooling would rule against this diagnosis in favor of myotonia congenita. In addition, the fact that the patient's stiffness improves rather than worsens with repeated contractions favors the diagnosis of myotonia congenita over paramyotonia congenita.

Case 36–3

History and Physical Examination

A 19-year-old male was referred for recurrent episodes of weakness that began in childhood. The episodic weakness usually was noted on waking in the morning and lasted minutes to hours, affecting proximal and distal muscles of the upper and lower extremities but never affecting respiration. Episodes of weakness often were accompanied by pain in his legs. Family history was notable for his father, one brother, and one sister having similar symptoms. A paternal aunt, grandfather, and several first cousins had similar symptoms.

On examination, his mental status was unremarkable. On cranial nerve examination, there was no bulbofacial weakness or ptosis. There was normal muscle strength in the neck and upper and lower extremities bilaterally. Percussion myotonia was noted over the thenar muscles. Deep tendon reflexes were normal throughout with flexor plantar responses. Sensation and coordination were normal throughout. There were no dysmorphic facial features or unusual physical features.

Laboratory studies were notable for a normal CK level, electrolyte levels, and thyroid function studies. However, the potassium level had been noted to be slightly elevated during episodes of weakness.

Summary

The history is that of a young man who presents with episodic weakness dating back to early childhood, lasting minutes to hours, exacerbated by cold, and noted most often on waking. The neurologic examination reveals no weakness, but there is percussion myotonia. There is a strong family history of similarly affected individuals, with an autosomal dominant pattern of inheritance. In summary, there is evidence of episodic weakness and myotonia in a young male, with no evidence of fixed weakness or extramuscular manifestations. Therefore, before proceeding to electrodiagnostic testing, the

CASE 36–3. Nerve Conduction Studies

Nerve Stimulated	Stimulation Site	Recording Site	Amplitude Motor = mV; Sensory = µV			Latency (ms)			Conduction Velocity (m/s)			F wave Latency (ms)		
			RT	LT	NL	RT	LT	NL	RT	LT	NL	RT	LT	NL
Median (m)	Wrist	APB	8.4		≥4	3.4		≤4.4				28		≤31
	Antecubital fossa	APB	8.2			8.1			54		≥49			
Ulnar (m)	Wrist	ADM	10.6		≥6	2.8		≤3.3				31		≤32
	Below elbow	ADM	10.4			6.8			56		≥49			
	Above elbow	ADM	10.2			8.2			64		≥49			
Median (s)	Wrist	Index finger	24		≥20	3.1		≤3.5	52		≥50			
Ulnar (s)	Wrist	Little finger	21		≥17	2.7		≤3.1	50		≥50			
Tibial (m)	Ankle	AHB	5.1		≥4	5.2		≤5.8						
	Popliteal fossa	AHB	4.2			12.5			44		≥41			
Sural (s)	Calf	Posterior ankle	12		≥6	3.8		≤4.4	46		≥40			
Short exercise test:														
Ulnar (m)	Wrist	ADM	No drop of CMAP amplitude after short exercise.											
Prolonged exercise test:														
Ulnar (m)	Wrist	ADM	Immediate increment of CMAP amplitude by 20%. Subsequent drop of CMAP amplitude by 55% with lowest CMAP at 40 minutes. Recovery to baseline at 60 minutes.											

m = motor study; s = sensory study; RT = right; LT = left; NL = normal; APB = abductor pollicis brevis; ADM = abductor digiti minimi; AHB = abductor hallucis brevis; CMAP = compound muscle action potential.

Note: All sensory latencies are peak latencies. All sensory conduction velocities are calculated using onset latencies. The reported F wave latency represents the minimum F wave latency.

CASE 36–3. Electromyography

Muscle	Insertional Activity	Spontaneous Activity		Voluntary Motor Unit Action Potentials				
		Fibrillation Potentials	Fasciculations	Activation	Recruitment	Configuration		
						Duration	Amplitude	Polyphasia
Right first dorsal interosseous	NL	0	0	NL	NL	NL	NL	NL
Right extensor digitorum communis	Myo	0	0	NL	NL	NL	NL	NL
Right biceps brachii	Myo	0	0	NL	NL	NL	NL	NL
Right medial deltoid	Myo	0	0	NL	NL	NL	NL	NL
Right triceps	Myo	0	0	NL	NL	NL	NL	NL
Right C7 paraspinal	Myo	0	0	NL	NL	NL	NL	NL
Right tibialis anterior	Myo	0	0	NL	NL	NL	NL	NL
Right medial gastrocnemius	Myo	0	0	NL	NL	NL	NL	NL
Right vastus lateralis	NL	0	0	NL	NL	NL	NL	NL
Muscle cooling to 20°C: No effect on needle EMG.								

Myo = myotonic discharges; NL = normal.

possibility of an inherited periodic paralysis syndrome should be considered.

Nerve conduction studies were carried out during an attack-free interval. The right median, ulnar, and tibial motor and F response studies reveal normal CMAP amplitudes, distal motor latencies, and conduction velocities. The median, ulnar, and sural sensory studies are normal, which is expected given the normal sensory examination. The short exercise test, stimulating the wrist and recording from ADM, is normal. The prolonged exercise test, stimulating the wrist and recording from ADM, shows an initial increment in CMAP amplitude of 20%, followed by a 55% drop in CMAP amplitude that reached a nadir after 40 minutes and recovered to baseline after approximately 1 hour.

On needle EMG study, myotonic discharges are noted in distal and proximal muscles of the upper and lower extremities. The MUAPs are normal throughout, and recruitment pattern is normal. Muscle cooling to 20°C has no appreciable effect on the needle examination. We now are ready to formulate our electrophysiologic impression.

IMPRESSION: *The electrophysiologic findings are consistent with a myotonic muscle disorder with no evidence of dystrophic features. The drop in amplitude with prolonged exercise testing and myotonic discharges noted on needle EMG are compatible with a diagnosis of hyperkalemic periodic paralysis.*

The history, neurologic examination, and laboratory findings are consistent with hyperkalemic periodic paralysis. The electrodiagnostic studies show the presence of myotonic discharges in distal and proximal muscles, with normal MUAPs, consistent with a myotonic muscle disorder without dystrophic changes. In addition, the prolonged exercise test shows a characteristic decline in CMAP amplitude over time. Although the prolonged exercise test does not distinguish hypokalemic from hyperkalemic periodic paralysis, the presence of myotonia points toward hyperkalemic periodic paralysis, as myotonia is not seen in the hypokalemic form of periodic paralysis. Although the periodic weakness and abnormal prolonged exercise test also might suggest Andersen–Tawil syndrome, myotonia is not a feature of this syndrome, and there is no note made of the characteristic facial features seen in this syndrome, nor of any abnormality on electrocardiogram in the patient or affected family members. Although periodic weakness may also be seen in paramyotonia congenita, the lack of effect of muscle cooling, the normal short exercise test, and the abnormal prolonged exercise test rule against this diagnosis in favor of hyperkalemic periodic paralysis.

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37 Approach to Electrodiagnostic Studies in the Intensive Care Unit

The majority of electrodiagnostic (EDX) studies are performed on outpatients, even in those electromyography (EMG) laboratories that are physically located within a hospital. However, in the past several years an increasing number of EDX studies are done on patients in the intensive care unit (ICU). In the ICU setting, the patients typically are profoundly ill, often with several serious overlapping medical problems. Most are intubated and receiving mechanical ventilation, which prevents them from traveling to the EMG laboratory, necessitating a portable study. EDX studies are most often requested in the ICU for the following indications:

- The patient presents with rapidly progressive weakness, with or without sensory symptoms, often leading to respiratory compromise and intubation. In these patients, the referring physician easily recognizes that the patient likely has a primary neurologic disorder. However, this group is much less common than the following scenarios.
- The patient is admitted to the ICU with a serious non-neurologic medical illness. Many have sepsis and/or multiple organ failure. Most are intubated and require sedation or pharmacologic paralysis with neuromuscular junction blocking agents (NMBAs) while on the ventilator. When the primary medical conditions are treated and begin to recover, and sedatives and other drugs are weaned, the patient begins to awaken and is able to cooperate. It is at this point that the medical staff recognizes that the patient has profound weakness of the extremities, often with flaccid tone and areflexia.
- This scenario overlaps with the preceding one. As the primary medical conditions are treated and begin to recover, the sedatives and other drugs are weaned in preparation for extubation. However, despite apparently intact cardiac and pulmonary function, the patient fails to wean off the ventilator. The question then arises if there is a neuromuscular disorder that is preventing extubation.

DIFFERENTIAL DIAGNOSIS OF NEUROLOGIC WEAKNESS IN THE ICU

Neurologic causes of profound weakness in an ICU patient include disorders of the central nervous system (CNS) and the peripheral nervous system (PNS) (Box 37–1). Some of these are primary neurologic disorders that result in admission to the ICU, whereas others occur while the patient is hospitalized for unrelated medical conditions (Box 37–2). One of the most common CNS diagnoses leading to weakness in the ICU is encephalopathy. Encephalopathy in the ICU often is multifactorial, secondary to a multitude of causes including electrolyte and metabolic disturbances, sepsis, and medications. Other CNS disorders can manifest as generalized weakness, including stroke, especially of the posterior circulation, seizures, anoxia, subarachnoid hemorrhage, and infectious meningitis. The spinal cord is part of the CNS, and spinal cord disorders also can present as

Box 37–1. Neurologic Differential Diagnosis of Weakness in the Intensive Care Unit

- Central Nervous System
  - Brain
    - Encephalopathy
    - Infarction
    - Seizures
    - Anoxia
    - Subarachnoid hemorrhage
  - Spinal cord
    - Infarction
    - Demyelination
    - Trauma
- Peripheral Nervous System
  - Anterior horn cell
    - Paralytic poliomyelitis
    - Amyotrophic lateral sclerosis (rare unless there is a coexistent exacerbating factor)
  - Nerve
    - Guillain–Barré syndrome
    - Critical illness polyneuropathy
    - Porphyria
    - Toxins
  - Neuromuscular Junction
    - Botulism
    - Myasthenia gravis
    - Persistent drug-induced neuromuscular junction blockade
    - Toxic
    - Lambert–Eaton myasthenic syndrome (rare unless there is a coexistent exacerbating factor)
  - Muscle
    - Critical illness myopathy
    - Adult-onset acid maltase deficiency myopathy
    - Inflammatory myopathy (severe)
    - Toxic
    - Periodic paralysis

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Box 37–2. Recognition of Neuromuscular Disorders by Presentation in the Intensive Care Unit

- Initial Presentation: Primary Rapidly Progressive Weakness With or Without Respiratory Weakness
  - Paralytic poliomyelitis
  - GBS
  - Porphyria
  - Severe toxic neuropathy
  - Botulism
  - MG (uncommon unless there is a coexistent exacerbating factor)
  - Toxic myopathy with rhabdomyolysis
  - Periodic paralysis (respiratory weakness rare)
- Initial Presentation: Primary Respiratory Failure in Isolation
  - Paralytic poliomyelitis (uncommon)
  - MG (uncommon)
  - GBS (uncommon)
  - Adult-onset acid maltase deficiency myopathy
  - Bilateral phrenic neuropathies (postinfectious)
- Generalized Weakness Discovered as the Patient is Recovering from Medical/Surgical Condition
  - CIM
  - CIP
  - Persistent NMJ blockade
- Failure to Wean as the Patient is Recovering from Medical/Surgical Condition
  - CIM
  - CIP
  - Unilateral/bilateral phrenic neuropathies (especially after thoracic surgery)
  - Persistent NMJ blockade (rare)
  - MG (if pneumonia provoked the admission)
  - ALS (if pneumonia provoked the admission)
  - LEMS (if calcium channel blockers or NMBAs were given)
  - Charcot-Marie-Tooth, type 2C

ALS, amyotrophic lateral sclerosis; CIM, critical illness myopathy; CIP, critical illness polyneuropathy; GBS, Guillain–Barré syndrome; LEMS, Lambert–Eaton myasthenic syndrome; MG, myasthenia gravis; NMBAs, neuromuscular junction blocking agents; NMJ, neuromuscular junction.

generalized weakness. Infarction, demyelination, or unrecognized trauma in the high cervical cord can present acutely as a flaccid quadriparesis with decreased or absent reflexes and loss of sensation. Remember that an acute CNS disorder often is associated initially with decreased tone and reduced reflexes (i.e., cerebral or spinal shock) and can mimic a PNS problem early on.

In the PNS, profound weakness can occur from a lesion anywhere in the motor unit, from the motor neuron (anterior horn cell) to the motor nerve, neuromuscular junction (NMJ), and muscle. Acute motor neuron disease is very uncommon and occurs only in the setting of paralytic poliomyelitis. As discussed in Chapter 28, poliomyelitis is a clinical syndrome that occurs from infection by several viruses, with West Nile virus now added to the list. Patients with chronic motor neuron disorders, such as amyotrophic lateral sclerosis (ALS), occasionally present to the ICU when the neurologic condition has not been previously recognized or diagnosed, and the patient comes to medical attention because of a concurrent acute medical problem, usually pneumonia. The typical scenario is that of a patient with bulbar-onset ALS who has undergone an exhaustive medical evaluation looking for a gastrointestinal or ENT etiology of the speech and swallowing dysfunction. The impaired speech and swallowing eventually lead to aspiration and an accompanying pneumonia, which superimposed on respiratory muscle weakness from the unrecognized ALS quickly leads to respiratory compromise and the need for intubation. It is only then, in the ICU, as the patient is recovering from the pneumonia but cannot be weaned from the ventilator, that it becomes more apparent that there is more generalized weakness that had not been appreciated earlier.

Moving down the motor unit, the most well-known acute neuropathy that results in marked weakness and respiratory compromise is Guillain–Barré syndrome (GBS). GBS is an acquired motor and sensory polyradiculoneuropathy that usually is demyelinating. Other variants have been described, including axonal forms, one of which is motor and sensory, and the other pure motor. GBS probably has an autoimmune etiology, often triggered by an infection either days or a few weeks earlier. Patients typically present with ascending numbness and weakness over several days, often with simultaneous paresthesias of the fingers and toes. Weakness may affect bulbofacial and respiratory muscles. Some patients present more abruptly, over hours, with associated early respiratory weakness. Other than GBS, it is rare to see an acute neuropathy as the cause for admission to the ICU. Notable exceptions include porphyria and some toxic (e.g., arsenic) neuropathies, which can mimic the presentation of GBS.

The most common severe neuropathy seen in the ICU patient is critical illness polyneuropathy (CIP). CIP usually occurs in patients who have been admitted to the ICU for a primary medical illness, most often sepsis and multiple organ failure. In contrast to GBS, which is usually demyelinating, CIP is an axonal sensorimotor polyneuropathy thought to be due to a complication of the systemic inflammatory response syndrome (SIRS). SIRS is a severe systemic response that can be caused by sepsis, but is also seen in other settings including trauma, burns, major organ failure and/or as a consequence of major procedures. SIRS is thought to be present in most patients hospitalized in the ICU for longer than one week. In SIRS, significant cellular and humoral responses are thought to alter the microcirculation in the body, including the microcirculation to nerve and muscle. These responses include changes in endothelial and inflammatory cells, in addition to the expression of numerous cytokines and coagulation factors, among other changes. In prospective studies of ICU patients studied with serial nerve conduction studies, CIP can occur as early as within 3 days after the onset of sepsis. In most patients, CIP is preceded by a septic encephalopathy (aka, toxic metabolic encephalopathy) which is extremely common in ICU patients. CIP usually comes to medical attention only when the patient begins to improve from their primary medical illness but is found to have profound weakness and sensory loss or fails to wean from the ventilator. As CIP results in axonal degeneration, recovery is typically very

slow and often incomplete, especially in severe cases. Indeed, in some cases, clinical and electrophysiologic evidence of CIP may remain for years after an ICU admission; rare patients remain profoundly disabled.

CIP is reported to be very common in ICU patients, and can occur by itself, or more commonly in association with critical illness myopathy (CIM). Indeed, the two occur so commonly together, depending on how closely the patient is examined clinically and electrically, that some have advocated the name critical illness polyneuromyopathy to describe the neuromuscular syndrome that commonly occurs in the ICU. In one study of ICU patients with SIRS, 50% developed a neuromuscular disorder. Of these, 80% had both CIP and CIM, 10% had CIP alone, and 10% had CIM alone.

In addition to severe polyneuropathies, mononeuropathies of one or both phrenic nerves can directly result in respiratory compromise. Phrenic neuropathies may be idiopathic, presumably autoimmune and postinfectious, similar in etiology to other mononeuropathies such as Bell's palsy. In addition, phrenic neuropathy can occur rarely as part of neuralgic amyotrophy, either in isolation or more commonly in a more widespread pattern of multiple mononeuropathies. The other situation where unilateral or bilateral phrenic neuropathies occur is as a complication of thoracic surgery. Some cases of phrenic neuropathy following coronary artery bypass surgery may be due to cold-induced injury occurring secondary to the use of topical cooling with ice slush for prevention of myocardial ischemia.

Moving next to the NMJ, several disorders should be considered in the ICU setting. The one disorder of NMJ that presents acutely as rapidly progressive weakness in an adult is botulism. The typical presentation is one of descending paralysis, often associated with gastrointestinal and autonomic symptoms. Of course, a large number of chemical and biologic toxins can poison the NMJ acutely, among them organophosphates, spider venom, and "nerve gas."

Although myasthenia gravis (MG) typically is diagnosed in an outpatient presenting with ptosis, double vision, slurred speech, and fluctuating weakness, an occasional previously undiagnosed patient may present to the ICU in acute primary respiratory failure. This can occur from selective involvement of the diaphragm and other muscles of respiration or, similar to the patient with unrecognized ALS, bulbar weakness leading to aspiration and pneumonia, quickly followed by respiratory failure.

Patients with Lambert–Eaton myasthenic syndrome (LEMS) are distinctly uncommon in the ICU. First, the disorder is extremely rare. Second, the disorder usually presents subacutely over months, and respiratory muscles are not typically involved. Clinically, it is most often confused with a myopathy. However, rare patients with LEMS present to the ICU as a failure to wean after elective surgery. In these cases, LEMS probably is unmasked when the patient receives a calcium channel blocker or an NMBA at the time of surgery.

Rare patients without any underlying NMJ or muscle disorder fail to extubate as a result of delayed clearance of an NMBA given during anesthesia in preparation for surgery. Most often, these patients have renal insufficiency or frank renal failure and thus fail to clear the NMBA effectively from their system.

The final component of the motor unit is the muscle. By far, the most common muscle disorder seen in the ICU is critical illness myopathy (CIM), also known as *acute quadriplegic myopathy, thick myosin filament myopathy, and intensive care myopathy*, among many other names. CIM occurs most often in the setting of high-dose intravenous steroids used in conjunction with NMBAs. Rarely, it is seen in association with only one of the two; exceptional cases have been reported in sepsis and multiple organ failure in the absence of steroids and NMBAs. Pathologically, there is dissolution of the thick myosin filaments in most cases. Rarely, there is a necrotizing myopathy on muscle biopsy. One of the most common clinical situations in which CIM occurs is in patients with status asthmaticus, with estimates as high as a third of patients developing some component of CIM. These patients typically are intubated and treated with high-dose intravenous methylprednisolone. Because intubation often is difficult in these patients, pharmacologic paralysis with NMBAs is common. As the asthma improves, it becomes apparent that the patient is flaccid, areflexic, and profoundly weak. Once intubated, the patient may fail to wean for a prolonged period of time. CIM recovers in most patients in 3 to 6 months. However, in patients with SIRS, CIM often occurs in conjunction with CIP. When both are present, the recovery is much longer and may result in permanent disability because of the CIP component.

Other myopathies seldom cause respiratory arrest or severe generalized weakness in the ICU. Rarely, severe cases of inflammatory myopathy (i.e., polymyositis or dermatomyositis) may result in profound generalized weakness. Likewise, severe toxic myopathies are uncommon in the ICU, although rare cases of rhabdomyolysis associated with alcohol, drugs, or other toxins can present as profound weakness. Periodic paralysis, especially hypokalemic periodic paralysis, presents as severe, rapidly evolving weakness during an attack, but only rarely does it affect the respiratory muscles. Finally, although extremely rare, the myopathy associated with adult-onset acid maltase deficiency characteristically affects respiratory and abdominal muscles and can present as a primary neuromuscular cause of respiratory insufficiency.

ELECTRODIAGNOSTIC STUDIES IN THE INTENSIVE CARE UNIT: TECHNICAL ISSUES

There are a number of challenging technical issues unique to performing EDX studies in the ICU (Table 37–1). Some are related to patient factors, whereas others involve central and intravenous lines and electrical equipment that

Table 37–1. Technical Problems in the Intensive Care Unit

Problem	Guidelines/Recommendations
Poor cooperation – cannot place their limb in an optimal position	Need a second person to help immobilize the limb
Poor cooperation – heavily sedated	Do the entire study except for the portion of the needle EMG looking at MUAPs; inquire if sedation can be temporarily reduced. Some agents, such as propofol, can be easily adjusted
Poor cooperation – cannot perform 10 seconds of exercise	Use 50 Hz repetitive nerve stimulation
Poor cooperation – cannot activate muscles for needle EMG	Choose muscles which will contract reflexively when withdrawing from a painful stimulus
Cannot roll on side for the sural sensory study	One person holds the leg with the knee flexed, taking care not to touch recording electrodes, while the second person stimulates
Cannot roll on side to sample gluteal muscles	Study the tensor fascia lata or gluteus medius; they are in the lateral thigh when supine
Cannot roll on side to sample posterior shoulder girdle muscles	Study the medial or anterior deltoid
Cannot roll on side to sample paraspinal muscles	Omit; if absolutely necessary, need additional personnel to help roll the patient
Cannot roll over to the prone position for the H reflex	Omit the H reflex; if absolutely necessary, can be performed supine
External pacemaker wire present	Do not do any electrodiagnostic studies – risk of electrical injury too high
Subclavian or internal jugular central line present	Study contralateral side; if not possible, avoid proximal stimulation (i.e., axilla and Erb's point)
Excessive electrical noise	Use coaxial cables, good skin preparation; proper use of electrode gel; turn off other devices if possible; operator and patient should not touch the metal bed.
Poor access to median/ulnar nerves at the wrist or elbow due to lines	Choose the contralateral side if possible; stimulate the median nerve in the mid-arm instead of the antecubital fossa

interfere with the performance of the study. Good patient rapport and cooperation are indispensable to the efficiency and reliability of the EMG study in the outpatient setting. Unfortunately, these goals are much more difficult, if not impossible, to accomplish with the ICU patient. Many ICU patients are encephalopathic and cannot cooperate with the EMG examination. They may become easily agitated, making both the nerve conduction and needle examination difficult to accomplish. On the other hand, patients who are intubated are often sedated with benzodiazepines or narcotics. Some may be placed in a pharmacologic coma with propofol or barbiturates. Although such patients may not be agitated, they are unable to cooperate with routine nerve conduction and EMG studies. Neither the agitated patient nor the sedated patient is able to give the electromyographer proper feedback during the study, for example whether he or she is feeling the stimulus during the nerve conduction studies. Nor can such patients place their limbs in the correct position for the nerve conduction studies or the spontaneous activity assessment portion of the needle examination. Finally, they cannot cooperate with the examiner to activate their muscles when trying to assess motor unit action potentials (MUAPs) during the needle examination.

Because of these and other difficulties (described later), it is always recommended that two individuals perform the study together in the ICU. One person can run the EMG machine while the other performs the nerve conduction studies and needle examination, adjusting the patient's limbs to the extent possible.

Access to certain anatomic locations in the ICU can be difficult. The presence of arterial lines, especially at the wrist, often interferes with the ability to stimulate the distal median and ulnar nerves. Because the antecubital fossa is a common site for intravenous lines, the proximal median stimulation site may not be accessible. This can be remedied by moving more proximally toward the axilla where the median nerve can often be easily stimulated. The presence of intravenous lines in the antecubital fossa may also make it difficult to flex the elbow during ulnar motor conduction studies. As noted in Chapter 19, if ulnar motor conduction studies are not performed with the elbow in a flexed position, factitious slowing across the elbow may easily occur.

Patients who are intubated or cannot cooperate due to encephalopathy or sedation will have great difficulty moving to certain positions that are required for some nerve conduction studies and needle EMG. Of the nerve conduction studies, the sural sensory potential is the one most at risk to be compromised because it is optimally performed with the patient rolled onto his or her contralateral side. If the patient cannot be rolled onto the contralateral side or maintain that position, the study can be done with the patient supine and the leg flexed at the knee. This usually will require the assistance of another person to help hold the leg in place, and the waveform may still be suboptimal. Likewise, the tibial H reflex is best performed with the patient prone, which is essentially not possible in any ICU patient. If a central catheter is in place, proximal stimulation (i.e., axilla, Erb's point, and nerve root) is relatively contraindicated in the ICU patient (see Chapter 40). During the needle EMG examination, it often is very difficult or impossible to sample certain muscles because of the patient's inability to roll on his or her side. Most important among them are the gluteal, hamstring, posterior shoulder girdle, and paraspinal muscles.

In addition to the technical problems posed by the patient in the ICU, several technical problems related to electrical devices in the ICU may compromise the EDX study. First, the typical ICU room is filled with numerous electrical devices that are potential sources of electrical noise. Electrical noise can obscure the nerve conduction potentials (especially sensory potentials, which are orders of magnitude smaller than motor potentials) and needle EMG potentials. Second, ICU patients lie in beds with metal frames and side restraints. These beds usually are electrical devices themselves, with motors, wires, and controls as part of the actual bed. Many of the electrical devices in the room are attached to the patient (e.g., electrocardiograph, blood pressure monitor, etc.). The presence of multiple electrical devices attached to the patient, each with its own ground electrode, increases the potential risk of an electrical injury if the EMG machine is not maintained or if proper protocol is not followed (see Chapter 40). Finally, the presence of any line that traverses through the patient's skin and lies close the heart (e.g., central catheter, external pacemaker) results in the so-called "electrically sensitive patient." In this situation, extremely small leakage currents from the EMG machine can pose a risk to the patient, whereas such small currents would be of no consequence to the typical outpatient (see Chapter 40).

IMPORTANT ELECTRODIAGNOSTIC PATTERNS IN THE INTENSIVE CARE UNIT

A limited number of nerve conduction and needle EMG patterns are seen in the ICU, based on the neurologic conditions that may result in respiratory or generalized weakness requiring ICU admission (Table 37–2). Each pattern suggests a specific localization; in some cases, the pattern may suggest additional studies to be performed.

Nerve Conduction Studies

Normal Motor and Sensory Conduction Studies with Normal F Responses

This pattern usually implies that the PNS is intact and that the etiology of the weakness most likely is central. However, this pattern can also occur in several neuromuscular conditions. The most important to exclude is a postsynaptic NMJ disorder (e.g., MG). Whereas presynaptic NMJ disorders typically have low motor amplitudes, most postsynaptic disorders usually are normal at baseline. Thus, in patients with generalized weakness and normal routine motor and sensory conduction studies, it is essential to perform slow (3 Hz) repetitive nerve stimulation in at least one nerve to look for a decremental response.

One also must be careful when interpreting the significance of normal motor and sensory nerve conduction studies unless the process is at least 1 week old, which is sufficient time for wallerian degeneration to have occurred. Otherwise, this pattern cannot exclude an acute neuropathic process (i.e., anterior horn cell or peripheral nerve).

Normal Motor and Sensory Conduction Studies with Abnormal F Responses

This is the characteristic pattern seen within the first few days of GBS. GBS typically begins at the root level as a demyelinating polyradiculopathy. As time proceeds, it turns into a demyelinating polyradiculoneuropathy. Thus, nerve conduction studies often are normal initially, except for the F responses, which are delayed, impersistent, dispersed, or absent. In the case of absent F responses, however, there is one very important proviso before attributing absent F responses to proximal demyelination. Recall that the circuitry of the F response includes the anterior horn cell in the spinal cord. The anterior horn cell is susceptible to suprasegmental facilitatory influences. This is why the Jendrassik maneuver is useful in eliciting F responses. Likewise, the anterior horn cell is susceptible to suprasegmental inhibitory influences. *Thus, if a patient is heavily sedated or in coma, absent F responses are of no significance and may be a normal finding in this population.* Thus, absent F responses can be considered a marker of proximal demyelination only if the patient is awake and alert.

Low or Absent Motor Responses with Normal Sensory Responses

Although this pattern can be seen in polyradiculopathy, most often this pattern implies a pure motor disorder, at the level of the muscle, NMJ, or motor neuron. This pattern is distinctly unusual in most myopathies, which preferentially affect proximal muscles, which are not recorded in routine nerve conduction studies. Even in the unusual case of adult-onset acid maltase deficiency, distal muscles are not affected. However, diffusely low motor responses are the classic pattern seen in CIM, which affects proximal and distal muscles. It also is the classic pattern

Table 37–2. Neurologic Diagnoses and Associated Electrodiagnostic Findings in the Intensive Care Unit

Disorder	Motor NCS	Sensory NCS	RNS	Needle EMG findings
Encephalopathy/ other central nervous system disorders	Normal; F responses may be absent if patient is sedated or in coma	Normal	Normal	Poor activation
ALS	Axonal loss pattern or normal	Normal	Rarely will decrement on slow RNS	Diffuse active denervation and reinnervation with decreased recruitment and activation of MUAPs
Poliomyelitis	Axonal loss pattern or normal	Normal	Normal	First weeks – decreased recruitment of normal configuration MUAPs; later active denervation followed by reinnervation
GBS	Demyelinating, especially absent F responses early in the course	Initially normal, later "sural sparing," followed by low amplitudes and slowed velocities	Normal	First weeks – decreased recruitment of normal configuration MUAPs; later active denervation followed by reinnervation
CIP	Axonal loss pattern or absent	Axonal loss pattern or absent	Normal	Distal pattern of decreased recruitment with or without denervation and reinnervation, depending on the time course.
Phrenic neuropathy	Absent or low amplitudes on phrenic motor studies	Normal	Normal	Normal in limbs. If EMG of the diaphragm is done, it will show a neuropathic pattern
Botulism	Low amplitudes throughout	Normal	Decrement on slow RNS, increment on rapid RNS or brief exercise (however, the absence of an increment cannot exclude botulism)	Unstable or small, short and polyphasic MUAPs with normal or early recruitment
MG	Normal	Normal	Decrement on slow RNS; repair of the decrement after brief exercise	Normal or unstable or small, short and polyphasic MUAPs with normal or early recruitment
LEMS	Low amplitudes throughout	Normal	Decrement on slow RNS, increment on rapid RNS or brief exercise	Normal or unstable or small, short and polyphasic MUAPs with normal or early recruitment
Persistent NMJ blockade	Low amplitudes throughout	Normal	Decrement on slow RNS	Normal or unstable or small, short and polyphasic MUAPs with normal or early recruitment
CIM	Low amplitudes throughout	Normal	Normal	Small, short and polyphasic MUAPs with normal or early recruitment; active denervation may be present
Adult-onset acid maltase deficiency myopathy	Normal	Normal	Normal	Myotonic discharges and fibrillation potentials with small, short and polyphasic MUAPs, restricted to paraspinal, abdominal and very proximal muscles
Periodic paralysis	Low amplitudes during an attack	Normal	Normal	Normal; small short and polyphasic MUAPs late in the course; myotonic discharges may be present in hyperkalemic periodic paralysis

Abbreviations: ALS – amyotrophic lateral sclerosis; GBS – Guillain–Barré syndrome; MG – myasthenia gravis; LEMS – Lambert–Eaton myasthenic syndrome; CIP – critical illness polyneuropathy; CIM – critical illness myopathy; RNS – repetitive nerve stimulation; EMG – electromyogram; MUAP – motor unit action potential.

seen in presynaptic NMJ disorders, such as botulism and LEMS. Finally, it also is the pattern seen in acute anterior horn cell disease, as occurs in paralytic poliomyelitis, if the nerve conduction studies are performed after 5 days of onset, when there has been sufficient time for wallerian degeneration to occur. Because the differential diagnosis of this pattern includes a presynaptic NMJ disorder, it is essential to perform slow (3 Hz) and rapid (50 Hz) repetitive nerve stimulation. If the patient can cooperate, brief exercise testing should be used in lieu of 50 Hz stimulation, which is quite painful (see Chapter 6).

Low or Absent Motor and Sensory Responses

The presence of abnormal sensory responses denotes that a neuropathy must be present. However, caution must be taken before attributing weakness in the ICU to the neuropathy, because many patients in the ICU have comorbidities that may cause an incidental neuropathy, such as preexisting diabetes, renal failure, or liver failure. If such preexisting comorbidities do not exist, however, then the presence of low or absent motor and sensory responses likely indicates a new peripheral neuropathy. If the conduction velocities and latencies are in the axonal range, this pattern is most suggestive of critical illness neuropathy. Although rare, one cannot exclude the possibility of the acute motor and sensory axonal neuropathy (AMSAN) variant of GBS. Another possibility to consider, although extremely rare, is one of the axonal variants of Charcot–Marie–Tooth disease that involves limb, diaphragm, vocal cord, and intercostal muscles (Type 2C). Rare patients with this disorder will decompensate from a respiratory illness, necessitating an ICU admission.

As noted above, one must always consider the possibility that the patient has a preexisting peripheral neuropathy with a new superimposed process affecting the motor neuron, NMJ, or muscle. In this case, the abnormal sensory potentials may not be related to the current presentation of weakness. For example, in a patient with diabetes admitted to the ICU with new onset of blurred vision and rapidly descending paralysis, with low or absent sensory and motor potentials on nerve conduction studies, the diagnosis of botulism must be considered. The abnormal sensory responses may be secondary to a peripheral neuropathy related to the patient's diabetes. If this possibility is not considered and repetitive nerve stimulation studies are not performed, the correct diagnosis may be missed. Finally, when low or absent sensory potentials are seen in the ICU, it may be difficult to interpret these findings in the setting of electrical interference or other factors that might preclude recording small potentials. In these cases, one must always consider the possibility that the patient has a primary disorder of the motor neuron, NMJ, or muscle and that the absent sensory potentials are due to technical factors. In this case, repetitive nerve stimulation studies should be considered. This underscores the importance of always keeping in mind the patient's clinical history and neurologic examination when performing EDX studies.

Motor and Sensory Nerve Conduction Studies with Demyelinating Features

Demyelinating features include very prolonged or absent F responses, markedly prolonged distal motor latencies, and markedly slowed conduction velocities. Additionally, asymmetry in conduction studies from side and side, especially if there is conduction block and/or temporal dispersion of motor nerves at non-entrapment sites, usually signifies an acquired demyelinating neuropathy. In this case, the acute inflammatory demyelinating polyneuropathy (AIDP) variant of GBS should be considered if the condition is less than 4 weeks in duration or chronic inflammatory demyelinating polyneuropathy (CIDP) if more than 6 to 8 weeks in duration. If there is no conduction block, temporal dispersion, or significant asymmetry, caution must be taken, as one may have incidentally discovered an inherited demyelinating peripheral neuropathy (e.g., Charcot–Marie–Tooth, type I), unrelated to the etiology of the patient's ICU admission.

Needle Electromyography

Decreased Recruitment with Normal Configuration Motor Unit Action Potentials

This is the pattern seen in either an acute axonal lesion or a demyelinating lesion with conduction block. This pattern in an ICU patient with profound weakness is consistent with GBS, early critical illness polyneuropathy, or paralytic poliomyelitis. Caution must be taken in interpreting a decreased recruitment pattern. Patients who are weak from central causes may have poor activation of normal configuration MUAPs, resulting in an incomplete interference pattern on the EMG screen, which should not be confused with a decreased recruitment pattern (see following).

Decreased Recruitment with Reinnervated Motor Unit Action Potentials

This is the pattern of a subacute or chronic neuropathic disorder, typically many weeks and usually months in duration. This pattern would be expected in ALS, a preexisting polyneuropathy, or CIP in a patient who has had a prolonged hospitalization.

Short-duration, Low-amplitude Motor Unit Action Potentials

This is the pattern seen in a myopathy, often associated with an early recruitment pattern. This pattern occurs in CIM and other severe myopathies. However, it is important to keep in mind that severe NMJ disorders can display a similar pattern. In this case, muscle fibers are not lost but blocked, resulting in fewer muscle fibers per motor unit. Because of the variability in the safety factor of the NMJ in these disorders, MUAPs often will be unstable, varying in configuration from potential to potential.

Decreased Activation

Activation is the ability to fire the available MUAPs faster. Activation is a central process. Thus, decreased activation implies that the source of the weakness resides in the CNS.

This can result from actual CNS disease, as well as sedation, pain, or poor cooperation.

Normal Recruitment, Activation, and Motor Unit Action Potential Morphology

The problem with this pattern is the apparent lack of a clinical–electrophysiologic correlation. If a patient is truly profoundly weak, the needle EMG examination should be abnormal, displaying decreased recruitment (neuropathic), decreased activation (central), or early recruitment and myopathic appearing MUAPs that signify either a myopathy or an NMJ disorder if there is blocking. In this situation, it is important to reexamine the patient and possibly reassess the needle EMG. If one is convinced that the findings are real, one should consider the possibility of an NMJ disorder, especially one that is presynaptic. Soon after activating their muscles, some patients with LEMS will quickly facilitate and their MUAPs will appear normal.

NERVE CONDUCTION AND ELECTROMYOGRAPHIC PROTOCOL IN THE INTENSIVE CARE UNIT

When studying a patient in the ICU, one needs to perform EDX studies that address the possible differential diagnoses discussed earlier (Box 37–3). At a minimum, one motor nerve conduction study with its F response should be performed in an upper and lower extremity. In the lower extremity, the tibial motor nerve is preferable to the peroneal, as the tibial F responses are always easy to elicit. Indeed, most consider absent peroneal F responses to have little value as they can be a normal finding. Likewise, at least one sensory nerve conduction study should be done in an upper and lower extremity. Clearly, the sural sensory potential is the most challenging in the ICU patient. If the patient cannot turn on his or her side, the sural still can be studied provided two individuals are available. One person can hold the foot with the knee flexed allowing access to the posterior calf, taking care not to touch the recording electrodes, while the other individual works the stimulator.

If any of the motor amplitudes are low, it is imperative to perform slow repetitive nerve stimulation looking for a decrement and rapid repetitive nerve stimulation looking for an increment. In a patient who can cooperate, 10 seconds of exercise is best substituted for rapid repetitive nerve stimulation, which is quite painful. However, if the patient cannot cooperate because of sedation or encephalopathy, then rapid (50 Hz) repetitive nerve stimulation is required to exclude a presynaptic NMJ disorder. It is reasonable to consider repetitive nerve stimulation in all patients who have weakness and normal sensory responses. Slow (3 Hz) repetitive nerve stimulation is a useful screen for both presynaptic and postsynaptic disorders. Although the overall sensitivity of repetitive nerve stimulation is reported in the 50 to 70% range for MG, the sensitivity is much higher in the ICU patient with an NMJ disorder. By definition, if a patient is profoundly weak from MG, many muscle fibers must not be reaching threshold and are blocked. Any patient with MG with significant blocking will have abnormal repetitive nerve stimulation studies.

The approach to the needle EMG examination of the ICU patient is very similar to that of the pediatric patient. It is important to go where the money is. If possible, one needs to choose muscles that the patient is able to move. Obviously, information about spontaneous activity can be determined from any muscle at rest. However, differentiation among a central process, a neuropathic process, and an NMJ disorder requires assessment of activation, recruitment, and MUAP morphology. This can only be done by examining the MUAPs. If the patient is unable to move any muscle voluntarily because of sedation, encephalopathy, or profound weakness, then it is best to choose muscles that can be activated reflexively. For instance, the tibialis anterior muscle will activate as part of the normal withdrawal

Box 37–3. Recommended Nerve Conduction and Needle Electromyography Protocol in the Intensive Care Unit

Routine nerve conduction studies
1. At least one motor nerve conduction study with its corresponding F wave in an upper and lower extremity. In the lower extremity, the tibial nerve is preferred, as the F responses are normally present and easy to evoke
2. At least one sensory nerve conduction study in an upper and lower extremity

Routine needle electromyography
1. Lower extremity: at least one distal and one proximal muscle
2. Upper extremity: at least one distal and one proximal muscle

Special considerations:
- If adult-onset acid maltase deficiency myopathy is in the differential diagnosis, sampling the paraspinal muscles is essential.
- If the patient cannot cooperate, choose flexor muscles that can be activated reflexively as part of the withdrawal mechanism to a painful stimulus.

Repetitive nerve stimulation
1. Routine slow (3 Hz) repetitive nerve stimulation in at least one nerve
2. In any patient with absent, low, or borderline motor amplitudes, exercise for 10 seconds and repeat the distal stimulation to the corresponding nerve, looking for an abnormal increment. If the patient cannot cooperate with voluntary exercise, use 50 Hz stimulation looking for an abnormal increment, in at least one motor nerve

Other useful studies in selected situations:

Direct muscle stimulation
- Compare the CMAP amplitude from direct muscle stimulation to that obtained with nerve stimulation (differentiation between critical illness myopathy and critical illness polyneuropathy)

Phrenic motor studies (bilateral studies)
- Assess integrity of the phrenic nerves

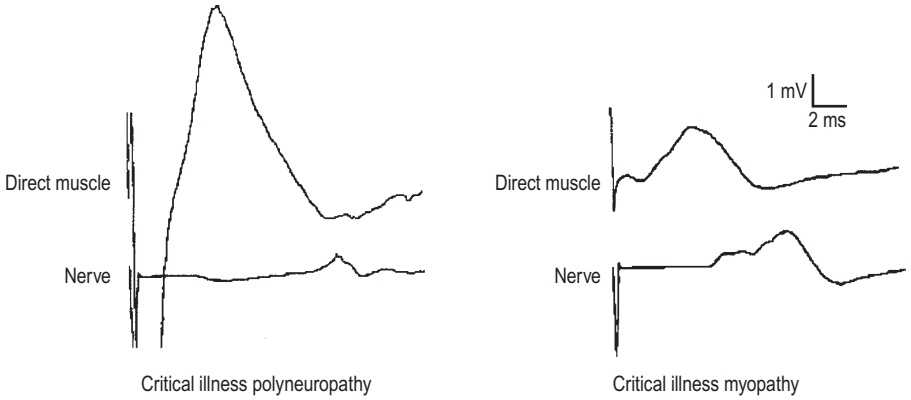

FIGURE 37–1 Direct muscle stimulation. Compound muscle action potentials from the tibialis anterior muscle of a patient with critical illness neuropathy **(left)** and critical illness myopathy **(right).** Note the higher amplitude with direct muscle stimulation compared to nerve stimulation in the patient with critical illness neuropathy, whereas there is little difference in amplitude between direct muscle and nerve stimulation in the patient with critical illness myopathy.
(Adapted from Rich, M.M., Bird, S.J., Raps, E.C., et al., 1997. Direct muscle stimulation in acute quadriplegic myopathy. Muscle Nerve 20, 665–673, with permission.)

response to tickling the sole or applying pressure to a nail bed. In general, flexor muscles are easier to check because they are activated as a normal withdrawal reflex to pain.

Additional Useful Studies in Selected Situations

Direct Muscle Stimulation

Both CIP and CIM often show reduced motor amplitudes. Because lower extremity sensory responses may be difficult to obtain in the ICU for technical reasons or because many patients in the ICU may have a preexisting neuropathy, nerve conduction studies may not be able to differentiate between CIP and CIM. In patients with CIM, muscle fibers often are inexcitable to direct muscle stimulation. In contrast, in neuropathic situations, the motor amplitudes may be low due to loss of axons, but the muscle fibers are fundamentally intact. Thus, in neuropathic conditions, muscle can be activated by direct stimulation. In some situations, therefore, it is possible to differentiate CIM from CIP using direct muscle stimulation (Figure 37–1).

Direct muscle stimulation is performed by placing a monopolar needle stimulating electrode (as the cathode) in the distal third of the muscle with a nearby subdermal needle electrode placed laterally as the anode. The muscle is stimulated using a 0.1 ms duration stimulus, gradually increasing current from 10 to 100 mA until a clear twitch is felt or seen. Based on where the twitch is seen, another subdermal needle electrode (active recording electrode) is placed 1 to 3 cm from the stimulation electrode, with a surface electrode placed several centimeters distally as the reference electrode. During stimulation, both the stimulating monopolar needle electrode and the active recording subdermal needle electrode can be adjusted to optimize the response at low levels of stimulation intensity. The stimulation intensity is increased until a maximal response, the direct muscle action potential (dmCMAP), is obtained. Next, using the same recording electrode montage, the nerve to the muscle is stimulated in the usual manner to obtain a nerve-evoked compound muscle action potential (neCMAP).

The dmCMAP is compared to the neCMAP. In CIM, the neCMAP/dmCMAP ratio is close to one, because both amplitudes are proportionally reduced. In CIP, the ratio is much lower and may be zero because of the disproportionately lower neCMAP compared with the dmCMAP.

Phrenic Motor Study

One possible mechanism in intubated patients who fail to wean is dysfunction of one or both phrenic nerves. The phrenic nerves are most often affected as a postinfectious process or as a complication of thoracic surgery. However, the phrenic nerves can also be affected by a severe diffuse polyneuropathy, including GBS and CIP. The phrenic motor study can be performed recording the diaphragm with the active electrode placed two fingerbreadths above the xiphoid process and the reference electrode 16 cm from the active electrode over the anterior costal margin. The nerve can be stimulated in the lateral neck either posterior to the sternocleidomastoid muscle, approximately 3 cm above the clavicle, or between the sternal and clavicular heads of the sternocleidomastoid just above the clavicle (Figure 37–2). Unfortunately, a normal phrenic nerve conduction study evokes a CMAP of only a few hundred microvolts. Thus, the presence of electrical noise, which is not uncommon in the ICU, can easily obscure the response.

An intact phrenic motor response confirms the integrity of the phrenic nerve. However, several technical problems with this study must be taken into account, especially in the ICU. First, it often is difficult to perform phrenic conduction studies on obese individuals or those with a thick neck. Second, the study cannot be performed safely if the patient has an external pacemaker in place. Finally, if a central line is present, the study is contraindicated on the side with the catheter (see Chapter 40).

This study is most helpful if responses on both sides are present and normal, or if one side is present and normal

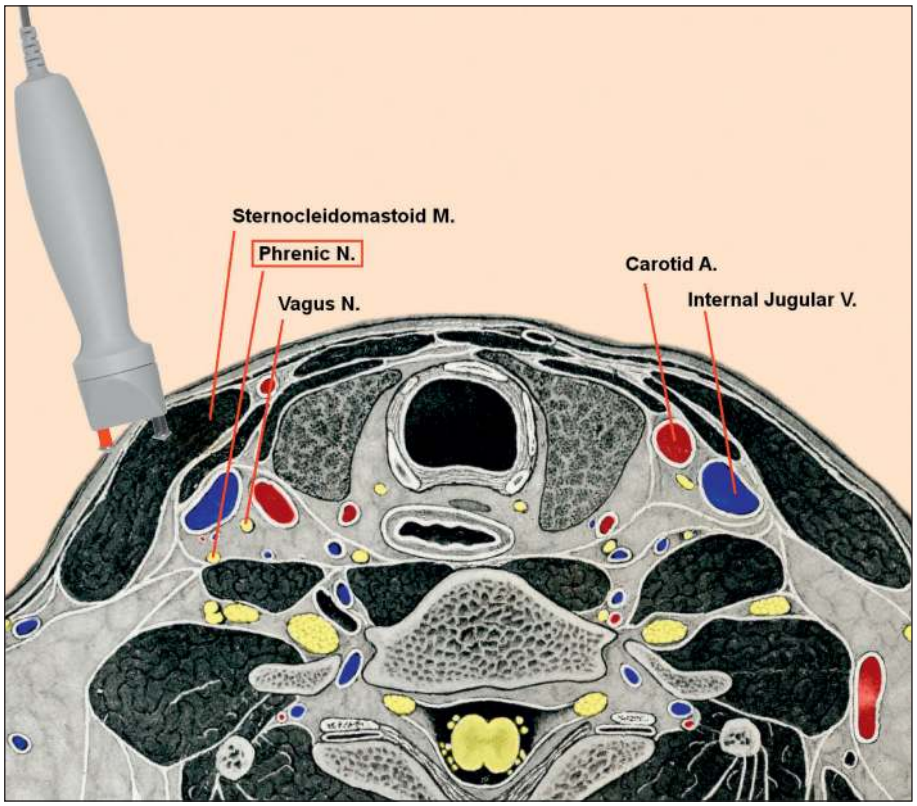

FIGURE 37–2 Cross-sectional anatomy: phrenic nerve stimulation site. The phrenic nerve is stimulated in the lateral neck either posterior to the sternocleidomastoid muscle or between the sternal and clavicular heads of the sternocleidomastoid just above the clavicle. Note that the phrenic nerve is deep to both the internal jugular vein and carotid artery.

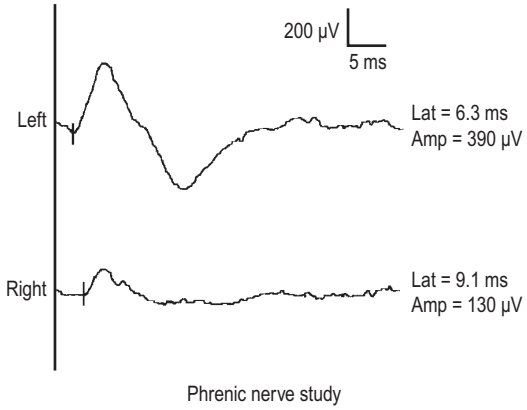

FIGURE 37–3 Phrenic neuropathy. Phrenic motor studies in a patient with an elevated right hemidiaphragm, following right upper lobectomy. Note the lower amplitude and delayed response on the right compared to the left.

and the other side is abnormal or absent (Figure 37–3). If both responses are absent or low in amplitude, it is difficult to draw a firm conclusion: possibly both responses are truly absent or low, or both responses are abnormal due to technical reasons.

Suggested Readings

Bolton, C.F., 1996. Sepsis and the systemic inflammatory response syndrome: neuromuscular manifestations. Crit Care Med 24, 1408–1416.

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38 Approach to Pediatric Electromyography

In conjunction with the clinical examination, electrodiagnostic (EDX) studies frequently play a key role in the evaluation of neuromuscular disorders in infants and children. Indeed, there are a large number of neuromuscular disorders that present in the pediatric age group. In many of these cases, EDX studies are used to help guide further evaluation (e.g., muscle biopsy, genetic testing); less commonly, they can make a definitive diagnosis. A complete discussion of pediatric neuromuscular disorders and electrodiagnosis is beyond the scope and purpose of this chapter (see Suggested Readings). Although the fundamental principles of EDX studies are the same for pediatric and adult age groups, there are significant differences that the electromyographer needs to keep in mind when studying infants and children. These differences include both physiologic and non-physiologic factors that may vary considerably between age groups.

NEUROMUSCULAR DIAGNOSES ARE DIFFERENT IN CHILDREN THAN IN ADULTS

The most common referral diagnoses to the typical electromyography (EMG) laboratory include radiculopathy, polyneuropathy, and carpal tunnel syndrome. However, adults are more commonly studied in the EMG laboratory, so this group of diagnoses reflects neuromuscular conditions seen in the adult age group. In contrast, the neuromuscular disorders seen in children often are different. For example, entrapment neuropathies are very common in adults but are extremely rare in children. Likewise, radiculopathy, probably the most common of all EMG referral diagnoses, is virtually unheard of in children, except in cases of trauma. Although peripheral neuropathies occur in children, they are most often genetic, whereas most peripheral neuropathies in adults referred to the EMG laboratory are acquired disorders, usually toxic, metabolic, inflammatory, or associated with other coexistent medical illnesses. Unlike adults, the more common diagnoses in children referred to the EMG laboratory are inherited disorders of the motor unit, including the anterior horn cell (e.g., spinal muscular atrophy), peripheral nerve (e.g., Charcot–Marie–Tooth), or muscle (e.g., muscular dystrophy).

Children with neuromuscular disorders often present clinically as a delay in motor milestones. In many cases, it may not be clear from the symptoms and signs whether the etiology is central or peripheral. One of the best examples of this predicament is that of the floppy infant, in whom the differential diagnosis includes the entire length of the neuraxis, from brain to muscle. In this regard, EDX studies often are helpful in differentiating peripheral from central etiologies and, accordingly, guiding the subsequent evaluation in a useful and logical direction.

MATURATION ISSUES

When studying children, it is essential to appreciate *what is normal for what age*. This is especially important when interpreting conduction velocities and differentiating a normal conduction velocity from axonal loss or demyelination. Most adult electromyographers who study adults are well versed in the EDX criteria for demyelination:

- Conduction velocities less than 75% the lower limit of normal
- Distal latencies and late responses greater than 130% the upper limit of normal
- Conduction block, which signifies not only demyelination but acquired demyelination

However, infants and young children often have slowed conduction velocities that would be considered in the "demyelinating range" for adults. In most cases, this is not because infants and young children have demyelinated nerves; rather, they have nerves that have yet to be myelinated in the first place. The process of myelination is age dependent, beginning *in utero*, with nerve conduction velocities in full-term infants approximately half that of adult normal values. *Accordingly, nerve conduction velocities of 25 to 30 m/s are normal at birth*. Conduction velocity rapidly increases after birth, reaching approximately 75% of adult normal values by age 1 year, and the adult range by age 3 to 5 years, when myelination is complete. Accordingly, when a child is studied in the EMG laboratory, it is essential that age-based normal control values are used (Tables 38–1 and 38–2).

One interesting aspect of myelin maturation is often observed during the nerve conduction studies. Many are familiar with the fact that different white matter tracts in

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Table 38–1. Pediatric Motor Conduction Studies by Age

	Median Nerve				Peroneal Nerve			
Age	DML (ms)	CV (m/s)	F (ms)	AMP (mV)	DML (ms)	CV (m/s)	F (ms)	AMP (mV)
7 days–l month	2.23 (0.29)*	25.43 (3.84)	16.12 (1.5)	3.00 (0.31)	2.43 (0.48)	22.43 (1.22)	22.07 (1.46)	3.06 (1.26)
1–6 months	2.21 (0.34)	34.35 (6.61)	16.89 (1.65)	7.37 (3.24)	2.25 (0.48)	35.18 (3.96)	23.11 (1.89)	5.23 (2.37)
6–12 months	2.13 (0.19)	43.57 (4.78)	17.31 (1.77)	7.67 (4.45)	2.31 (0.62)	43.55 (3.77)	25.86 (1.35)	5.41 (2.01)
1–2 years	2.04 (0.18)	48.23 (4.58)	17.44 (1.29)	8.90 (3.61)	2.29 (0.43)	51.42 (3.02)	25.98 (1.95)	5.80 (2.48)
2–4 years	2.18 (0.43)	53.59 (5.29)	17.91 (1.11)	9.55 (4.34)	2.62 (0.75)	55.73 (4.45)	29.52 (2.15)	6.10 (2.99)
4–6 years	2.27 (0.45)	56.26 (4.61)	19.44 (1.51)	10.37 (3.66)	3.01 (0.43)	56.14 (4.96)	29.98 (2.68)	7.10 (4.76)
6–14 years	2.73 (0.44)	57.32 (3.35)	23.23 (2.57)	12.37 (4.79)	3.25 (0.51)	57.05 (4.54)	34.27 (4.29)	8.15 (4.19)

*Mean (SD). DML = distal motor latency; CV = conduction velocity; F = F-latency; AMP = amplitude.

From Parano, E., Uncini, A., DeVivo, D.C., Lovelace, R.E., 1993. Electrophysiologic correlates of peripheral nervous system maturation in infancy and childhood. J Child Neurol 8, 336–338.

Table 38–2. Pediatric Sensory Conduction Studies by Age

	Median Nerve		Sural Nerve	
Age	CV (m/s)	AMP (μV)	CV (m/s)	AMP (μV)
7 days–l month	22.31(2.16)*	6.22 (1.30)	20.26 (1.55)	9.12 (3.02)
1–6 months	35.52 (6.59)	15.86 (5.18)	34.63 (5.43)	11.66 (3.57)
6–12 months	40.31 (5.23)	16.00 (5.18)	38.18 (5.00)	15.10 (8.22)
1–2 years	46.93 (5.03)	24.00 (7.36)	49.73 (5.53)	15.41 (9.98)
2–4 years	49.51 (3.34)	24.28 (5.49)	52.63 (2.96)	23.27 (6.84)
4–6 years	51.71 (5.16)	25.12 (5.22)	53.83 (4.34)	22.66 (5.42)
6–14 years	53.84 (3.26)	26.72 (9.43)	53.85 (4.19)	26.75 (6.59)

*Mean (SD); CV = conduction velocity; AMP = amplitude.

From Parano, E., Uncini, A., DeVivo, D.C., Lovelace, R.E., 1993. Electrophysiologic correlates of peripheral nervous system maturation in infancy and childhood. J Child Neurol 8, 336–338.

the central nervous system myelinate at different times. Indeed, one can often use the pattern of myelination on a brain magnetic resonance imaging (MRI) scan to correctly predict the age of a young child. Similarly, different fibers in the peripheral nervous system myelinate at different times as well. In the EMG laboratory, this often manifests as a *bifid morphology* (i.e., two separate peaks) on sensory nerve action potentials (SNAPs) in infants and children (Figure 38–1). This bifid morphology is due to some fibers having already been fully myelinated (the first peak), whereas others have not and trail behind (i.e., the second peak). It is not unusual to see bifid SNAPs between the ages of 3 months and 4 to 6 years. These bifid SNAPs are a completely normal finding. Eventually, as the fibers in the second peak fully myelinate, the second peak moves to the left and merges with the first peak. This forms a larger sensory response, as is typically seen in adults.

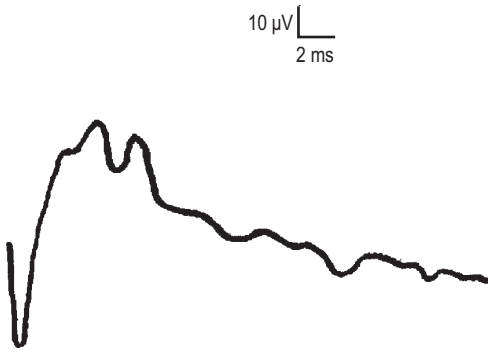

FIGURE 38–1 Sural sensory nerve action potential in a young child. Note the bifid morphology. These bifid sensory responses are a completely normal finding between the ages of 3 months through 4 to 6 years. They occur as different populations of fibers myelinate at different times. Eventually, the group of fibers in the second peak will fully myelinate. The second peak will move to the left and merge with the first peak to form a larger sensory response.

As with adults, the F response can be easily studied in children. Although the F response often is thought of as evaluating the proximal nerve segments, it assesses the entire length of the nerve, from the stimulation point to the spinal cord and back, and then past the stimulation point to the muscle. Thus, the F response latency depends not only on the conduction velocity and distal latency but also on the length of the limb. Because infants and children have slower conduction velocities than adults, one would expect the F responses to be very long. However, counterbalancing this is the very short limb length of a child compared to an adult. Thus, there are two opposing influences on the F response in children: limb length and conduction velocity. In infants and young children, the influence of the limb length is more overriding, resulting in F-wave latencies that are much shorter in children than adults (typically in the range of 16–19 ms in the upper extremities). Thus, whenever an F response is performed on a child, it is essential to compare it to normal control values for the child's age or height.

The most important maturation issue for the needle EMG portion of the examination is the size of the motor unit. It is no surprise that the physical size of a motor unit of a newborn is much smaller than that of an adult. Transverse motor unit territory increases greatly with age, doubling from birth to adulthood, mostly because of the increase in individual muscle fiber size. Thus, normal motor unit action potentials (MUAPs) in infants typically are very small, representing the physical size of the motor unit. *Indeed, in infants, it often is difficult to differentiate normal MUAPs from myopathic ones*. This once again underscores that when one interprets EDX findings in children, including MUAPs, it is essential to use age-based normal control values (Table 38–3).

TECHNICAL ISSUES

A large number of unique technical issues must be kept in mind when studying infants and children so that reliable and accurate data can be obtained. The first important issue is measurement of distances and its relationship to technical errors. Because a child's limb is much smaller than an adult's, much shorter distances are used. When short distances are used, a small error in measurement creates a much larger error in computed conduction velocities than when longer distances are used. For instance, in an adult, if the distance between the wrist and elbow is measured at 20 cm but is off by 1 cm (i.e., the true measurement is 21 cm), this results in an error of 5% when calculating a conduction velocity. However, in a newborn baby, if the measured distance is 7 cm but is off by 1 cm (i.e., the true measurement is 8 cm), the error in conduction velocity increases to 14%. Thus, one needs to be especially careful when measuring distances in children.

Second, smaller electrodes often are needed in infants and young children because their limbs and muscles are so small. The typical bar electrode that has the active and reference contacts separated by 2.5 cm often is too large for most infants and small children (Figure 38–2). Standard 10 mm disc electrodes often will suffice for most ages, except for newborns in which smaller electrodes generally are needed. Likewise, the standard adult stimulator often is too large for infants and young children because of the size of the prongs and the distance between the cathode and anode. Often it is preferable to use a pediatric-sized stimulator so that the nerve of interest is more accurately stimulated (Figure 38–3).

Because a child's limbs are so much smaller than an adult's, one needs to take great care when stimulating the

Table 38–3. Mean Motor Unit Action Potential Duration Based on Age and Muscle Group

Age of Subjects (yrs)	Arm Muscles (ms)					Leg Muscles (ms)					
	Deltoid	Biceps	Triceps	Thenar	ADM	Quad, BF	Gastroc	Tib Ant	Per Long	EDB	Facial
0–4	7.9–10.1	6.4–8.2	7.2–9.3	7.1–9.1	8.3–10.6	7.2–9.2	6.4–8.2	8.0–10.2	6.8–7.4	6.3–8.1	3.7–4.7
5–9	8.0–10.8	6.5–8.8	7.3–9.9	7.2–9.8	8.4–11.4	7.3–9.9	6.5–8.8	8.1–11.0	5.9–7.9	6.4–8.7	3.8–5.1
10–14	8.1–11.2	6.6–9.1	7.5–10.3	7.3–10.1	8.5–11.7	7.4–10.2	6.6–9.1	8.2–11.3	5.9–8.2	6.5–9.0	3.9–5.3
15–19	8.6–12.2	7.0–9.9	7.9–11.2	7.8–11.0	9.0–12.8	7.8–11.1	7.0–9.9	8.7–12.3	6.3–8.9	6.9–9.8	4.1–5.7
20–29	9.5–13.2	7.7–10.7	8.7–12.1	8.5–11.9	9.9–13.8	8.6–12.0	7.7–10.7	9.6–13.3	6.9–9.6	7.6–10.6	4.4–6.2
30–39	11.1–14.9	9.0–12.1	10.2–13.7	10.0–13.4	11.6–15.6	10.1–13.5	9.0–12.1	11.2–15.1	8.1–10.9	8.9–12.0	5.2–7.1
40–49	11.8–15.7	9.6–12.8	10.9–14.5	10.7–14.2	12.4–16.5	10.7–14.3	9.6–12.8	11.9–15.9	8.6–11.5	9.5–12.7	5.6–7.4
50–59	12.8–16.7	10.4–13.6	11.8–15.4	11.5–15.1	13.4–17.5	11.6–15.2	10.4–13.6	12.9–16.9	9.4–12.2	10.3–13.5	6.0–7.9
60–69	13.3–17.3	10.8–14.1	12.2–15.9	12.0–15.7	13.9–18.2	12.1–15.8	10.8–14.1	13.4–17.5	9.7–12.7	10.7–14.0	6.3–8.2
70–79	13.7–17.7	11.1–14.4	12.5–16.3	12.3–16.0	14.3–18.6	12.4–16.1	11.1–14.4	13.8–17.9	10.0–13.0	11.0–14.3	6.5–8.3

ADM, abductor digiti minimi; BF, biceps femoris; EDB, extensor digitorum brevis; Gastroc, gastrocnemius; Per long, peroneus longus; Quad, quadriceps; Tib ant, tibialis anterior.

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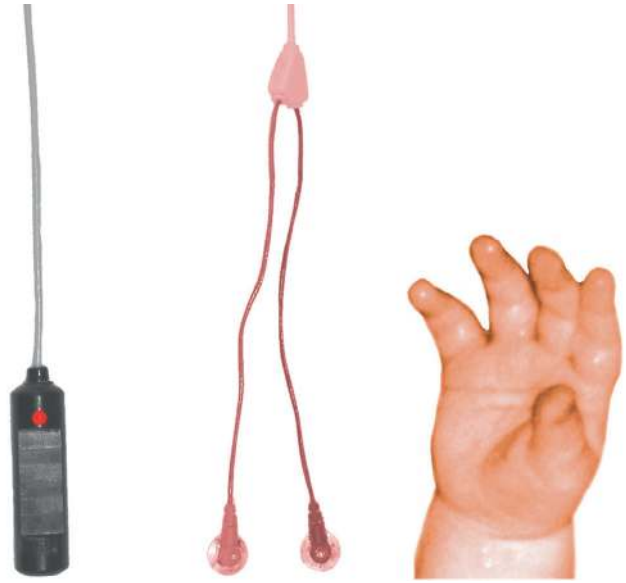

FIGURE 38–2 Pediatric electrodiagnostic studies and recording electrode size. The standard bar electrode **(left)** and 10 mm disc electrodes **(middle)** are compared to the size of an infant's hand **(right).** Smaller electrodes may be needed in infants and young children because their limbs and muscles are so small. Standard 10 mm disc electrodes often will suffice for most age groups, including infants. In newborns, however, smaller electrodes are needed. Other standard electrodes, like the bar electrode, are too large for a newborn or infant's hand.

FIGURE 38–3 Pediatric electrodiagnostic studies and stimulator size. The standard stimulator can be used for adults and most children. However, for infants and young children, it is preferable to use a pediatric-sized stimulator so that the nerve of interest is more accurately stimulated.

nerves. The stimulus intensity needs to be kept as low as possible, for patient cooperation and tolerance but also to prevent co-stimulation of nearby nerves. Co-stimulation of nerves is much more likely to occur in a young infant or child than in an adult, even at low intensities, because of the small size of the limb and the close physical proximity of the nerves to each other.

During the needle EMG examination, additional technical issues arise. Because the physical size of the motor units in children is quite small, it is often very difficult, even for the most experienced pediatric electromyographer, to differentiate normal MUAPs from myopathic MUAPs, especially in infants. Decreased recruitment and large MUAPs, as seen in neuropathic conditions, are much more straightforward and easier to appreciate in infants and children than normal or myopathic MUAPs in this population.

Because individual muscle fibers are so small in infants and children, another common problem that arises in pediatric electromyography is the differentiation between fibrillation potentials and endplate spikes. The endplate zone in infants takes up a disproportionately large territory of the muscle compared with adults. Thus, it is not uncommon to encounter endplate potentials when studying pediatric patients. Endplate spikes can easily mimic fibrillation potentials. One needs to pay especially close attention to the firing pattern (regular vs. irregular) and the initial waveform deflection (positive vs. negative) to properly differentiate fibrillation potentials from endplate spikes. Because fibrillation potentials signify active denervation, it is essential not to mistake endplate spikes for fibrillation potentials, especially in the pediatric population, where such findings may portend a particularly grave diagnosis, such as infantile spinal muscular atrophy (Werdnig–Hoffmann disease).

APPROACH TO THE CHILD AS A PATIENT

Although many adults are apprehensive of EDX studies, most tolerate the study well, with minimal discomfort. In adults, explaining the test in advance and as it proceeds is often one of the most helpful ways of allaying any fears and creating good patient rapport. However, a different approach must be taken to allay fears and create rapport with an infant or child in the EMG laboratory. As most children are accompanied by their parent(s), it is often extremely helpful to have a parent in the room with the child. The parent can help comfort the child and be a valuable asset to the electromyographer. The electromyographer also might consider removing his or her white coat before entering the examination room. Speaking with the child in a supportive and comforting manner, using uncomplicated words and phrases, will help allay the child's fears. Of course, the task is much more difficult in infants, who cannot understand the situation, and in these cases having a parent in the room is extremely valuable.

There are a few helpful techniques that can be used with children to gain their cooperation. When performing the nerve conduction studies, the electromyographer can explain to the child that the stimulator will feel like a tap, buzz, or static electricity, similar to when he or she rubs the feet along the floor and then touches the refrigerator. *It is best to avoid the word "shock" when explaining the nerve conduction part of the study, because the term likely has negative connotations for both children and adults.* One extremely effective maneuver is to have the child hold the stimulator and stimulate the examiner's median nerve at

the wrist, using a low-stimulus current. In this way, the child can see the muscle twitch. More importantly, the child will see that the examiner is not distressed by the experience (hopefully). In children aged 5 through 10 years, we routinely have them stimulate our own nerves before we begin the study. One will find that the parent in the room often is interested in knowing what the stimulator feels like on themselves. *Regarding the needle part of the test, the word "needle" should always be avoided*. No one likes needles, including children. Children are very familiar with needles, usually receiving one or more vaccinations almost every time they visit their pediatrician. It is best to use the word "electrode" or "microphone" when describing the needle part of the examination. If a child is told that a very small microphone is going to be put into his or her muscle so that he or she will be able to hear the muscles along with you, the child may become very interested and engaged in the test.

The most difficult age for EDX studies is between the ages of 2 and 6 years. In the infant, who cannot understand and who also cannot move around very much, EDX studies usually can be done fairly easily and quickly, with minimal discomfort to the infant, with an assistant helping immobilize the limb being studied. However, in rambunctious toddlers, EDX studies can be very difficult without their cooperation. Indeed, in this age group, conscious sedation often is very helpful.

In the past, a mild sedative such as chloral hydrate was often used. This form of sedation usually was inadequate, with the child often sleeping well on the ride home after the study but not during the study. In the modern day, conscious sedation with propofol (Diprivan), under the supervision of an anesthesiologist, can be used to obtain good data with minimal discomfort to the child. Propofol is an intravenous sedative–hypnotic agent used for induction of anesthesia or for sedation. Its major advantage is that it produces hypnosis rapidly, usually within 40 seconds from the start of the injection. As with other rapidly acting intravenous anesthetic agents, the half-time of the blood–brain equilibration is approximately 1 to 3 minutes. While the child is sedated with propofol, nerve conduction studies and/or repetitive nerve stimulation studies can be performed easily. Likewise, the needle EMG study can be performed, looking for abnormal spontaneous activity, while the child is sedated. The propofol then can be turned down, and, as the child is coming out of the sedation, MUAPs can be analyzed (Figure 38–4).

Pediatric electromyography nevertheless remains a challenge, even if these recommendations are followed. The more experience one has with children, the easier the testing goes. In pediatric electromyography, more than in any other situation, it is important to always follow the Willie Sutton rule: *Go where the money is!* One needs to carefully choose the nerves and muscles to study based on the following:

- Which studies are essential to help support or exclude a diagnosis

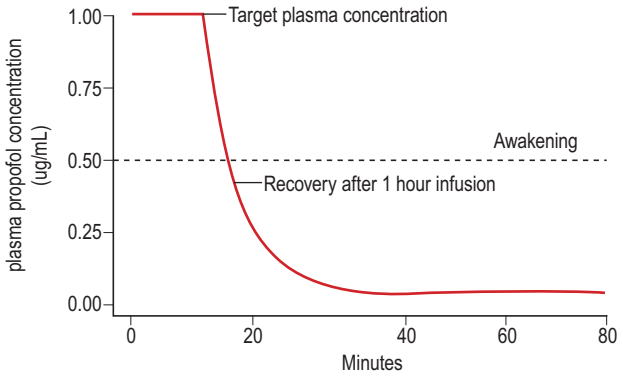

FIGURE 38–4 Propofol plasma concentration kinetics. Under the direction of an anesthesiologist, propofol can be used successfully to sedate young children undergoing electrodiagnostic studies. Its major advantage is that it produces a rapid hypnosis. Upon stopping the infusion, the concentration rapidly declines and the child begins to awaken within a few minutes. While the child is sedated, nerve conduction studies, repetitive nerve stimulation studies, and needle electromyography (assessing spontaneous activity) can be performed. As the child begins to awaken, motor unit action potentials can be analyzed.

- Which nerve conduction studies are the fastest and easiest to perform
- Which muscles are the easiest to activate and the least painful to study

For example, the median motor nerve is much easier to stimulate and record than the tibial motor nerve, which is difficult and painful to stimulate behind the popliteal fossa. Likewise, it is important to choose muscles that are less painful and easier to activate than others. For instance, the first dorsal interosseous (FDI) and the abductor pollicis brevis (APB) both are distal upper extremity C8–T1-innervated muscles. However, the FDI is much less painful to sample than the APB. In children, it is always best to purposefully choose the least painful muscles to examine, unless it is absolutely necessary to examine a muscle that is known to be painful. In addition, it is important to choose muscles that are easy to activate. In children who cannot cooperate, it often is useful to choose muscles that can be activated by withdrawing to a sensory stimulus. For instance, tickling the foot will result in contraction of the tibialis anterior and hamstring muscles as the child reflexively pulls his or her leg away.

One of the most important rules in pediatric electromyography is: "Take what you can get, when you can get it!" When examining an adult, the electromyographer is accustomed to placing the needle electrode in the muscle, looking first at insertional and spontaneous activity, and then changing the gain to 200 μV per division while having the patient contract to look at the MUAPs. In a child, if one puts the needle electrode into a muscle and MUAPs are firing, do not try to get the child to relax the muscle. It is much more productive to quickly change the sensitivity to 200 μV per division and look at the MUAPs while they are firing, because you might not get another chance!

Do not expect to follow the same regular routine in a child that you normally would follow in an adult.

GOALS OF THE PEDIATRIC ELECTRODIAGNOSTIC EXAMINATION

The goals of the EDX study in infants and children are similar to those in adults. The first goal is to discern if a neuromuscular disorder is present. Differentiating between a central and peripheral cause of weakness is of prime importance to the referring physician. If the problem is peripheral, the next goal is to determine if the pathology is neuropathic, myopathic, or due to a disorder of the neuromuscular junction. This differentiation then allows for a more efficient and logical use of further laboratory testing. If the condition is neuropathic, the next goal is to determine if motor, sensory, or a combination of fibers is involved. This relies primarily on whether SNAPs are present, reduced, or absent. Take the example of a young child with diffuse denervation and reinnervation on needle EMG associated with low motor amplitudes on nerve conduction studies. Taken together, these findings denote a neuropathic process. If the SNAPs are normal, then the disorder most likely localizes to the anterior horn cells. Although these findings also might be seen in a pure motor neuropathy, this would be very unlikely in an infant or child. On the other hand, if the SNAPs are abnormal, then a peripheral neuropathy likely is present, which has a very different differential diagnosis and prognosis. If a peripheral neuropathy is present, the next important piece of information to discern from the EDX study is whether or not the pathology is demyelinating. Because so many pediatric peripheral neuropathies are genetic in nature and because the demyelinating forms of Charcot–Marie–Tooth

Table 38–4. Recommended Approach to Childhood Neuromuscular Disorders

	Diagnostic Test/Procedure			
Suspected Clinical Diagnosis	**Option:**	**1st**	**2nd**	**3rd**
Duchenne–Becker MD		DNA	MBx	
LGMDs		DNA[1]	MBx	EMG/NCS[2]
Congenital muscular dystrophies		MBx	DNA	EMG/NCS[2]
Emery–Dreifuss MD		DNA	MBx	EMG/NCS[2]
FSH MD		DNA	MBx	EMG/NCS[3]
MyD		DNA	EMG/NCS	
Periodic paralysis/myotonias		DNA	EMG/NCS	
Metabolic		MBx	DNA	EMG/NCS[3]
Congenital myopathies		MBx	DNA[4]	EMG/NCS[5]
DM/PM		MRI	MBx	EMG/NCS[3]
Indeterminate proximal weakness		EMG/NCS	RMNS	MBx/DNA
SMA		DNA	EMG/NCS	MBx[6]
CIDP		EMG/NCS	CSF	NBx
AIDP (GBS)		CSF	EMG/NCS	
HMSNs		EMG/NCS	DNA	
Neuromuscular transmission disorders		EMG/NCS	RMNS	Antibodies/DNA[7]

AIDP, acute inflammatory demyelinating polyneuropathy; BMD, Becker muscular dystrophy; CIDP, chronic inflammatory demyelinating polyneuropathy; CSF, cerebrospinal fluid examination; DM/PM, dermatomyositis/polymyositis; DMD, Duchenne muscular dystrophy; DNA, deoxyribonucleic acid/genetic testing; EMG, electromyography; FSH, facioscapulohumeral; GBS, Guillain–Barré syndrome; HMSNs, hereditary motor and sensory neuropathies; LGMD, limb-girdle muscular dystrophy; MBx, muscle biopsy; MD, muscular dystrophy; MRI, magnetic resonance imaging; MyD, myotonic dystrophy; NBx, nerve biopsy; NCS, nerve conduction studies; RMNS, repetitive motor nerve stimulation; SMA, spinal muscular atrophy.

Note that even in the era of molecular diagnostics, electromyography continues to play a prominent role in the evaluation of pediatric neuromuscular disorders.

1. DNA testing is now available for many of the LGMDs. In addition, DNA testing is helpful in a limb-girdle phenotype to also exclude DMD/BMD;
2. In atypical, sporadic cases with low creatine kinase values;
3. Optional;
4. If available;
5. In certain cases, EMG/NCS may be the first option;
6. If EMG/NCS consistent with SMA but DNA test is negative;
7. For congenital myasthenic syndromes.

From Darras, B.T., Jones, H.R. Jr., 2000. Diagnosis of pediatric neuromuscular disorders in the era of DNA analysis. Pediatr Neurol 23, 289–300, with permission.

disease are the most common, the presence of conduction velocities in the demyelinating range has great importance. Of course, there also are instances of acquired demyelinating neuropathies in children, which can usually be distinguished from genetic forms of demyelinating neuropathy using the same guidelines that apply to adults (see Chapter 26).

In general, there is a very good correlation between the results of EDX studies and the final diagnosis. This is especially true for neuropathic disorders (i.e., anterior horn cell disorders and peripheral neuropathy). They are also helpful but not as good for myopathic disorders, especially in children younger than age 2. As noted earlier, motor units in young children are normally quite small, making the differentiation between normal and myopathic motor unit action potentials very demanding. In addition, some myopathies are fairly "bland" on needle EMG, most often the congenital myopathies. This is in contradistinction to the muscular dystrophies and myositis which are much more easily recognized as myopathic on needle EMG. One might think that in the present era of molecular genetics wherein DNA and other forms of genetic analysis are available for many of the inherited neuromuscular conditions (e.g., spinal muscular atrophy, many of the muscular dystrophies, and many forms of Charcot–Marie–Tooth disease), EDX studies would play less of a role than in the past. This is true for the infant or child who has a classic phenotype of a well-known inherited disorder. In these cases, especially if there is a positive family history, the diagnosis can often be confirmed by genetic testing, without the need for EDX studies. However, this remains a minority of the cases. In the evaluation of a child with weakness or a delay in motor milestones, EDX studies still play a major role in guiding the evaluation process in a logical and efficient manner, with occasional diagnoses made directly from data obtained from EDX studies (Table 38–4). For instance, Dejerine–Sottas syndrome (DSS) is a term applied to a group of genetically heterogeneous demyelinating neuropathies that typically present in infancy or early childhood. DSS can easily mimic the clinical presentation of Werdnig–Hoffman (spinal muscular atrophy type 1). However, DSS is associated with the slowest conduction velocities ever recorded in humans, typically less than 12 m/s and usually less than 6 m/s. The finding of such a slowed conduction velocity on nerve conduction studies will immediately point to the diagnosis of DSS. Afterward, appropriate genetic testing can be undertaken looking for the known mutations associated with DSS, which include mutations of the *P0*, *MP22*, and *EGR2* genes, among others.

Without doubt, the pediatric EDX study is much more challenging and difficult to perform than a similar study in an adult. However, being aware of the unique maturational and technical issues associated with studying infants and children and approaching the examination with a different philosophy will offer the electromyographer the same kinds of useful information that can be obtained in adults.

Suggested Readings

Darras, B.T., Jones, H.R., 2000. Diagnosis of pediatric neuromuscular disorders in the era of DNA analysis. Pediatr Neurol 23, 289–300.

Gabreels-Festen, A., 2002. Dejerine–Sottas syndrome grown to maturity: overview of genetic and morphological heterogeneity and follow-up of 25 patients. J Anat 200, 341–356.

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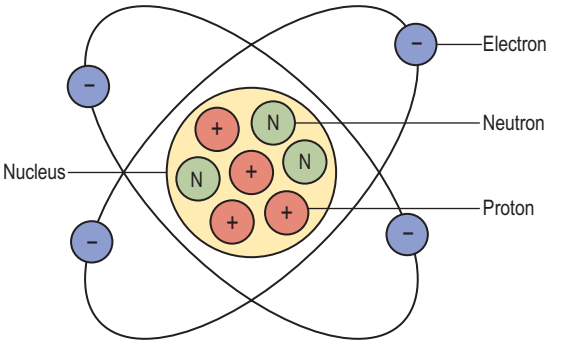
39 Basics of Electricity and Electronics for Electrodiagnostic Studies

In the office, hospital, and home, we are surrounded by equipment, appliances, and many other devices powered by electricity. Although knowledge of electricity and electronics is not needed to watch television, talk on the telephone, or use a toaster, these examples are just the tip of the electrical and electronic iceberg in the world we live in as electromyographers.

One might ask, is it really necessary to understand the basics of electricity and electronics in order to perform routine electrodiagnostic (EDX) studies? Although a degree in electrical engineering certainly is not needed, the answer clearly is yes. First, and most important, understanding the basics of electricity is essential to safely perform EDX studies and prevent potential electrical injuries to patients (see Chapter 40). Second, all of the responses recorded during nerve conduction studies and needle electromyography (EMG) are small electrical signals that are amplified, filtered, and then displayed electronically. Knowledge of electricity and electronics allows for a better understanding of what these potentials represent. Finally, and equally as important, knowledge of electricity and electronics is critical to understand and correct the variety of technical problems that frequently arise during EDX studies (see Chapter 8).

BASICS OF ELECTRICITY

All atoms have a nucleus composed of positively (+) charged particles, *protons*, and particles with no charge, *neutrons*. Orbiting around the nucleus are negatively (–) charged particles, *electrons*. Most atoms have the same number of protons and electrons; the electrons remain bound in their orbit by their magnetic attraction to the protons (i.e., in magnetism, opposites attract).



Electricity is formed when electrons are removed from their orbit and flow to adjacent atoms. Materials that allow electrons to move freely are known as *conductors*. In contrast, materials that inhibit the flow of electrons are known as *insulators*. Conductors typically are metals, most often copper. Insulators most often are rubber, plastic, or ceramic. To understand basic electrical circuits, one needs first to be acquainted with several important terms:

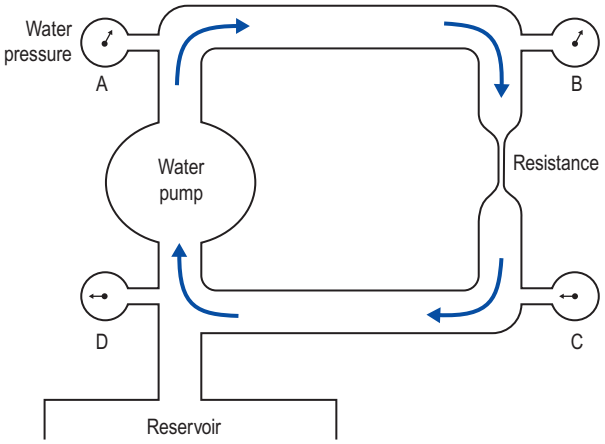
- ***Coulomb*** is the standard unit of electric charge, approximately equal to 6.24×10^{18} electrons.
- ***Current***, represented by the symbol ***I***, is the actual flow of electrons. The ampere is a measure of current, designated by the letter ***A***. An ***ampere*** is defined as 1 coulomb passing a point in a conductor in 1 second. Current can only flow when a complete circuit exists.
- ***Voltage*** is the electromotive force required to make electricity flow through a conductor. This electromotive force results from a fundamental property of magnetism that oppositely charged particles attract each other. Any source with an excess of electrons (negatively charged particle) will be drawn to a source with a lack of electrons (positively charged particle). Voltage is designated by the symbol ***E***. Its unit of measurement is ***volts***, which is designated by the letter ***V***.

DOI: 10.1016/B978-1-4557-2672-1.00039-8

- ***Resistance*** opposes the flow of electrons. Resistance is designated by the symbol ***R***. The unit of measurement for resistance is ***Ohms***, which is designated by the Greek letter ***Ω***. All materials, even conductors, impede the flow of electrical current to some extent. In general, resistance increases with the length of the conductor and decreases as the cross-section of the conductor increases.

Analogy between Electricity and Water

Because current and electrons cannot be seen, it may be difficult to relate to electricity and its basic definitions. One useful way of understanding electricity and its properties is to make an analogy to the flow of water. The analogy to water and plumbing often is easier to grasp and can be extrapolated to the understanding of electricity.

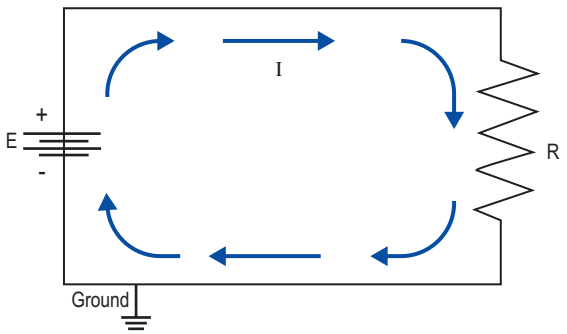


Water can be measured as a specific volume (e.g., a liter or gallon). Thus, a gallon of water is analogous to a coulomb of electricity, an amount of charge. For water to flow, it must have some force that is driving or pushing it. This force can be gravity, in the case of water stored in a water tower, or a pump that mechanically propels the water. In either case, water is put under pressure. Pressure is measured as force per unit area, typically as pounds per square inch (psi). Thus, water pressure is analogous to voltage, the driving electromotive force. Water will flow if there is a pressure difference between two points (i.e., from an area of high pressure to low pressure). Likewise, electrons will flow if there is a difference in voltage between two points. Flow is the actual movement of water, which is measured as volume passing by a point in a specific time period (e.g., gallons per second). Thus, flow of water is analogous to current, the movement of electrons, which is measured in amperes (1 coulomb passing a point in a conductor in 1 second). Lastly, resistance to water flow is determined by the physical characteristics of the pipes it is traveling through. Longer and especially narrow-diameter pipes impede the flow of water. Thus, the mechanical resistance of a water pipe is analogous to the electrical resistance of a circuit.

The flow of water is determined by *Poiseuille's law*:

$$\text{Flow} = \frac{\text{Change in water pressure between two points}}{\text{Water resistance}}$$

At point D in the figure above, the water pressure is essentially zero. Water is taken up by the pump and pressurized, resulting in a high pressure at point A. Water will now flow because it is under high pressure at point A and low pressure at point D. The water pressure at point B will still be high because the diameter of the pipe is so large that it offers little resistance to flow. However, the marked narrowing of the pipe between points B and C increases the resistance to flow. The higher the resistance, the less the flow. Conversely, the higher the water pressure difference, the more the flow. At point C, the water pressure is now very low. However, it must still be slightly higher than point D so that water will flow from point C to D. If extra water were to somehow get into the system and be a greater amount than the water pump could pump, it could easily be diverted to the reservoir (analogous to the ***ground***, see later).



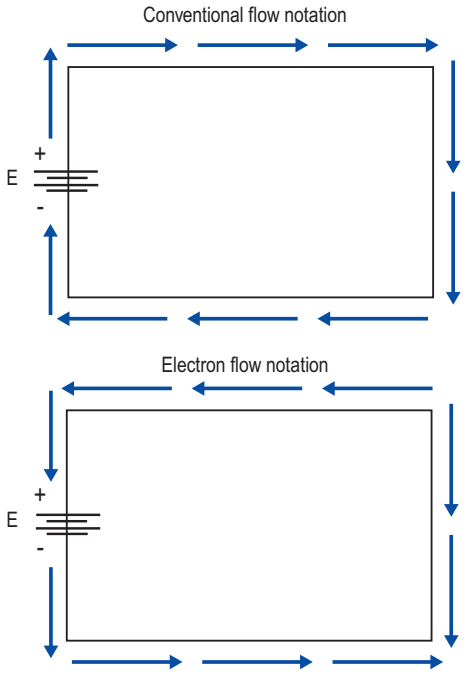
Ohm's Law

The most important basic principle of electricity is *Ohm's law*, which defines the relationship among current, voltage, and resistance in a circuit. Ohm's law is directly analogous to Poiseuille's law for water. *For electrical circuits, Ohm's law states that:*

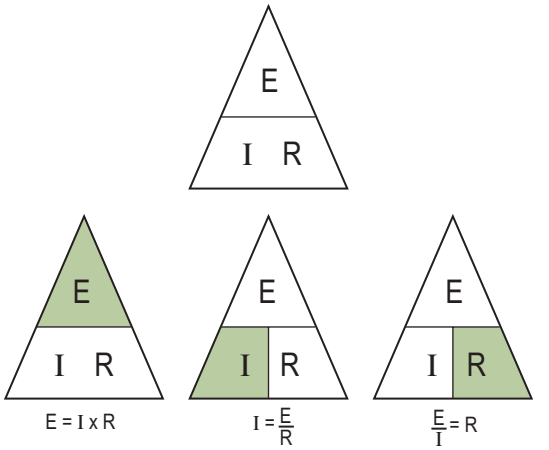
$$\text{Current} = \frac{\text{Change in voltage between two points}}{\text{Resistance}}$$

$$I = \frac{E}{R}$$

The figure above depicts a simple circuit consisting of a battery (E) (an electromotive source of electrons) connected to one resistor (R). The amount of current (I) flow is determined by Ohm's law, $I=E/R$, where E is the voltage from the battery, and R is the resistance. Also note the presence of the ground connection. The ground is ideally a true electrical zero. Most often true grounds are physically connected to the earth (e.g., through a pipe).



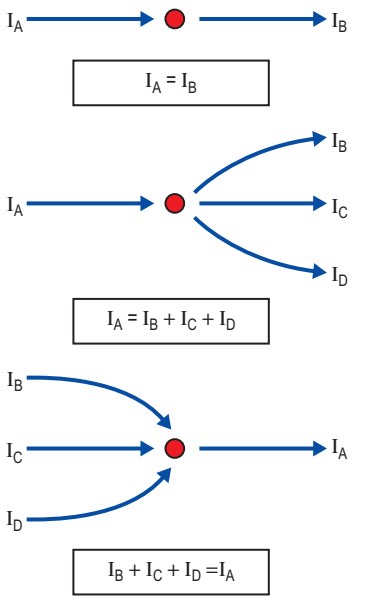
One of the confusing aspects of electricity is figuring out the direction that current actually flows. In the *conventional flow notation*, electric charges move from the positive (surplus) side of the battery to the negative (deficiency) side. However, as electricity comes about by the flow of electrons, which are negatively charged, the actual flow of electrons occurs from the negative to the positive. In the *electron flow notation*, electric charges moves from the surplus of negative charges at the negative side of the battery to the positive side of the battery which has a deficiency of negative electrical charges. Both notations are correct when used consistently. The conventional flow notation is used by most electrical engineers and found in most electrical engineering textbooks, and will be used in this chapter.



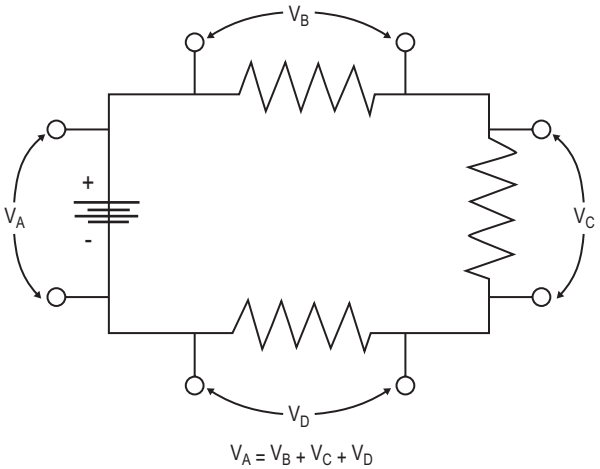
One helpful aid in remembering the relationships in Ohm's law is the Ohm's triangle illustration (above). If a triangle is constructed with E at the top and I and R at the bottom as shown, the value of E, I, or R can readily be determined by blocking the variable of interest (shaded in the figure) and looking at the relationship between the other two parameters.

Kirchhoff's Laws

In addition to Ohm's law, there are two other important principles, known as *Kirchhoff's laws*, with which one must be familiar in order to understand basic electricity.



Kirchhoff's current law states that the algebraic sum of all the currents meeting at any point in a circuit must be zero. Put another way, the sum of incoming currents must equal the sum of outgoing currents. This law represents the conservation of charge. The number of electric charges that flow toward a point must equal the number of electric charges that flow away from that point.

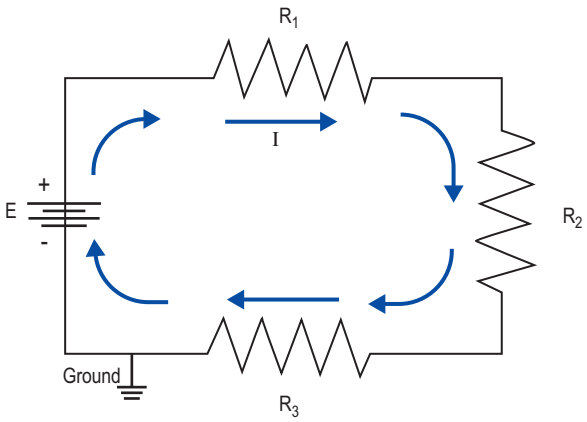


Kirchhoff's voltage law states that, in a closed circuit, the algebraic sum of all the voltage (i.e., potential) drops is equal to the electromotive source voltage of the circuit. The figure above shows a battery with a voltage (V_A) connected in series to three resistors (B, C, D). The current running through the three resistors results in a voltage drop across each resistor, V_B, V_C, and V_D, respectively. Kirchhoff's voltage law requires that the sum of the voltage drops across all three resistors equals the voltage of the battery (i.e., $V_B+V_C+V_D=V_A$).

Simple Resistive Circuits

Resistors in Series

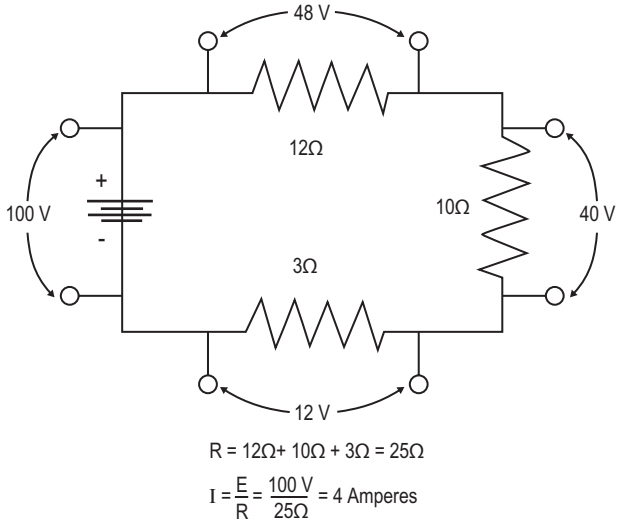
From Ohm's and Kirchhoff's laws, one can predict the behavior of simple resistive circuits.



First, take the example of a simple circuit with a battery (E) connected to three resistors in series. From Kirchhoff's current law, the current (I) must be the same going through each resistor (i.e., current flowing into any point equals the current flowing out of that point). From Ohm's law, a voltage drop will be present across each resistor ($E=I\times R$). Thus, the voltage drops for the three resistors must be $I\times R_1$, $I\times R_2$, and $I\times R_3$, respectively. From Kirchhoff's voltage law, the voltage from the battery (E) must equal the sum of all the voltage drops across the three resistors ($V_B+V_C+V_D$). With this information, applying simple algebra:

$E=V_B+V_C+V_D$	(Kirchhoff's voltage law)
$E=I\times R_1+I\times R_2+I\times R_3$	(Ohm's law)
$E=I\times\ (R_1+R_2+R_3)$	(Algebra)
$E=I\times R$	(Ohm's law)
$R=R_1+R_2+R_3$	(Algebra, using substitution)

Thus, resistors in a series can be directly added together to calculate a net resistance. Take an example of the same circuit of a battery connected to a series of three resistors, using real values.



The battery has a voltage of 100 V. The resistors have a resistance of 12, 10, and 3 Ω, respectively. Thus, the total resistance of the circuit is the sum of the resistors (12+10+3) =25 Ω. With this information, the current can be easily calculated from Ohm's law:

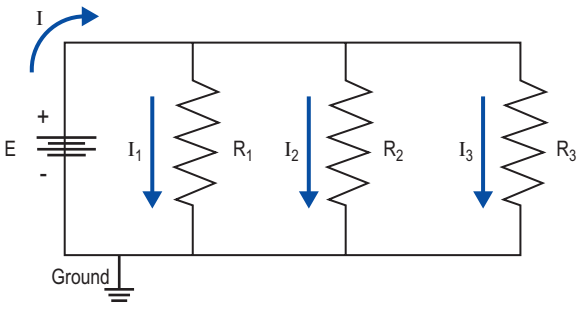
$$I=\frac{E}{R}$$

$$I=\frac{100\ \text{V}}{25\ \Omega}=4\ \text{A}$$

Knowing the current, the individual voltage drop across each resistor (48 V, 40 V, 12 V) can be calculated from Ohm's law ($E=I\times R$).

Resistors in Parallel

When resistors in a circuit are placed in parallel, a net resistance can also be calculated using Ohm's and Kirchhoff's laws.



Take an example of a simple circuit with a battery (E) connected to three resistors in parallel. From Kirchhoff's current law, the total current (I) must be the sum of the individual currents going through each resistor:

$$I=I_1+I_2+I_3$$

From Ohm' law, the voltage across each resistor can be calculated:

$$V_1 = I_1 \times R_1$$

$$V_2 = I_2 \times R_2$$

$$V_3 = I_3 \times R_3$$

From Kirchhoff's voltage law, the voltage from the battery must equal the voltage drops along any closed circuit. Thus, the same voltage (E) from the battery must be present across each of the three resistors:

$$E = V_1 = V_2 = V_3$$

With this information, we can solve the equation for total current:

$$I = I_1 + I_2 + I_3$$

$$I = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

$$I = \frac{E}{R_1} + \frac{E}{R_2} + \frac{E}{R_3}$$

$$I = E \times \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right)$$

Now, we can solve for the total resistance:

$$R = \frac{E}{I}$$

$$R = \frac{E}{E \times \left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \right)}$$

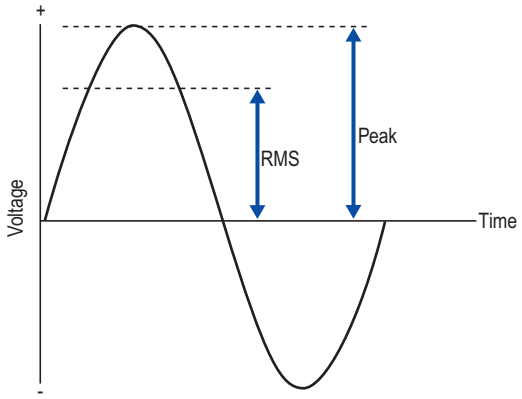
$$R = \frac{1}{\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}}$$

Thus, resistors in parallel reduce the total resistance, as opposed to resistors in series, which increase the total resistance. For instance, three resistors in series, each 100 Ω, result in a total resistance of 300 Ω. However, three resistors in parallel, each 100 Ω, result in a net resistance of 33 Ω. The analogy to water is as follows. Imagine a bucket full of water. The weight of the water creates a water pressure against the bottom of the bucket. If a hole is drilled through the bottom of the bucket, water will start to flow, based on how large the hole is (i.e., the resistance) and the water pressure in the bucket. If another hole is drilled nearby (i.e., in parallel), there are now two ways for water to escape (under the same pressure), and hence the amount of water leaving the bucket (i.e., the current) will increase. Thus, the two holes in parallel effectively decrease the resistance to water leaving the bucket.

Direct Current and Alternating Current

Direct current (DC) is current that always flows in the same direction. In DC, electrons flow uniformly from the power source through a conductor to a load (i.e., an electrical device) and back to the power source. The most common example of a DC power source is the battery.

However, current also can be supplied as an ***alternating current*** (AC). In an AC, electrons follow the path of a sine wave, flowing first in one direction and then reversing. The current reverses polarity many times a second [measured as cycles per second (cps) or Hertz (Hz)]. The most common example of AC is the conventional 60 Hz electricity in wall sockets in houses and offices.



Because DC and voltage are constant, their measurements are straightforward. However, AC measurement is more complicated, because voltage and current are constantly changing values. There are several ways to measure AC, including measuring baseline to peak or peak to peak. A mean would not be useful, because the mean of an AC current is actually zero. However, the most common method of measuring AC is the root mean square (RMS) value. The RMS is calculated by dividing the waveform into many small increments. The value of each increment is squared and a mean of all the squares determined. Finally, the square root of the mean results in the RMS value. The RMS value is the most useful way of measuring AC because *power* in a circuit is defined as voltage multiplied by current:

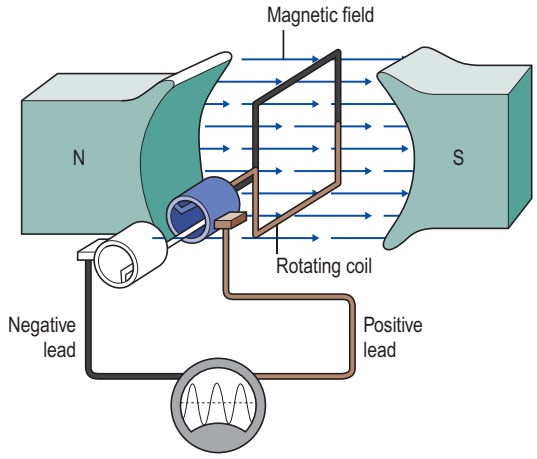
$$\text{Power (watts)} = E \times I$$

$$= E \times \frac{E}{R} \text{ (substituting } E/R \text{ for } I \text{ per Ohm's law)}$$

$$= \frac{E^2}{R}$$

Thus, power is proportional to the square of the voltage. Accordingly, for the same resistance, 1 volt RMS of AC delivers the same power as 1 volt DC. For the typical house or office AC, the RMS voltage is approximately 0.707 multiplied by the voltage measured between baseline and the maximum value. Thus, in the United States, 120 V RMS corresponds to approximately 170 V baseline to peak.

One natural question to ask is: why alternating current? Current constantly flowing back and forth in opposite directions many times a second seems confusing and counterintuitive. However, alternating current arises from all the common ways that electricity is generated. Whether the source is a windmill, hydroelectric, nuclear, coal, or natural gas, all ultimately result in a rotational mechanical movement (e.g., wind and hydro directly turning an axis; nuclear, coal, and natural gas heating water to steam which then turns a turbine). Electricity is then created by attaching a coil (a conductor shaped as a loop) to the mechanical rotation with the coil placed in a strong magnetic field. As the conductor rotates in the magnetic field, electricity is generated and flows to an attached load. The angle and direction of the coil in the magnetic field determines the amount and direction of the electricity. When the coil is perpendicular to the magnetic field and moving with the positive side of the coil up, the maximal current is generated (i.e., the top of the sine wave). However, when the coil is perpendicular to the magnetic field and moving with the negative side of the coil up, the maximal current is generated in the other direction (i.e., the bottom of the sine wave). When the coil is parallel to the magnetic field, no current is generated (the zero crossings of the sine wave). It is this rotation of a coil within a magnetic field that creates an alternating current with its characteristic sinusoidal waveform.



CAPACITANCE, INDUCTANCE, AND REACTANCE

Beyond simple resistive circuits, one needs to move next to the basics of capacitance, inductance, and reactance. Although these concepts are more complicated, they have direct relevance to EDX studies regarding (1) low- and high-frequency filters, and (2) stray leakage currents that potentially pose a risk of electrical injury to patients undergoing EDX studies (see Chapter 40).

Although capacitance and inductance are present in DC circuits, they are more germane to AC circuits. The concept of reactance is only applicable to AC circuits. As noted in the following, capacitance and inductance share many fundamental properties but also have significant and important differences.

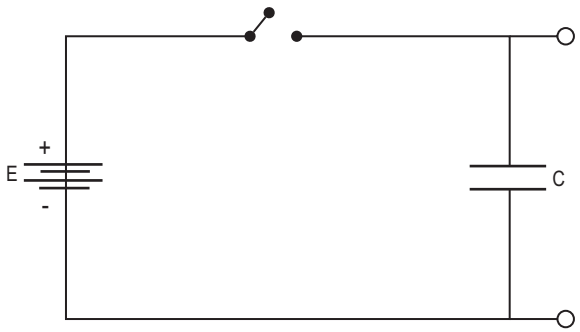
Capacitance

Capacitance, represented by the symbol C, is a property of a circuit that allows it to store an electrical charge. The *farad* is a measure of capacitance, designated by the letter *F*. A capacitor is an electronic component made from a pair of conductive plates separated by a thin layer of insulating material (the insulating material is known as a *dielectric*). When a voltage is applied across the plates of a capacitor, electrons are forced onto one plate and pulled away from the other. The plate with an excess of electrons is negatively charged, whereas the opposite plate with a deficiency of electrons is positively charged. The amount of charge stored in a capacitor is proportional to the voltage across it as described by:

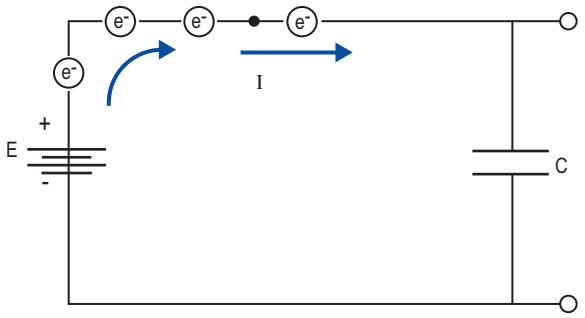
$$Q = C \times V$$

where Q is the charge in coulombs, C is capacitance in Farads, and *V* is voltage in volts.

Because of the dielectric material between the plates, no actual current (i.e., flow of electrons) moves across the plate; however, there is an "apparent flow," also known as a ***capacitive current***.

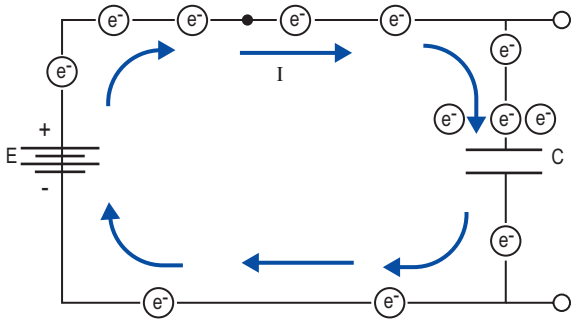


Take the above example of a battery connected to a single capacitor with a simple open and closed switch.

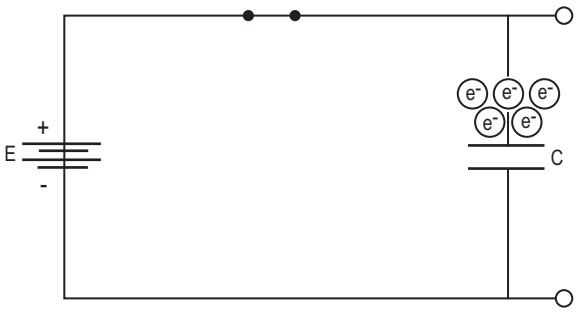


When the switch is moved to the closed position, electrons flow from the power source to the conductive plate

of the capacitor. This flow of electrons will create an actual current in the conductor. When the electrons arrive at the negative plate, they do not actually cross the plate.



However, the buildup of electrons at the negative plate results in the electrons at the opposite plate being repelled (in magnetism: opposites attract, but likes repel). Thus, there will be an "apparent current" across the capacitor. This will continue until the voltage across the capacitor equals the voltage from the power source.



At that time, no further apparent current will flow. The capacitor will be fully charged, and an electric field will exist between the two plates.

The rate of accumulation of charge (and the resulting voltage) at a capacitor occurs exponentially, based on the equation:

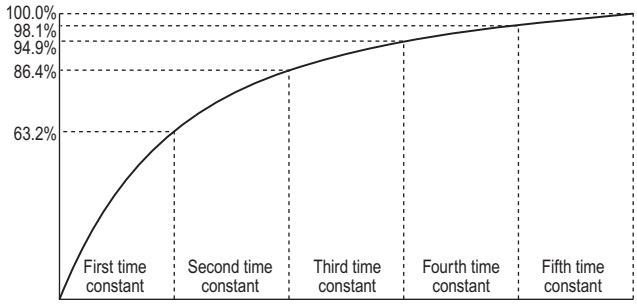
$$\text{Voltage} = 1 - e^{-t/RC}$$

where t is time
e (natural logarithm base) is 2.718281828459045235
R is resistance of the circuit in Ohms
C = capacitance in Farads

Note that, in the above equation, the time required for voltage to rise to its maximum value in a circuit is dependent on the product of resistance (R) multiplied by capacitance (C). This product (RC) is known as the ***time constant*** of a capacitive circuit.

When $t = RC$

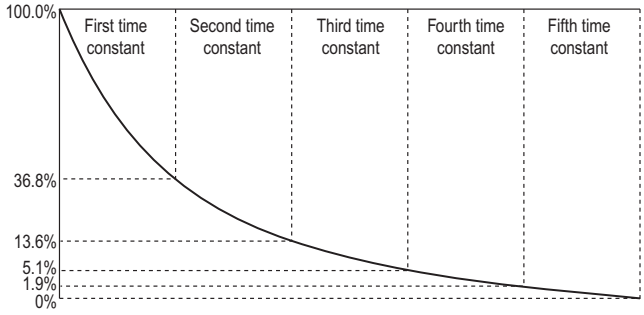
$$\text{Voltage (at the capacitor)} = 1 - e^{-1}$$
$$= 0.632 = 63.2\%$$



Thus, one time constant (RC) defines the time it takes for the voltage across a capacitor to reach 63.2% of its maximum value. During the second time constant, voltage will rise to 63.2% of the remaining 36.8%, or a total of 86.4%. It takes about five time constants for voltage across the capacitor to reach its maximum value.

Once fully charged, what happens if the power source is then turned off? The opposite occurs. The capacitor will discharge, with the excess electrons now flowing away (i.e., in the opposite direction than during charging) from the negative plate of the capacitor. Again, an apparent capacitive current will occur on the other side of the circuit and continues until the capacitor is fully discharged. The discharge of a capacitor follows a similar exponential fall, described by the equation:

$$\text{Voltage (at the capacitor)} = e^{-t/RC}$$



Thus, after one time constant, the voltage across the capacitor will have dropped to 36.8% of its original value. Again, it takes approximately five time constants for a capacitor to completely discharge.

In a DC circuit, when the circuit initially is turned on, current flows. However, after five time constants, the capacitor is fully charged and no further current occurs. At this point, the capacitor effectively acts as an open circuit. Understanding these properties of a capacitor in a simple DC circuit allows one to extrapolate to what occurs in an AC circuit.

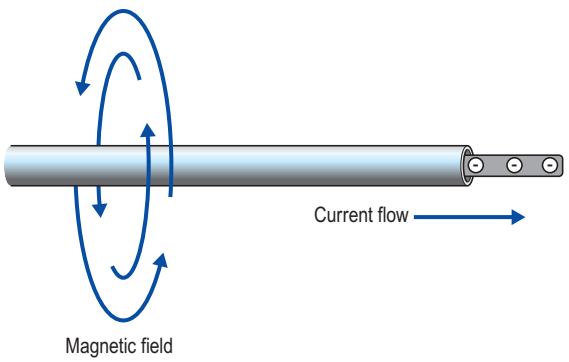
Take the example of an AC circuit where the frequency of the current is much faster than the frequency $1/RC$. When current is first applied to a capacitive circuit, it flows readily because of the apparent or capacitive current. If the AC then reverses before the capacitor is fully charged, a capacitive or apparent current will flow in the opposite direction. Thus, in essence, a capacitor is effectively a short

circuit for high frequencies. Conversely, if the frequency of the current is much slower than the frequency 1/*RC*, the capacitor can fully charge before the current reverses. Thus, a capacitor can act like an open circuit for low frequencies. These properties can be used to an advantage in designing low and high filters (see following sections).

In an AC circuit, also note that a capacitor constantly charges and discharges. When charge accumulates between the two plates of the capacitor, an electric field develops between the plates. Thus, in an AC circuit, there is a constantly expanding and collapsing electrical field around a capacitor. Other conductors near this changing electrical field may develop capacitive currents. This is of importance in understanding the concept of stray capacitance and the risks of leakage currents (see following sections).

Inductance

The property of an electrical circuit that causes it to oppose any ***change in current*** is known as ***inductance***. Inductance is designated by the symbol ***L*** and is measured in ***henries (H)***. Inductance is somewhat similar to mechanical inertia, which must be overcome to get a mechanical object moving or stopping. *Whereas resistance opposes all current flow, inductance only opposes a change in current*. If current increases, inductance tries to hold it down; conversely, if current decreases, inductance tries to hold it up.



Inductance occurs as a result of magnetic fields induced by a current. Whenever current flows, a magnetic field develops around the conductor, known as an *electromagnetic field*. Moving a conductor through a magnetic field will induce a voltage in a conductor. Likewise, having a stationary conductor in a magnetic field that is either expanding or collapsing will also induce a voltage in the conductor. Thus, when current first begins to flow in a conductor, an expanding magnetic field develops. This expanding (i.e., changing) magnetic field induces a voltage in the conductor that opposes the flow of current, known as a *counter electromotive force*. This counter electromotive force results in a time delay for current to reach a steady value. Once a steady value is reached, the magnetic field around a conductor is static, and no further opposing voltage develops.

Similar to the calculation for capacitance, the resulting current in a circuit with an inductor occurs exponentially and is described by the following equation:

$$\text{Current} = 1 - e^{-t/\frac{L}{R}}$$

where t is time
e (natural logarithm base) is 2.718281828459045235
L is inductance in Henries
R is resistance of the circuit in Ohms

Note that, in the above equation, the time required for current to rise to its maximum value in a circuit is dependent on the value of inductance divided by resistance. This value (L/R) is known as the ***time constant*** of an inductive circuit.

When $t = L/R$

$$\text{Current} = 1 - e^{-1}$$
$$= 0.632 = 63.2\%$$

Thus, one time constant (L/R) defines the time it takes for the current to reach 63.2% of its maximum value. During the second time constant, current will rise to 63.2% of the remaining 36.8%, or a total of 86.4%. It takes about five time constants for current to reach its maximum value.

At steady state, what happens if the power source is then turned off? The opposite occurs. The electromagnetic field collapses and induces a counter electromotive force in the conductor, opposing the flow of current. The current flow follows a similar exponential fall, described by the equation:

$$\text{Current} = e^{-t/\frac{L}{R}}$$

Thus, after one time constant, the current will have dropped to 36.8% of its original value. Again, it takes approximately five time constants for current to completely dissipate. Once the current has reached a steady state (in this case zero), there will be no changing magnetic field, and no further opposing voltage will be induced.

In a DC circuit, when the circuit is turned on, current flows but is initially impeded by inductance. However, after five time constants, the current reaches steady state and no further inductive voltage occurs. At this point, an inductor effectively acts as a short circuit. From understanding these properties of inductance in a simple DC circuit, one can extrapolate what happens in an AC circuit. Take an AC circuit where the frequency of the current is much slower than the frequency 1/(L/R). When current is first applied to the circuit, it is impeded due to inductance. However, after five time constants, the current has reached steady state and no further inductance occurs. Thus, for low frequencies, inductors allow current to flow and reach their maximum. However, in AC circuits with frequencies higher than 1/(L/R), the AC reverses before the current can reach its steady state. In this case, the

inductor effectively attenuates high-frequency currents from flowing.

Thus, as a capacitor stores energy as charge in an electrical field, an inductor stores energy in the form of a magnetic field. Just like capacitance, inductance is dependent on the frequency. If the frequency is low, the current has more time to reach its maximal value, before the polarity of the sine wave reverses. Conversely, if the frequency is very high, the current has less time to reach its maximal value. Thus, inductance attenuates high frequencies much more than low frequencies; this is exactly the opposite of capacitance. Taken to the limit, an inductor is essentially a short circuit at low frequencies and an open circuit at high frequencies.

In an AC circuit, current will be constantly flowing and then reversing, resulting in an expanding and collapsing magnetic field around any conductor. This can induce voltages in other conductors near this changing magnetic field, which is important to understanding the concept of stray inductance and the risks of leakage currents (see following sections).

Reactance and Impedance

In a purely resistive circuit, either DC or AC, opposition to current flow is termed *resistance*. However, in an AC circuit, current can also be opposed by inductance, capacitance, or both. Opposition to current flow from capacitance is the ***capacitive reactance***, termed ***XC***. The larger the capacitor, the smaller the capacitive reactance. Opposition to current flow from inductance is the ***inductive reactance***, termed ***XL***. The larger the inductor, the larger the inductive reactance. Similar to resistance, reactance is measured in Ohms (Ω). Thus, total reactance in an AC circuit depends on both inductive and capacitive reactances. Clearly, from the earlier discussion, inductive and capacitive reactances depend on frequency. In the case of inductance, reactance is much higher for high frequencies. Conversely, in the case of capacitance, reactance is much lower for high frequencies.

Capacitive and inductive reactance can be calculated by the following equations:

$$XC = \frac{1}{2\pi fC}$$

where f is frequency, and C is capacitance.

$$XL = 2\pi fL$$

where f is frequency, and L is inductance.

Lastly, ***impedance***, designated by the letter Z, is also measured in Ohms (Ω). *Impedance incorporates the total opposition to current flow in an AC circuit, including resistance, capacitive reactance, and inductive reactance.* Impedance is calculated using the following equation:

$$\text{Impedance}\,(Z) = \sqrt{R^2 + (XL - XC)^2}$$

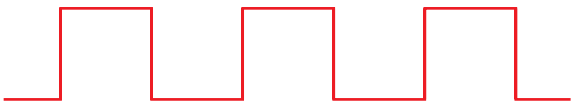
Thus, from the above equation, one can appreciate several facts about impedance:

- Impedance = Resistance, in circuits with no inductance or capacitance
- Impedance = Resistance, in circuits where inductive reactance equals capacitive reactance
- Inductive and capacitive reactances directly oppose each other.

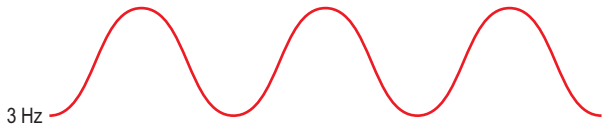
WAVEFORMS, FREQUENCY ANALYSIS, AND FILTERING

During nerve conduction studies and needle EMG, every displayed waveform represents a small bioelectrical potential (i.e., voltage) that is recorded, amplified, and then filtered. The last process, filtering, improves the quality of the recorded potential by preventing a wandering baseline and eliminating much unwanted electrical noise. To understand the process of filtering, one must first appreciate the frequency spectrum of any recorded waveform.

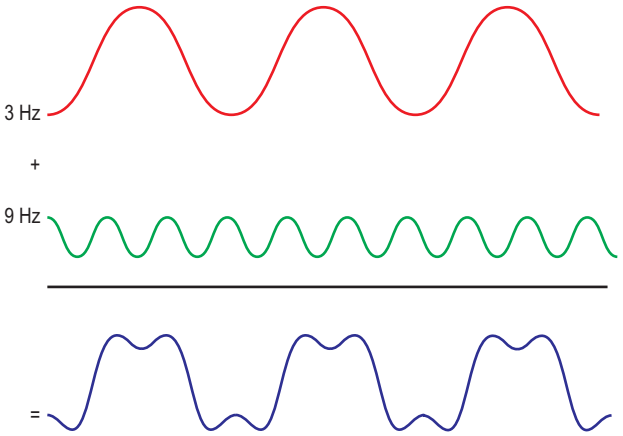
The Fourier analysis is a mathematical construct that states that any waveform can be derived by adding a series of sine waves. The sine waves may vary by amplitude, frequency, or phase. One of the most illustrative examples is that of a square wave, which also can be constructed by adding a series of sine waves.



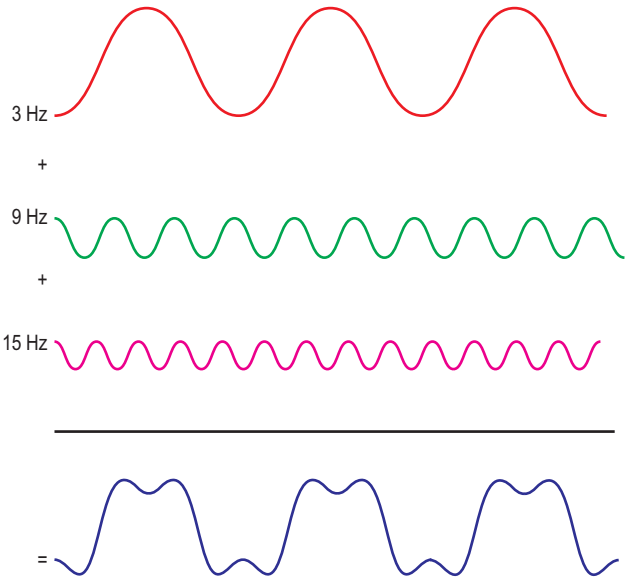
Take the above example of a square wave with a frequency of 3 Hz.



The square wave can first be approximated by a 3 Hz sine wave.



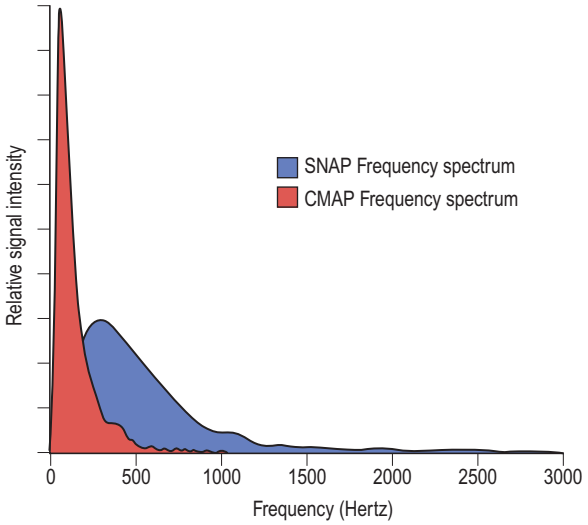
If a smaller-amplitude 9 Hz sine wave is added to the 3 Hz sine wave, the following waveform results. This is now starting to look somewhat like a square wave.



If now an even smaller-amplitude 15 Hz sine wave is added to the two earlier sine waves, the resultant waveform is generated. If one continues this analysis, the actual Fourier analysis for a square wave with a frequency (x) can be derived from the following equation:

$$= \sin(x) + 1/3\sin(3x) + 1/5\sin(5x) + 1/7\sin(7x) + 1/9\sin(9x) + 1/11\sin(11x) + \ldots$$

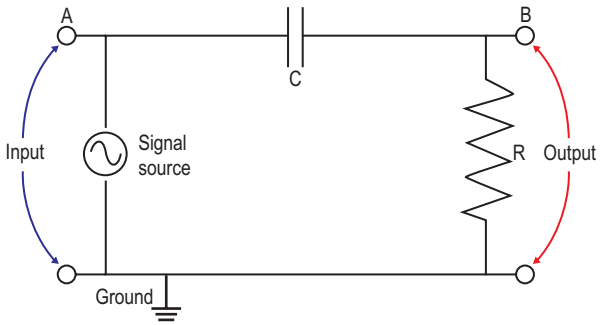
The above waveform represents the Fourier reconstruction of ten separate sine waves. Thus, as more waveforms with higher frequencies and smaller amplitudes are added, the reconstructed waveform continues to more closely approximate that of a true square wave. Thus, a 3 Hz square wave contains the following frequencies: 3, 9, 15, 21, and 27 Hz, in addition to other higher frequencies.



A similar analysis can be performed for all waveforms recorded during routine EDX studies. The figure above shows the relative frequency components of a compound muscle action potential (CMAP) compared to that of a sensory nerve action potential (SNAP) (from Gitter and Stolov, 1995). Note that the SNAP has higher-frequency components compared to the CMAP.

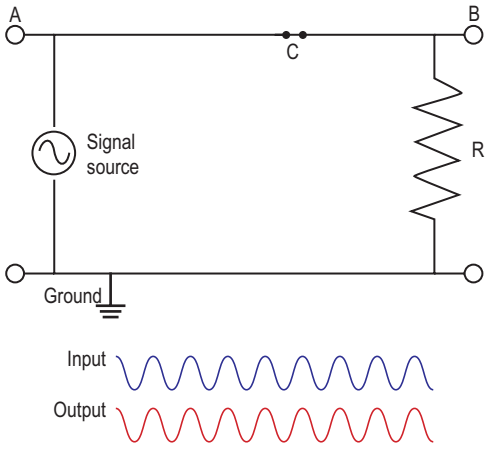
Ideally, one would like an EMG machine to display the amplified bioelectric signal of interest exactly. However, if a signal is contaminated with electrical noise, it can be difficult to properly record and interpret it. In general, very low frequencies will contaminate the signal of interest by causing the baseline to wander and very high frequencies can easily obscure many small waveforms (e.g., SNAPs, fibrillation potentials). Thus, it is desirable to filter out unwanted low and high frequencies while retaining the frequency spectrum of the actual waveform as much as possible.

Low-Frequency (High-Pass) Filters

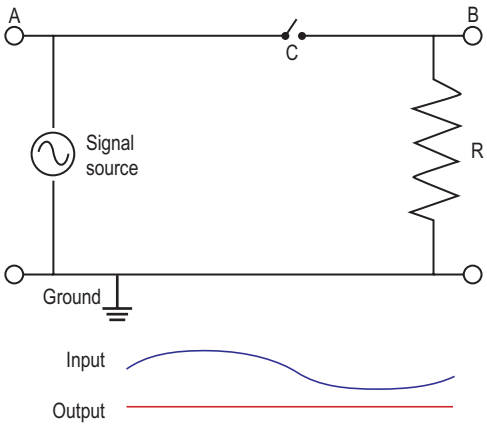


Low-frequency filters remove undesirable low frequencies while allowing high frequencies to pass. Analog low-frequency filters can be constructed with a capacitor followed by a resistor. In the illustration above and those that follow, the Signal Source will be modeled to generate either

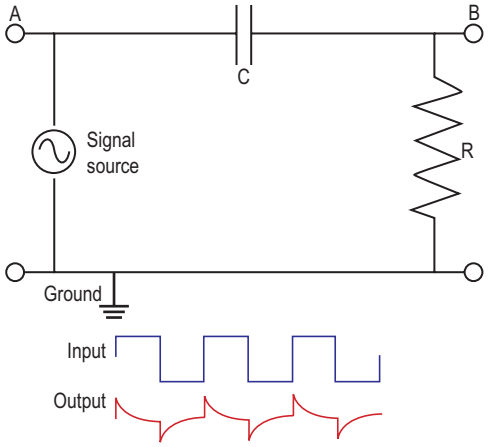
a low frequency, high frequency, or square wave input to the circuit. The input to the circuit is measured from point A (to a reference or ground), and the output of the circuit is measured from point B (to a reference or ground).



Recall from earlier discussions that for an AC with a high frequency, the capacitor effectively acts like a short circuit, allowing the current to pass. If the AC changes direction before the capacitor has charged, the apparent or capacitive current will continue unaltered.

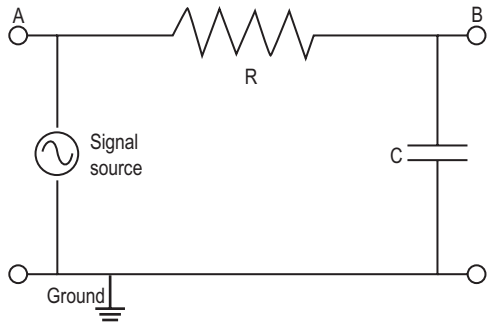


Conversely, for an AC with a very low frequency, the capacitor effectively acts like an open circuit. In this case, there will be ample time for the capacitor to fully charge before any change in current direction occurs. Once the capacitor is fully charged, no current, real or apparent, will flow. At this point, the capacitor will act as an effective open circuit, not allowing the waveform to pass from point A to the output at point B.

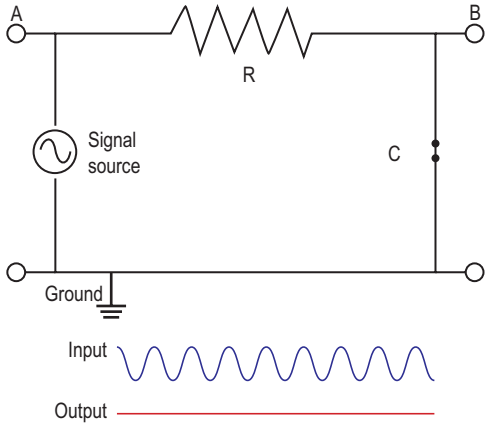


Of course, most waveforms have a combination of low and high frequencies. If a square wave is put through a low-frequency filter, the high frequencies will pass, but the lower frequencies will be filtered out.

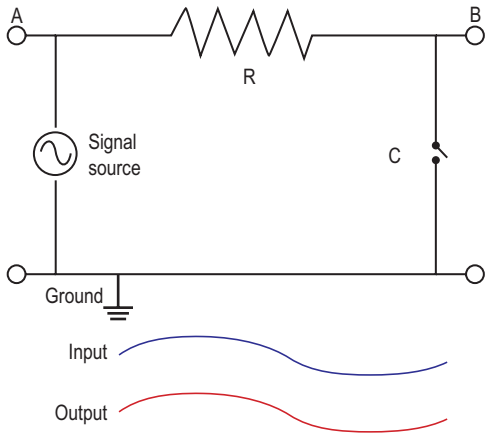
High-Frequency (Low-Pass) Filters



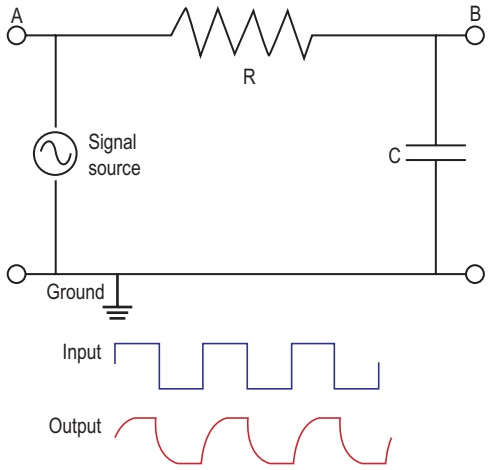
High-frequency filters remove undesirable high frequencies while allowing low frequencies to pass. Analog high-frequency filters can be constructed with a resistor followed by a capacitor.



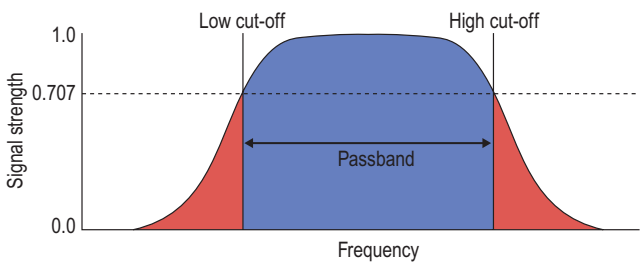
In the case of an AC with a high frequency, the capacitor effectively acts like a short circuit and shunts the signal to ground.



Conversely, for a very low-frequency AC, the capacitor effectively acts like an open circuit. In this case, there will be ample time for the capacitor to fully charge before any change in current direction occurs. Once the capacitor is fully charged, no current, real or apparent, will flow. At this point, the capacitor will act as an effective open circuit, allowing the waveform to be present at the output at point B.



Of course, most waveforms have a combination of low and high frequencies. If a square wave is put through a high-frequency filter, the low frequencies will pass, but the higher frequencies will be filtered out.



Putting low- and high-frequency filters in tandem allows for a ***passband***, whereby frequencies above and below the cutoff values are filtered out. However, no passband removes frequencies above or below a cutoff value with perfect precision. There is a normal roll-off of the frequencies that pass through. In general, cutoff frequency values for both high and low filters are defined as the point where the power of the signal is reduced by 50% [i.e., approximately 0.707 of its voltage. Remember that power is proportional to the square of the voltage and that $(0.707)^2 = 0.50$.]

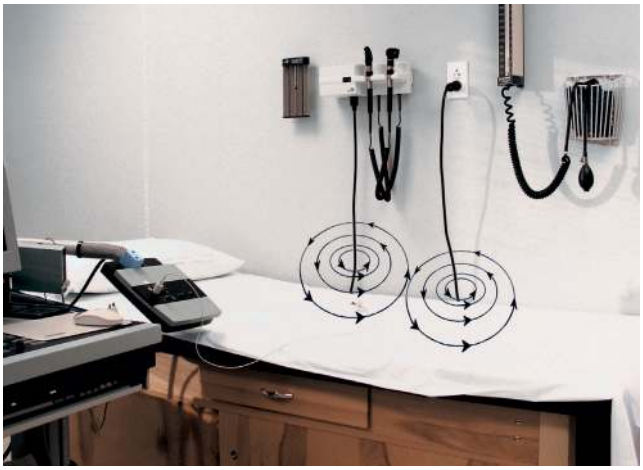
PRACTICAL IMPLICATIONS FOR ELECTRODIAGNOSTIC STUDIES

Congratulations. You have almost reached the end of this chapter, but you still may be asking whether basic knowledge of electricity and electronics really is needed to perform EDX studies. The answer clearly is yes, because there are many practical implications for performing EDX studies based on the principles learned in this chapter. Most important among them are the following:

- ***Filters.*** Understanding that all waveforms, including those recorded during EDX studies, have their own unique frequency spectrum allows for the use of electronic filters to remove unwanted low- and high-frequency noise while permitting the principal frequencies of the waveform to pass unaffected (i.e., passband). Although filters remove unwanted electrical noise, they also impact the waveform of interest and can alter certain characteristics of the waveform (especially amplitude for high-frequency filters and duration for low-frequency filters).
- ***Tissue acting as a filter: nerve conduction studies.*** Skin and subcutaneous tissue act as a high-frequency filter. Accordingly, if surface electrodes are not optimally placed directly over a nerve or muscle, much of the waveform's higher frequencies will be filtered out. Amplitude is predominantly a high-frequency response. SNAPs contain more high frequencies than CMAPs. Thus, if the surface electrodes are not optimally placed, amplitudes on nerve conduction studies will be reduced, more so for SNAPs than for CMAPs. If a patient has limb edema, then even if the surface electrodes are optimally placed, the increased tissue and edema between the nerve or muscle and the recording electrode will result in an artificially low amplitude.
- ***Tissue acting as a filter: needle EMG.*** During the needle EMG examination, tissue between the motor unit action potentials and the needle electrode also acts as a high-frequency filter. Again, as amplitude is predominantly a high-frequency response, MUAP amplitude can be markedly influenced by the distance between the needle and the motor unit. During needle EMG, the proper location to analyze an MUAP is reached when the major spike (i.e., the highest frequency component of the MUAP) is very

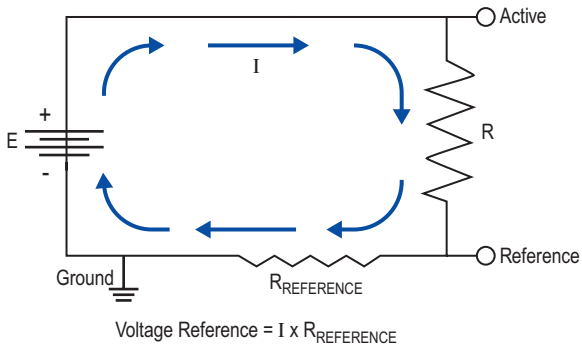
short, less than 500 μs. This ensures that the needle is very close to the motor unit. Likewise, this property of tissue acting as a filter also explains why duration is a much better determinate of motor unit size than is amplitude. Duration is predominantly a low-frequency function. Thus, tissue, which acts as a high-frequency (low-pass) filter, allows the low-frequency components from distant muscle fibers of the same motor unit to be recorded.

- ***Inductive electrical noise from the environment.*** How does a nearby radio or coffee maker result in electrical interference during EDX studies? Every power cord contains a 60 Hz AC signal. Around that power cord is a continuously expanding and collapsing magnetic field. If a conductor (e.g., a recording electrode) is near that magnetic field, an inductive voltage can be generated on that lead, which then can be amplified, often saturating the amplifier and obscuring the signal of interest.



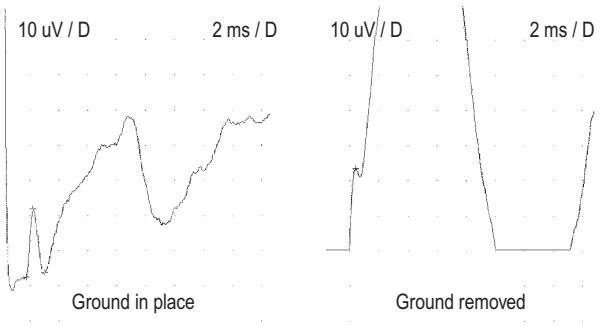
The photo above is a real example of this problem from one of our laboratories. Note the ophthalmoscope hanging on the wall adjacent to the EMG table and the power cord next to it. Even in the off position, AC is present in the power cord, resulting in an unseen expanding and collapsing magnetic field. When recording electrodes were placed near the magnetic field, an induced current was generated in the leads. Sensory responses could not be recorded without excessive electrical noise unless the power cord plug was physically pulled out of the socket.

- ***The stimulator cable and the recording electrodes should not cross or be near each other.*** When the stimulator is discharged, a brief current flows through the stimulator, creating an expanding and then collapsing magnetic field around the stimulator cable. If the recording electrodes or their leads are near that field (especially if the cables are crossed and touching), an inductive voltage can easily be generated in the recording leads, resulting in a large stimulus artifact.
- ***Importance of eliminating electrode impedance mismatch.*** Despite one's best efforts, there will always be some electrical noise in every EMG laboratory, usually 60 Hz AC from nearby electrical equipment. However, if the impedances (which include resistance, capacitive reactance, and inductive reactance) of the active and reference electrodes are identical, then any current resulting from electrical noise contaminating the recording electrodes will create the same extraneous voltage on each lead (from Ohm's law: Voltage=$\text{Current}_{\text{Noise}}\times$Impedance). Because all signals are amplified by way of a differential amplifier, the extraneous voltage will be canceled out. Several important techniques help ensure that the recording electrodes have the same impedance, among them, the use of a coaxial cable, good skin preparation, and an ample amount of conductive paste between each electrode and the skin.
- ***Importance of the ground electrode.*** One might assume at first glance that there is no difference between the reference and the ground lead, both being at electrical zero. However, all voltages are relative potentials, determined by the difference between two points in a circuit. Thus, one can measure a potential of 10 V between a point on a circuit that is 10 V higher than the ground (which is at electrical zero). However, 10 V also can be measured in a circuit between a point that is 20 V above ground and another point that is 10 V above ground. Thus, in most electronic applications, there is usually a potential difference (i.e., a voltage) between the neutral or reference electrode, and the ground electrode.



Whenever a waveform is recorded, current flows from the active to the reference lead. Even though the reference electrode is a conductor, there is a small amount of resistance in all materials, including conductors. Thus, a small voltage will be present on the reference lead, as determined by Ohm's law ($E=I\times R_{\text{Reference}}$). Accordingly, the ground potential is actually at a lower potential than the reference electrode. If a stray current develops on the patient, the ground allows a safe pathway to dissipate the current, thereby protecting the patient from possible electrical injury (see Chapter 40). In addition, because the ground is

at a lower potential than the reference electrode, any stray current will be preferentially shunted to the ground electrode rather than the reference electrode (electricity follows the path of least resistance). Thus, the electrical noise will not contaminate the reference electrode and obscure the potential of interest.



This is easily demonstrated in the EMG laboratory. In the example above, a routine radial sensory response is recorded from a normal individual, first with the ground electrode attached and then with the ground electrode disconnected. Note that with the ground electrode disconnected, there is a large superimposed 60 Hz electrical signal, making the sensory response barely visible.

- ***Leakage currents: stray capacitance and inductance.*** Although EMG machines are designed to minimize leakage currents, there will always be some leakage current on the machine chassis from stray capacitance and inductance. This is because any circuitry with ACs containing capacitors will have expanding and collapsing electrical fields. Likewise, any circuitry with ACs will have expanding and collapsing magnetic fields. If any part of the machine chassis is metal (i.e., a conductor) and near enough to electrical or magnetic fields from internal circuitry, stray capacitive or inductive currents potentially can be produced. These small leakage currents pose a potential electrical risk to certain vulnerable patient groups (see Chapter 40). With preventative maintenance of the machinery and by closely following specific protocols these possible hazards can be eliminated (see Chapter 40).

40 Electrical Safety and Iatrogenic Complications of Electrodiagnostic Studies

Electrodiagnostic (EDX) studies are generally well tolerated and rarely associated with any significant side effects. Most nerve conduction studies (NCSs) use surface stimulation and recording electrodes, which are not invasive. However, electrical current is applied to the patient when stimulating peripheral nerves. In patients with pacemakers, cardioverter-defibrillators, and other similar cardiac devices, this current may pose a risk under certain situations. In contrast, needle EMG is an invasive test and, rarely, may be associated with iatrogenic complications, most important of which are pneumothorax, bleeding, infection, and local injury. In addition, the patient is connected to the electromyography (EMG) machine via the recording electrodes during NCSs and the needle EMG study. Thus, during both portions of the examination, a patient is at risk from stray leakage currents. This risk is much higher in the so-called *electrically sensitive* patient, a situation often encountered in the intensive care unit (see later).

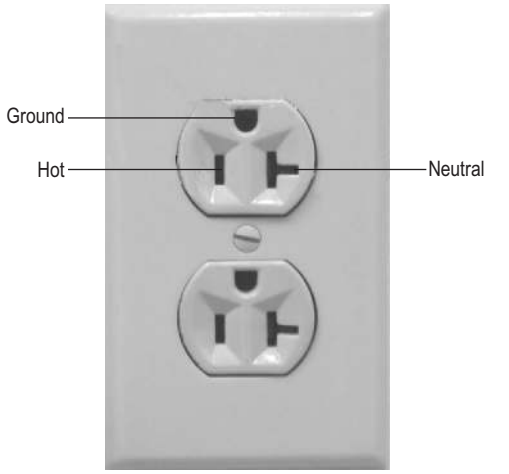


FIGURE 40–1 Standard electrical wall receptacle. A safe electrical receptacle must contain three inputs: a black "hot" lead that carries 120 V of 60 Hz alternating current, a white "neutral" lead near 0 V, and a green ground lead that is used to dissipate leakage currents. It is essential that all electromyography machines use a three-input receptacle, which includes a ground, for electrical safety.

ELECTRICAL ISSUES

All electrical devices, including EMG machines, require current to operate. Current is delivered from an electrical cord plugged into a wall receptacle (Figure 40–1). A typical electrical receptacle in the United States contains three inputs: a black "hot" lead that carries 120 volts (V) of 60 Hz alternating current, a white "neutral" lead near 0 V, and a green ground lead that is used to dissipate leakage currents. When a circuit is created, current flows from the hot lead to the EMG machine and then returns via the neutral lead, based on the amount of resistance between the two leads as determined by Ohm's law (see Chapter 39). Every wire, including power cords, has some small resistance; thus, a small voltage develops on the neutral lead, which equals the current flowing multiplied by the resistance in the power cord (Figure 40–2). The voltage increases with the length of the power cord and increases further if extension cords are added to the power cord. In addition, small voltage leaks often are present on the machine chassis, caused by stray capacitance and inductance from internal electronics (Figure 40–3). Thus, leakage currents may be transmitted onto the patient either from stray voltages on the machine chassis or on the neutral (reference) lead. As the ground electrode is close to true

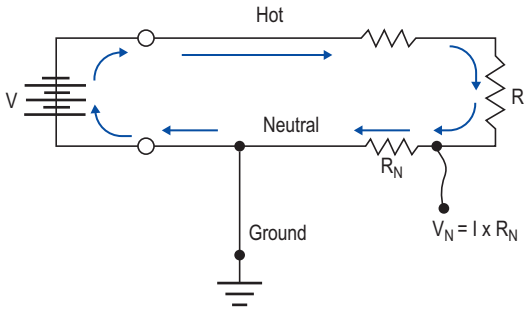


FIGURE 40–2 Stray leakage current: reference lead. Because every wire, including power cords, has some small resistance (R_N), a small voltage (V_N) develops on the neutral or reference lead as determined by Ohm's law ($V=I\times R$, where I is the current). The voltage increases with the length of the power cord and increases further if extension cords are added to the power cord. Thus, the voltage on the reference electrode is not zero and is a potential source for a leakage current transmitted to a patient.
(Adapted from Kimura, J., 1983. Electrodiagnosis in diseases of muscle and nerve. FA Davis, Philadelphia, pp. 615–619, with permission.)

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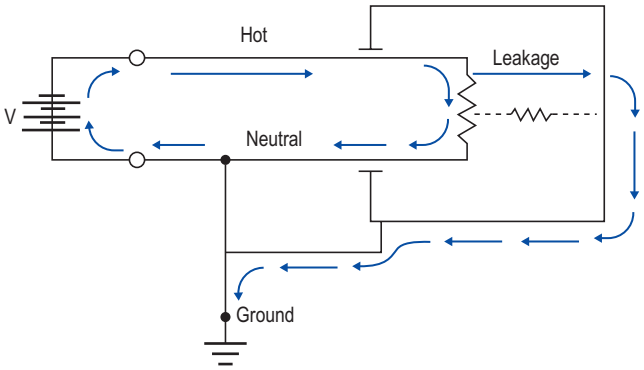


FIGURE 40–3 Stray leakage current: stray voltages from the electromyography machine. Small voltage leaks often are present on the machine chassis, caused by stray capacitance and inductance from internal electronics. These stray voltages are another potential source for leakage current that can be transmitted to a patient.

FIGURE 40–4 Wooden bed and electrodiagnostic studies. Wood does not conduct electricity; therefore, wooden examining tables are preferable to metal tables to ensure safety during electrodiagnostic studies.

electrical neutral, the ground lead allows a pathway for stray current leaks to harmlessly dissipate.

The risk of electrical injury depends on the amount of leakage current and whether the circuit passes through the heart. A very small current [e.g., 200 microamperes (μA)] applied directly to the heart can result in ventricular fibrillation and death. However, the normal, healthy individual typically is well protected by two important mechanisms. First, dry and intact skin provides a high resistance. Second, the large volume of soft tissue that surrounds the heart dilutes any current applied to the body (e.g., a current applied from arm to arm degrades to 1/1000 of the original signal when it reaches the heart, due to the dissipation from surrounding tissues).

The risk of electrical injury from leakage current increases in the following situations

- Malfunctioning of the electrical equipment
- Multiple electrical devices attached to the patient
- Loss of the body's normal protective mechanisms

The latter two (multiple electrical devices attached to the patient and loss of the body's normal protective mechanisms) result in the "electrically sensitive" patient, a common situation in the intensive care unit.

To prevent the possibility of an electrical injury during EDX studies, it is essential for equipment to be regularly maintained, to always use a ground electrode, and to follow simple guidelines when using electrical devices attached to the patient (Box 40–1). A wooden examining table is preferable to a metal table, as it does not conduct electricity. Machines should be turned on *before* attaching electrodes to the patient and turned off *after* disconnecting the patient, to minimize the risk of power surges. Equipment should be periodically inspected by a biomedical engineer to measure leakage current and verify proper grounding. In general, the maximum amount of acceptable leakage current is 100 μA or less, measured from chassis to ground, and 50 μA or less from any input lead to ground. Extension cords should be avoided to reduce the risk of voltages developing on the reference electrodes. Ground electrodes should always be used to avoid current flows from reaching the patient. The ground needs to be placed on the same limb as the active electrodes so that leakage currents cannot flow in a path through the heart (Figure 40–5A).

The issue of an intact ground electrode and proper ground placement is most important when a patient is connected to other electrical devices. If the ground from the EMG machine is not functioning (i.e., ground fault), stray current from the EMG machine could flow to a ground electrode from a different electrical device. If the pathway included the heart and the amount of current was large enough, a cardiac arrhythmia could theoretically occur (Figure 40–5B).

Box 40–1. Measures to Ensure Proper Grounding

- Always use a three-hole power receptacle with properly grounded outlet.
- Unnecessary electrical equipment should be kept outside the EMG examining room.
- Suspect improper grounding if
  - Equipment is wet or has been subjected to spillage of liquids
  - Equipment has been physically damaged or has loose parts
  - Equipment gives a tingling sensation when touched
  - Equipment becomes hot or gives off unusual odor or sound
  - There is damaged or cracked insulation in the power cable
- Use a wooden examining table if possible (metal conducts electricity) (Figure 40–4).
- Avoid patient contact with any metal objects or any part of the EMG machine.

EMG, electromyography.
From Al-Shekhlee, A., Shapiro, B.E., Preston, D.C., 2003. Iatrogenic complications and risks of nerve conduction studies and needle electromyography. Muscle Nerve 27, 517–526, with permission.

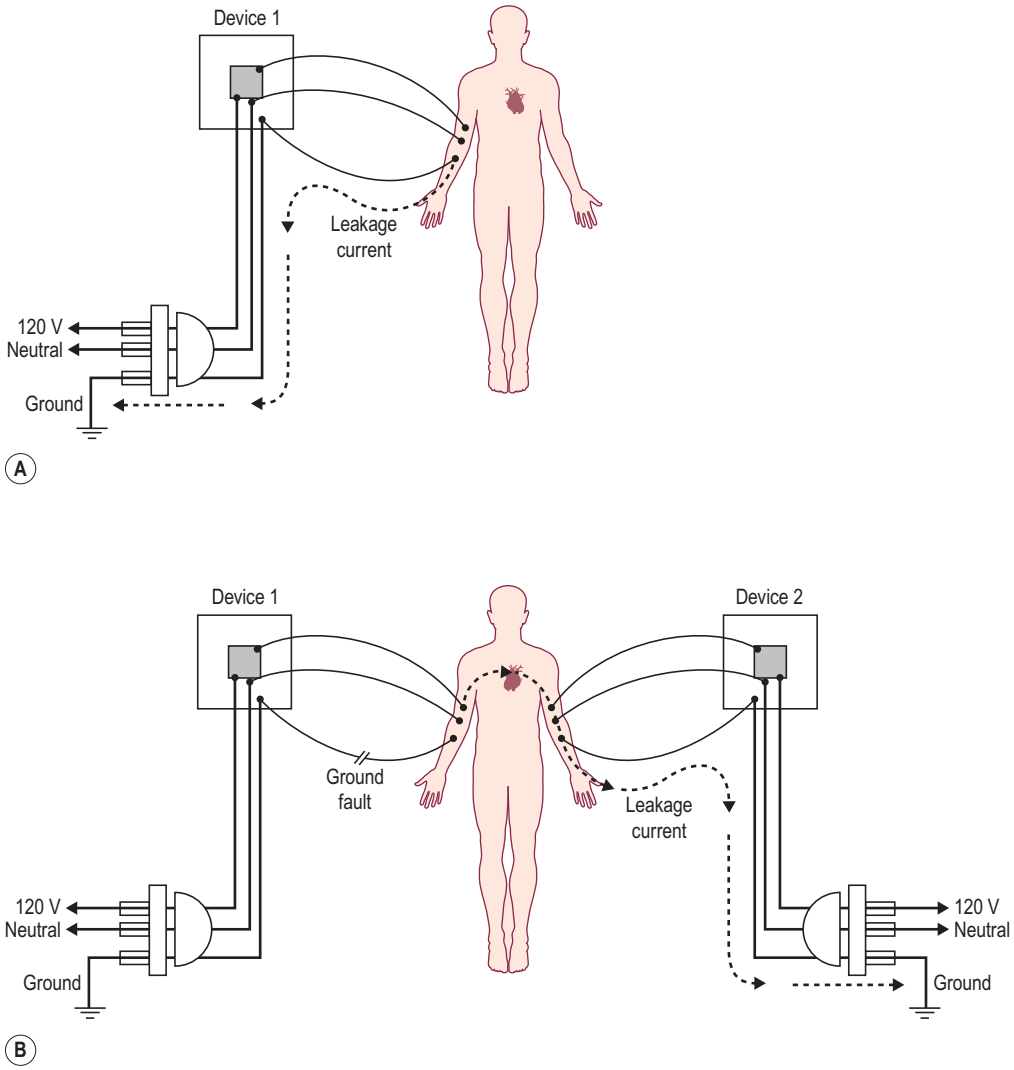


FIGURE 40–5 Leakage current and the risk of electrical injury. **A:** Correct placement of the ground electrode on the limb being studied. If a stray leakage current develops, the ground allows a pathway for the current to dissipate safely. **B:** When a patient is connected to two electrical devices, leakage current present on one device potentially can flow to another. In the example shown here, device 1 has a faulty ground electrode. A leakage current from that device creates a circuit by flowing to the ground electrode of the second device. If the pathway traverses the heart and the current is large enough, potentially dangerous arrhythmias may result.
(Adapted from Starmer, C.F., McIntosh, H.D., Whalen, R.E., 1971. Electrical hazards and cardiovascular function. N Engl J Med 284, 181–186, with permission.)

Risk of Electrical Injury

Central Lines and Electrical Wires

One of the more common ways a patient can become electrically sensitive is when the normal protective function of the skin is breached by intravenous lines and wires. This danger increases if the lines are actually in contact with or in close proximity to the heart, as occurs in central intravenous catheters (Figure 40–6). Most dangerous is the presence of an external wire near or in the heart, such as occurs with placement of a temporary external pacemaker and during the use of a guidewire while placing or changing a central line. Skin resistance typically is several million Ohms (MΩ). A central catheter traversing the skin reduces this resistance to 300,000 Ohms (kΩ). Any fluid spill where a catheter enters the body decreases the resistance even further. If a catheter has an internal guidewire, the resistance drops to 70 Ohms (Ω). An external pacemaker wire essentially has no resistance. In situations where the resistance is so low, small leakage voltages may result in small leakage currents, known as *microcurrents*. Whereas microcurrents are completely harmless in a patient with intact skin, they are potentially very dangerous in an electrically sensitive patient (i.e., a patient with a central line, external pacemaker wires, etc.).

Thus, EDX studies should never be performed on patients with external wires in place (i.e., external pacing wire, guidewires, etc.) because the conductive pathway to the heart is so vulnerable. However, studies can be performed on patients with central lines provided certain precautions are followed. Equipment must be maintained. Ground electrodes must always be used. If an upper extremity must

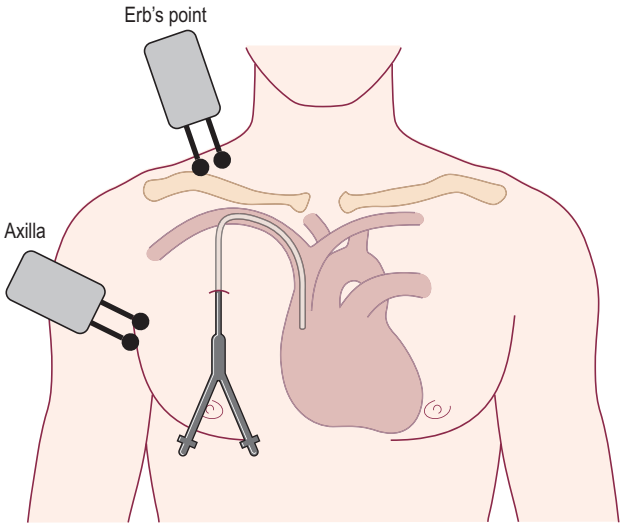


FIGURE 40–6 Risk of electrical injury from central lines: stimulation sites to avoid. One of the more common ways that a patient can become electrically sensitive is when the normal protective function of the skin is breached by intravenous lines and wires that are in contact with or in close proximity to the heart, as occurs in central intravenous catheters. Nerve conduction studies can be performed safely in these patients, provided certain precautions are taken. Proximal stimulation sites should be avoided, most importantly at the axilla and Erb's point.

be studied, in general it is preferable and safer to study the upper extremity contralateral to the one with the central line. If that is not possible, one should refrain from proximal stimulation sites (i.e., axilla, Erb's point, and root). Likewise, one should never proceed if there is a fluid spill where the central catheter enters the skin. It is important to note, however, that there is NO contraindication to performing routine nerve conduction studies on patients with peripheral IVs. Studies have been reported that specifically address this question and find that NCSs are completely safe in patients with peripheral IVs, regardless of whether they are infusing saline or any other solution.

Implanted Pacemakers and Cardioverter-Defibrillators

Patients with implantable cardiac pacemakers and cardioverter-defibrillators are at much lower risk from stray current leaks than patients with central lines or external wires in place, because these devices are implanted under the skin, which leaves the normal protective mechanism of the skin intact. Implantable pacemakers and cardioverter-defibrillators both have an electronic sensing as well as an electronic delivery function. Pacemakers are designed to treat bradycardia, as opposed to cardioverter-defibrillators which are primarily for tachyarrhythmias, especially ventricular fibrillation. In theory, stimulation delivered during NCSs might be mistaken as an abnormal cardiac rhythm. If the stimulator has a pulse duration greater than 0.5 ms and a stimulus rate greater than 1 Hz, a demand pacemaker might theoretically confuse such a stimulus with the ECG signal. There is only a single case report of an implantable pacemaker failure thought to be related to peripheral nerve stimulation. Other studies have shown no pacemaker inhibition or dysfunction with NCSs. Less is known about implantable automatic cardioverter-defibrillators (IACDs), which are now common. In theory, IACDs could be triggered by stimulation during NCSs, resulting in subsequent cardiac arrhythmias; however, there is no such reported case. One study directly addressed the safety of nerve conduction studies, including stimulating Erb's point, in patients with IACDs. Schoeck et al. studied ten patients with pacemakers and five with IACDs. No electrical impulse was detected by either the atrial or ventricular amplifiers of the pacemakers or of the IACDs during median and peroneal nerve conduction studies. These studies included Erb's point stimulation on the left. The authors emphasized that all modern pacemakers and IACDs use bipolar leads wherein both leads (active and reference for sensing, and cathode and anode for stimulating) are imbedded in the cardiac wall. This is in contradistinction to the pacemakers used 25 years ago wherein a single wire lead was placed in the heart, and the metal body of the pacemaker in the chest served as the reference. In modern pacemakers and IACDs, the bipolar leads are very close together in the heart, and very far away from the surface, making any electrical contamination from NCSs extremely unlikely. Although the number of patients in this study was small, the results are reassuring that NCSs can be safely performed in patients with pacemakers and IACDs.

If NCSs are performed in patients with implantable pacemakers or IACDs, several simple procedures are recommended to be followed in order to preserve safety (Box 40–2). Stimulation should not be performed near the actual implanted device. There should always be a minimum of 6 inches between the implanted device and the stimulator. Just as with NCSs performed in a patient with a central

Box 40–2. Guidelines for Pacemakers and Implantable Cardioverter-Defibrillators

- Do not perform studies on patients with external pacer wires.
- Ensure all ground electrodes are functional.
- Limit all electrodes, including the ground, to the extremity of interest, and keep all electrodes as far away from the heart as possible, without crossing cardiac devices or their wires.
- Do not stimulate near the device (allow a minimum of 6 inches) and avoid ipsilateral proximal stimulation sites (i.e., axilla, Erb's point, root stimulation).
- Use a stimulus duration of 0.2 ms or shorter and a stimulus rate of 1 Hz or slower. Thus, the typical repetitive stimulation done during neuromuscular junction testing is best avoided.
- Consult a cardiologist regarding performing studies in patients with an implantable automatic cardioverter-defibrillator.
- Laboratory emergency drugs should be available, including crash carts.

From Al-Shekhlee, A., Shapiro, B.E., Preston, D.C., 2003. Iatrogenic complications and risks of nerve conduction studies and needle electromyography. Muscle Nerve 27, 517–526, with permission.

line, it is preferable to use the contralateral arm if possible. High stimulus intensities should be avoided and stimulus pulse duration should be 0.2 ms or less so that the stimulation is not misinterpreted as a QRS complex. Stimulation rates should be no greater than 1 Hz so as to prevent the theoretical risk that the stimulation is misinterpreted as a cardiac rhythm. Thus, the typical repetitive stimulation done during neuromuscular junction testing is best avoided.

PNEUMOTHORAX

Pneumothorax is the most potentially serious iatrogenic complication of needle EMG. At any time during or just after the EMG examination, unexpected chest pain, shortness of breath, or cyanosis in a patient should alert the electromyographer to the possibility of a pneumothorax. If such symptoms develop, a prompt chest X-ray film is indicated to confirm the diagnosis, followed by urgent consultation with a thoracic surgeon as to whether a chest tube or observation is required. Although rare, this complication has been reported when sampling the following muscles (Figure 40–7):

- *Diaphragm*. Needle EMG of the diaphragm is sometimes used to help determine whether respiratory insufficiency has a neuromuscular basis. However, because the pleural fold is in close proximity to the diaphragm, a relatively small error in needle position may increase the risk of inadvertent pleural puncture and possible pneumothorax. The decision to sample the diaphragm must depend on the experience of the electromyographer and the potential benefit to the patient versus the risk of pneumothorax in that particular patient. Because patients for whom this study is ordered often have respiratory problems that prompt the study to be ordered, they may be the least able to handle an additional respiratory complication. In this text, we have purposely not included needle EMG of the diaphragm in Chapter 13. In our opinion, the risk-to-benefit ratio of sampling this muscle is too high to justify its use as a routine muscle to be sampled.
- *Serratus anterior*. The serratus anterior muscle lies between the scapula and the chest wall and inserts laterally on the ribs. An inadvertent puncture through the muscle between the ribs may allow the needle to enter the pleural space. To reduce the possibility of pneumothorax, the muscle can be sampled with the electromyographer's fingers placed in two adjacent inter-rib spaces while the needle is inserted into the muscle directly over the rib.
- *Supraspinatus*. The supraspinatus muscle lies within the supraspinous fossa of the scapula. The middle of the fossa may be very shallow in some individuals. Thus, if the muscle is sampled too deeply at this point, the needle may puncture the pleura (Figure 40–8). Complications can be prevented by either avoiding the muscle altogether or sampling it more

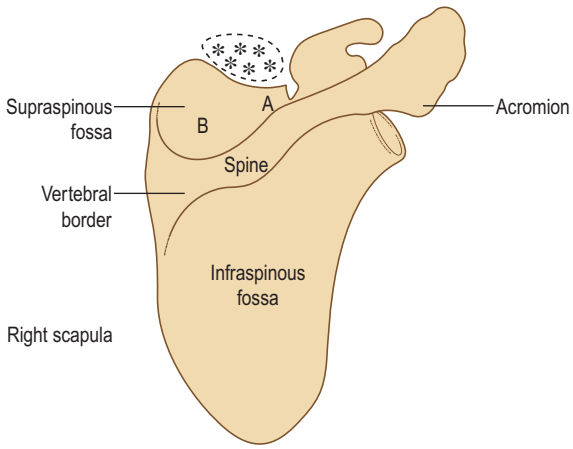
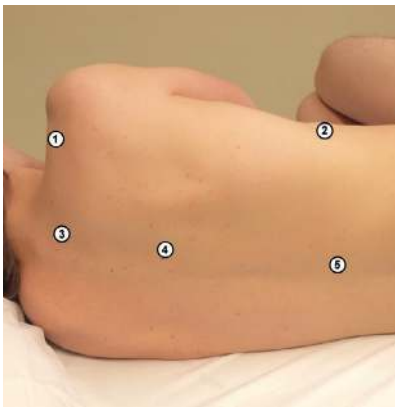


FIGURE 40–8 Supraspinatus muscle and risk of pneumothorax. The supraspinatus muscle lies in the supraspinous fossa. Needle electromyographic examination of this muscle may be complicated by pneumothorax if sampling is near the midpoint where the supraspinous fossa is narrowest (**A**). If the needle is placed deep above point A (area marked by *), there is a risk of pleural puncture. The muscle can be more safely sampled medially in the supraspinous fossa (**B**).
(Adapted from Reinstein, L., Twardzik, F.G., Mech, K.F. Jr., 1987. Pneumothorax: complication of needle electromyography of supraspinatus muscle. Arch Phys Med Rehabil 68, 561–562, with permission.)



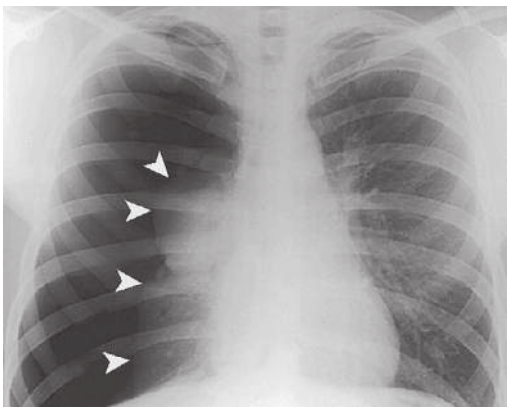


FIGURE 40–7 Needle electromyography (EMG) and the risk of pneumothorax. One of the most potentially serious complications of needle EMG is pneumothorax. **Right:** Note the absence of normal lung markings due to pneumothorax. Arrows point to the collapsed right lung. **Left:** Although rare, this complication has been reported when sampling the following common muscles: (1) supraspinatus, (2) serratus anterior, (3) lower cervical paraspinal muscles, (4) rhomboids, and (5) thoracic paraspinal muscles.

medially in the supraspinous fossa. This is performed by first palpating the acromion, the spine of the scapula, and the vertebral border of the scapula. The needle is then inserted just above the spine of the scapula at a point three quarters of the distance from the acromion to the vertebral border of the scapula. Often the supraspinatus can be avoided by sampling the infraspinatus instead. The infraspinatus muscle and infraspinous fossa are much larger than the supraspinatus and supraspinous fossa above. When screening for a suprascapular neuropathy, the infraspinatus muscle is the preferred muscle to study. Only if the infraspinatus muscle is abnormal is it then necessary to sample the supraspinatus to differentiate a lesion at the spinoglenoid notch from one at the suprascapular notch or above (see Chapter 31).

- *Rhomboids*. The rhomboids are infrequently sampled. However, they are useful to study in two situations: (1) to differentiate a C5 from a C6 radiculopathy (the rhomboids are derived from the C4–**C5** roots), and (2) to differentiate an upper trunk brachial plexopathy from a more proximal radiculopathy (the rhomboids are innervated by the dorsal scapular nerve, which arises directly off the nerve roots proximal to the brachial plexus). Because the rhomboids originate on the dorsal spine and insert onto the medial border of the scapula, a needle placed too deeply may pass through the rhomboids and thoracic paraspinal muscles resulting in a pleural puncture.
- *Cervical and thoracic paraspinal muscles*. The cervical paraspinal muscles are commonly sampled in the evaluation of cervical radiculopathy. Thoracic paraspinal muscles are one of the key sites to study in the evaluation of suspected motor neuron disease. These muscles can be safely studied, provided the needle placement is neither too lateral nor too deep. Considering the proximity of the thoracic paraspinal muscles to the lungs in the thorax, it is not unexpected that pneumothorax is a potential complication of thoracic paraspinal muscle sampling (Figure 40–9). However, pneumothorax can also occur during EMG examination of the lower cervical paraspinal muscles or when an EMG needle is used for cervical nerve root stimulation. Some patients, especially those who are thin with longer necks, may have lung tissue that reaches above the clavicle (Figure 40–10). In one study of 23 patients, 22% had lung tissue above the level of the clavicle. The average distance between skin and lung in these individuals was 3.3 cm, a distance clearly within the reach of a conventional 37 or 50 mm EMG needle. This complication is easily prevented by ensuring that the needle remains close to the midline, within the bulk of the paraspinal muscles.

BLEEDING

Needle EMG is generally well tolerated, with minimal or no bleeding. Some patients develop minor bruising that resolves within a few days. However, the possibility of bleeding and subsequent hematoma formation is a theoretic risk any time a needle punctures the skin, whether it occurs during phlebotomy, vaccination, aspiration, or needle EMG examination of a muscle. Clearly, the chance of bleeding increases if a patient has certain risk factors (discussed in the following section). However, bleeding can occur in the absence of any known risk factors or deviation from the usual performance of the examination.

In one report from Caress et al., a patient with a large asymptomatic paraspinal hematoma was discovered incidentally on magnetic resonance imaging (MRI) just after needle examination of the lumbar paraspinal muscles, which had been performed for evaluation of lumbar radiculopathy. By happenstance, the patient had an MRI of the lumbar spine scheduled immediately after the EMG. The patient was not anticoagulated and had no risk factors for increased bleeding. Following this case, a retrospective review of patients referred to the EMG laboratory followed by MRI the same day revealed four other patients with radiologically proven paraspinal muscle hematomas, presumably as a result of the needle EMG examination. All patients were asymptomatic and

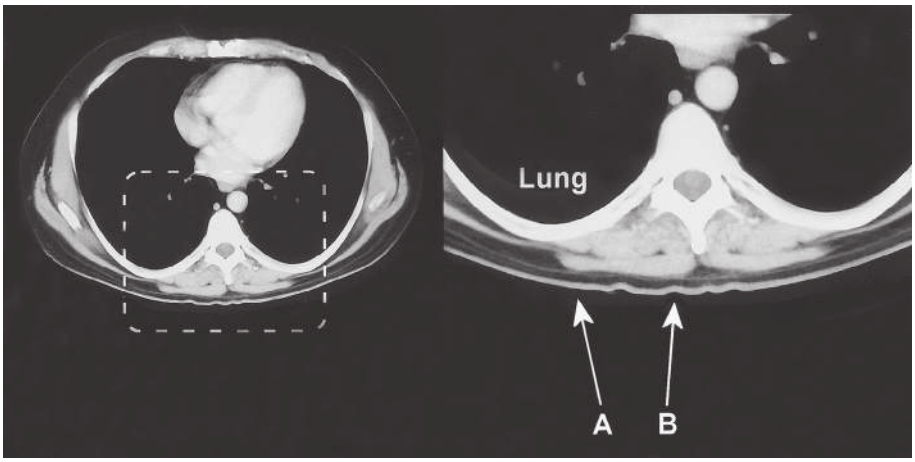


FIGURE 40–9 Thoracic paraspinal muscles and the risk of pneumothorax. Axial computed tomographic scan of a normal individual at the midthoracic level **(left)**, with magnified view of the thoracic paraspinal muscles **(right)**. Note the close proximity of the thoracic paraspinal muscles to the lungs. The correct location for sampling the paraspinal muscles is (B), just off the midline with the needle directed down and slightly medially. If the needle is placed too laterally (A) and directed deep and lateral, there is a risk of pneumothorax.

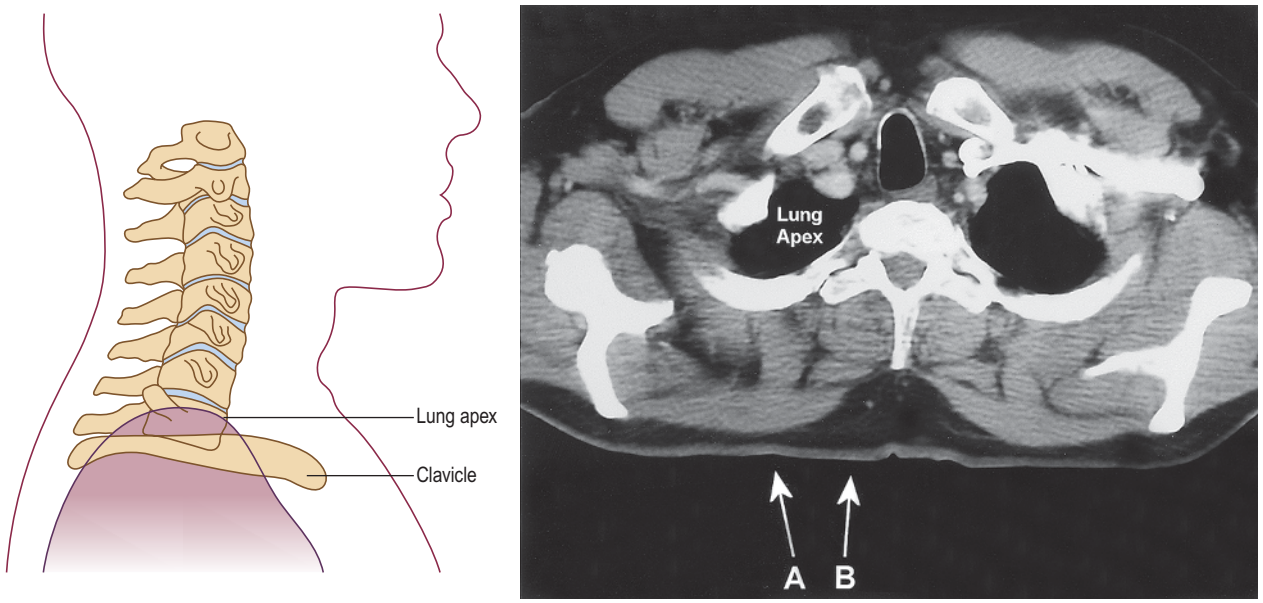


FIGURE 40–10 Lower cervical paraspinal muscles and the risk of pneumothorax. **Left:** In some individuals, the lung apex rises above the clavicle where it may be punctured from a laterally placed electromyographic needle. **Right:** Axial computed tomographic scan of a normal individual at the C7–T1 vertebral level. Note that the correct location for sampling the paraspinal muscles is (B), just off the midline with the needle directed down and slightly medially. If the needle is placed too laterally (A) and directed deep and lateral, there is a risk of pneumothorax at this level in some individuals.

had no history of anticoagulation or other known risk factors for bleeding.

However, in a recent large study from Gertken et al., 370 patients who underwent EMG studies that included the paraspinal muscles and who then had MRI scans at the concordant spinal level (168 MRIs were completed the same day as the EMG, and the remaining were completed within 7 days) were examined. A combined total of 431 spine segments were studied. No paraspinal hematoma was observed in any patient, including 139 patients taking aspirin, ten on warfarin (INRs between 1.2 and 2.9), eight on clopidogrel, and four patients who were on heparin, enoxaparin, or dalteparin.

In a prospective study by Lynch et al., EMG examination of the tibialis anterior muscle was followed by ultrasound to evaluate for the presence of a hematoma. Two of 101 patients on warfarin (INR values of 1.5 or above) had small, subclinical hematomas. Of 57 patients taking clopidogrel and/or aspirin, one patient was found to have a small, subclinical hematoma on ultrasound. None of the 51 control patients, who were not taking warfarin, aspirin, or clopidogrel, were found to have a hematoma by ultrasound. A recent prospective study by Boon et al. examined the incidence of hematoma, using ultrasound examination, after needle EMG of potentially "high risk" muscles (cervical, thoracic, and lumbar paraspinals; tibialis posterior; flexor digitorum longus; flexor pollicis longus; iliopsoas). A total of 205 patients were studied: 58 on warfarin, 78 on aspirin/clopidogrel; and 70 control patients taking none of these medications, with a minimum of 100 muscles per patient group. One patient in the aspririn/clopidogrel group had a subclinical hematoma in the tibialis posterior muscle, and one patient in the warfarin group had a subclinical hematoma in the flexor pollicis longus (INR 2.3). No patient in the control group had a hematoma.

In addition, there are two case reports of EMG needle-induced laceration or injury to nearby blood vessels that resulted in bleeding and a subsequent compartment syndrome requiring urgent fasciotomy and surgical evacuation of the hematoma. In one case, the compartment syndrome occurred in the superficial posterior compartment of the lower leg, presumably as a result of puncturing a small vessel. In the other case, needle EMG of the flexor carpi radialis inadvertently injured the ulnar artery, resulting in a compartment syndrome of the forearm. In neither of these cases was the patient anticoagulated or regularly taking any anti-platelet agents.

There are also some reports of bleeding following needle EMG in anticoagulated patients. In one anticoagulated patient (INR 2.5), a hematoma developed in the posterior calf along with a pseudoaneurysm of the posterior tibial artery. She improved with supportive care and holding the anticoagulation. In another case, a patient taking warfarin developed a large subcutaneous hemorrhage near an EMG needle insertion point.

Risk of Bleeding

Coexistent Medical Conditions

Several medical conditions are associated with an increased risk of bleeding and pose a potential risk during needle EMG. Thrombocytopenia with platelet counts below 50,000/mm^3 increases the chance of bleeding, and the risk increases markedly if the count drops below 20,000/mm^3.

Chronic renal failure is associated with dysfunctional platelets that increase the risk of bleeding. Patients with coagulopathies, either acquired (e.g., liver failure, disseminated intravascular coagulation) or inherited (e.g., hemophilia), are at a substantially higher risk of bleeding with invasive procedures.

Anticoagulation, Antiplatelet Agents, and Other Drugs

Similar to other invasive procedures, the risk of bleeding with needle EMG increases with the use of several prescription drugs as well as some over-the-counter (OTC) agents. Indeed, patients who are anticoagulated or taking an antiplatelet agent are often referred to the EMG laboratory. Anticoagulation with either intravenous heparin or oral warfarin carries the highest risk of bleeding. However, aspirin, nonsteroidal antiinflammatory drugs (NSAIDs), and other antiplatelet agents (e.g., clopidogrel) also increase the risk of bleeding. All of these agents are in common use for cardiovascular and stroke protection. Aspirin and NSAIDs are in widespread use for many painful conditions. In addition, some common OTC herbal remedies (e.g., Saw Palmetto, Ginkgo biloba, garlic, Ginseng, Hsien-Ho-T'sao) have a mild anticoagulant effect that now is appreciated to increase the risk of bleeding with invasive procedures and surgery.

Recommendations

Needle Electromyography and Patients at Risk of Bleeding

There is a paucity of evidence-based medicine to help guide the electromyographer in dealing with a patient referred for EDX studies who has an increased risk of bleeding. However, keep in mind that it is not common practice to report bleeding complications from invasive procedures in such patients, and the lack of reports by no means indicates that such complications cannot and do not occur. In patients with hemophilia, thrombocytopenia, and similar coagulopathies, use of replenishing clotting factors or platelets is indicated prior to the procedure. Regarding patients taking antiplatelet agents, it is the general consensus that needle EMG can be performed safely on these patients and that these agents do not need to be held before the procedure. However, in a survey of 47 academic EMG laboratories with an ACGME approved fellowship, 19% of laboratories reported curtailing some portion of the needle EMG examination in patients taking antiplatelet agents.

Due to the lack of guidelines and the theoretic risks of bleeding in anticoagulated patients, the patient who is anticoagulated with heparin or warfarin is the most problematic. In addition to the anecdotal case reports noted earlier, some information is available from anticoagulated patients who developed complications following other procedures that use needles. Compartment syndromes have been reported following venipuncture in the antecubital fossa. There is a single case report of a radial palsy following antecubital fossa venipuncture, presumably from a dissecting hematoma. However, in these cases, the risk of bleeding is expected to be higher than with needle EMG, where the goal is to avoid vascular structures rather than to enter them intentionally. In the lower extremity, gluteal compartment syndromes and compression of the sciatic nerve have been reported following intramuscular injections in anticoagulated patients. On the other hand, intramuscular vaccinations in the deltoid (e.g., flu vaccine) are commonly given in anticoagulated patients without complication.

Due to the theoretic risk of complications and concern about litigation if such a complication occurs, many electromyographers will not perform needle EMG on an anticoagulated patient. For many diagnoses, including carpal tunnel syndrome, ulnar neuropathy at the elbow, and peripheral neuropathy, useful information can be obtained from the NCSs alone. Nevertheless, without the needle EMG portion of the examination, some information will not be available to complete the picture (e.g., active vs. chronic denervation, the amount of denervation, etc.). On the other hand, some diagnoses rely principally on the findings obtained from the needle EMG examination, among them motor neuron disease, myopathy, and radiculopathy. If needle EMG is not performed on such patients, this may deny them the benefit of a procedure that might be the key to their diagnosis. It should be kept in mind that in the case of motor neuron disease and myopathy, needle EMG is a less invasive diagnostic procedure than muscle biopsy. In the survey of academic EMG laboratories mentioned above, only 21% reported a willingness to examine all muscles in anticoagulated patients. In others, some muscle groups were not examined in anticoagulated patients: 45% would not perform EMG on the cranial or facial muscles; 66% not on the paraspinal muscles; and 34% not in some limb muscles.

Some electromyographers choose to stop the anticoagulation prior to the procedure. Before dental work and minor invasive procedures (e.g., colonoscopy), it is common practice to advise patients to stop their anticoagulation several days before the procedure and restart it immediately afterward. In patients who are anticoagulated to prevent thromboembolism, especially stroke, the decision to stop anticoagulation is complex. Because it takes a few days for warfarin to have an effect, using this strategy will leave the patient unprotected for several days. For two of the more common conditions for which anticoagulation is prescribed, i.e., nonvalvular atrial fibrillation and a mechanical heart valve, the estimated stroke risk without anticoagulation is appropriately 3% per year. Thus, a patient who is not protected by anticoagulation for 5 to 10 days incurs a risk of stroke between one in 1000 and one in 2000. Although this risk is low, it is not one in a million, and the risk-to-benefit ratio of stopping anticoagulation, even for such a brief period of time, must be taken into account.

In general, if needle EMG is performed on an anticoagulated patient, the best strategy is to perform a limited needle EMG study using the following guidelines:

- Use the smallest gauge EMG needle available (e.g., 30 gauge).
- Limit the study to a few superficial muscles where prolonged compression over a puncture site can be performed if necessary.
- Avoid deep muscles that cannot be manually compressed and theoretically could result in a compartment syndrome if a hematoma developed. Most important among these are the antecubital fossa muscles (i.e., pronator teres and flexor carpi radialis), tibialis posterior, and flexor digitorum longus.
- Avoid muscles where hematomas theoretically could compress adjacent neurologic structures. Most important among these are the gluteal muscles near the sciatic nerve and the paraspinal muscles near the exiting spinal nerves.
- Avoid muscles with large arteries or veins located nearby so that inadvertent puncture of the vessel does not occur. Most important among these are the flexor pollicis longus near the radial artery, the iliacus near the femoral artery/vein, and the antecubital fossa muscles near the brachial artery.

This approach has been used successfully by us and several of our electromyography colleagues for many years without any complications. However, as in all invasive procedures, the potential benefits always need to be weighed against the potential risks in the individual patient before using any of these strategies in anticoagulated patients referred for an EDX procedure.

INFECTION

Electrodes and needles used for EDX studies carry the possible risk of transmitting infection between patients or between the electromyographer and the patient. Although this risk is higher during the needle EMG portion of the examination, skin preparation occasionally may abrade the skin, resulting in minor oozing or bleeding, potentially contaminating surface electrodes used for NCSs. *As learned from the human immune deficiency virus (HIV) epidemic, one should always assume that infection is possible and follow universal precautions*. Hand washing before and after a patient encounter is essential. Gloves should always be worn during potential exposure to blood, which occurs during every needle EMG examination. After every NCS, surface electrodes should be cleaned with a 1:10 dilution of bleach or 70% isopropyl alcohol. If reusable needle electrodes are used (i.e., single-fiber needle electrodes), they should be autoclaved after every use, similar to any other surgical instrument. Note that standard autoclaving does not neutralize Jacob–Creutzfeldt disease infection, and any reusable electrode used on such a suspected patient should be discarded.

Inadvertent needle sticks are a risk during needle EMG. Transmissible diseases include HIV as well as other infections, especially viral hepatitis, underscoring the importance of hepatitis B vaccinations for all electromyographers.

FIGURE 40–11 Reducing the risk of a needle stick. The risk of a needle stick can be markedly reduced if the needle is not recapped using two hands, and is placed safely out of the way when not in use. One successful approach is to use a foam rubber block attached to the preamp arm of the electromyographic machine. The needle cap can be placed in the block, so that the needle can be recapped safely with one hand.

Similar to precautions used with any needle, the EMG needle should not be recapped using the contralateral hand. The risk of a needle stick is markedly reduced if the needle is placed safely out of the way when it is not being used (e.g., in between sampling muscles or when explaining the next muscle movement to the patient). In our laboratory, we successfully use a foam rubber block attached to the preamp arm of the EMG machine (Figure 40–11). The block holds the needle cap so that the needle can be recapped safely with one hand.

Fortunately, there appears to be little risk of transmitting infection to the patient during NCSs and needle EMG. With the modern use of sterilized, single-use needle electrodes, this complication has not been reported. However, there are several conditions wherein the risk of infection with needle EMG is theoretically higher. An EMG needle should never be placed through an infected space (e.g., skin ulcer), to prevent the spread of infection into deeper tissues. Unresolved is whether needle EMG is contraindicated in the feet of patients with diabetic neuropathy or vascular insufficiency. Such patients are commonly advised by their physician to inspect their feet and to avoid minor infections that could potentially threaten the limb if the infection became severe. Although there are no such reported cases, it is reasonable to be very cautious when performing needle EMG on intrinsic foot muscles in patients with diabetes or significant peripheral vascular disease. Similarly, patients who have undergone axillary lymph node dissections (usually in the context of breast cancer surgery) are cautioned against blood drawing and similar procedures in the ipsilateral extremity because of the possibility that an infection could spread quickly in the setting of lymphedema and a reduced

number of lymph nodes proximally. Although there are no reported cases of infection in such patients following needle EMG, reasonable caution should be exercised in such patients.

Finally, the issue of using prophylactic antibiotics in patients at high risk for endocarditis should be addressed. Antibiotic prophylaxis is not recommended by the American Heart Association in patients undergoing needle EMG, where the risk is considered similar to phlebotomy.

LOCAL INJURY

Needle-induced local injury occurs rarely. Theoretically, an EMG needle could directly injure a nerve from direct intraneural puncture. To our knowledge, there is no reported case of such an injury. In near-nerve studies and during local anesthetic blocks, needle electrodes are intentionally placed very close to nerves, with intraneural placements not infrequently occurring without any sequelae. During routine needle EMG, there are several areas where nerves travel near or through the muscle of interest. Most important among these are the following:

- Sciatic nerve and the gluteus maximus
- Superficial radial nerve and the flexor pollicis longus
- Ulnar nerve and the flexor digitorum profundus
- Median nerve and the pronator teres

Needle-induced paresthesias of these nerves are encountered occasionally during routine needle EMG. When this occurs, the needle should immediately be withdrawn from the muscle, and one should wait for the paresthesias to resolve before continuing to sample an alternative muscle or the original muscle at a different site.

Although there are no reported cases of EMG needle-induced nerve trauma, there are reports of nerve trauma from other types of needles, most often occurring during venipuncture as well as other procedures. The median, lateral antebrachial, medial antebrachial, and superficial radial sensory nerves are the ones most often reported to be damaged during venipuncture.

SUMMARY

EDX studies as routinely performed often yield useful diagnostic information with minimal risks. However, it is essential that the electromyographer appreciate the known and theoretical complications discussed and follow the recommendations to minimize the chance of complications. Like all diagnostic tests, the electromyographer must always weigh the potential benefits of any EDX procedure versus the risks to the individual patient and use his or her best judgment.

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Appendix

NERVE CONDUCTION STUDIES: NORMAL ADULT VALUES

Upper Extremity Studies

Motor Studies

Nerve	Record	Amplitude (mV)	Conduction Velocity (m/s)	Distal Latency (ms)	Distal Distance (cm)
Median	Abductor pollicis brevis (APB)	≥4.0	≥49	≤4.4	7
Ulnar	Abductor digiti minimi (ADM)	≥6.0	≥49	≤3.3	7
Ulnar	First Dorsal Interosseous (FDI)	≥7.0	≥49	≤4.5	Variable (8–12*)
Radial	Extensor Indicis Proprius (EIP)	≥2.0	≥49	≤2.9	4–6

*Distance measured with calipers.

Antidromic Sensory

Nerve	Record	Amplitude (μV)	Conduction Velocity (m/s)	Distal Peak Latency (ms)	Distal Distance (cm)
Median	Digit 2	≥20	≥50	≤3.5	13
Ulnar	Digit 5	≥17*	≥50	≤3.1	11
Radial	Snuffbox	≥15	≥50	≤2.9	10
Dorsal ulnar cutaneous†	Dorsal D4–5 web space	≥8	≥50	≤2.5	8
Lateral antebrachial cutaneous†	Lateral forearm	≥10	≥55	≤3.0	12
Medial antebrachial cutaneous†	Medial forearm	≥5	≥50	≤3.2	12

*Many consider ulnar antidromic sensory amplitudes that are higher than 10 μV to be normal in adults older than 60.
†In these less commonly performed studies, side-to-side comparisons, especially of amplitude, often are more useful than normal value tables, when symptoms and signs are limited to one side.

Palmar Mixed Nerve Studies

Nerve	Amplitude (μV)	Conduction Velocity (m/s)	Peak Distal Latency (ms)	Distance (cm)
Median mixed	≥50	≥50	≤2.2	8
Ulnar mixed	≥12	≥50	≤2.2	8

*F Responses**

Nerve	Minimal F Latency (ms)
Median	≤31
Ulnar	≤32

*For tall or short patients, F responses must be normalized for height (see Chapter 4).

Median–Ulnar Internal Comparison Studies

Study*	Significant Latency	Difference (ms)†
Median mixed Ulnar mixed	Palm-to-wrist Palm-to-wrist	≥0.4
Median motor Ulnar motor	Wrist to second lumbrical Wrist to interossei	≥0.5
Median sensory Ulnar sensory	Wrist to digit 4 Wrist to digit 4	≥0.5
Median sensory Radial sensory	Wrist to digit 1 Wrist to digit 1	≥0.5

*For each paired study, identical distances are used for both the median and the ulnar study.

†Values that exceed these cutoffs imply focal slowing and are useful in the electrodiagnosis of both median neuropathy across the carpal tunnel and ulnar neuropathy across Guyon's canal.

Median Palmar Stimulation Studies

Study	Significant Palm-to-wrist Amplitude Ratio*
Median motor: Wrist to abductor pollicis brevis Median motor: Palm to abductor pollicis brevis	>1.2
Median sensory: Wrist to digit 2 Median sensory: Palm to digit 2	>1.6

*Values that exceed these cutoffs imply some element of conduction block of the median nerve across the carpal tunnel.

Major Upper Extremity Motor Latencies from Erb's Point Stimulation

Nerve	Muscle	Latency (ms)	Distances (cm)†
Axillary*	Deltoid	≤4.9	15–21
Musculocutaneous*	Biceps	≤5.7	23–29
Suprascapular	Supraspinatus	≤3.7	7–12
Suprascapular	Infraspinatus	≤4.3	10–15

*The axillary and musculocutaneous nerves also can be stimulated in the axilla, with typical distal motor latencies of up to 3.3 ms. Both axillary and Erb's point stimulations often are technically difficult. In patients with symptoms limited to one side, comparing both latencies and amplitudes side to side always is preferable to using normal value tables.

†Distance measured with calipers.

Source: Data from Kraft, G.H., 1972. Axillary, musculocutaneous, and suprascapular nerve latency studies. Arch Phys Med Rehab 53, 382; and Currier, D.P., 1971. Motor conduction velocity of axillary nerve. Phys Ther 51, 503.

*Phrenic Motor Study**

Nerve	Record	Amplitude (μV)	Distal Latency (ms)
Phrenic	Diaphragm	597 ± 139 μV >320 μV	6.3 ± 0.8 <8.0

*From Markand, O.N., Kincaid, J.C., Pourmand, R.A., et al., 1984. Electrophysiologic evaluation of diaphragm by transcutaneous phrenic nerve stimulation. Neurology 34, 606–614.

*Phrenic Motor Study: Detailed Normal Studies**

		Absolute Values			Interside Differences		
Parameter	**Phase**	**Mean ± SD**	**L/U Limits**	**5th/95th**	**Mean ± SD**	**Mean + 2SD**	**95th**
Onset latency (ms)	Inspiration	6.55 ± 0.69	5.18/7.92	5.53/7.72	0.23 ± 0.19	0.61	0.53
	Expiration	6.59 ± 0.67	5.25/7.92	5.58/7.72	0.40 ± 0.36	1.9	1.11
Amplitude (mV)	Inspiration	1.00 ± 0.27	0.46/1.54	0.66/1.46	0.25 ± 0.18	0.61	0.6
	Expiration	0.71 ± 0.19	0.33/1.10	0.50/1.06	0.14 ± 0.10	0.35	0.33
Duration (ms)	Inspiration	14.99 ± 3.14	8.70/21.28	11.18/20.25	2.14 ± 1.72	5.57	4.71
	Expiration	20.98 ± 3.30	16.13/28.32	11.18/20.25	2.44 ± 1.65	5.74	5.54

L/U, lower/upper limits; 5th/95th, 5th/95th percentile limits.

*From Resman-Gaspersc, A., Podnar, S., 2008. Phrenic nerve conduction studies: technical aspects and normative data. Muscle Nerve 37, 36–41.

Craniobulbar Studies

Motor Studies

Nerve	Record	Amplitude (mV)	Distal Latency (ms)
Facial	Nasalis	≥1.0	≤4.2
Facial	Orbicularis oculi	≥1.0	≤3.1

Blink Reflex

Side-to-Side Latency Response	Latency (ms)	Difference (ms)
R1 (ipsilateral)	≤13	≤1.2
R2 (ipsilateral)	≤41	≤5
R2 (contralateral)	≤44	≤7

Lower Extremity Studies

Motor Studies

Nerve	Record	Amplitude (mV)	Conduction Velocity (m/s)	Distal Latency (ms)	Distal Distance (cm)
Peroneal	Extensor digitorum brevis (EDB)	≥2.0	≥44	≤6.5	9
Peroneal†	Tibialis anterior (TA)	≥3.0	≥44	≤6.7	5–10
Tibial	Abductor hallucis brevis (AHB)	≥4.0	≥41	≤5.8	9
Tibial†	Abductor digiti quinti pedis (ADQP)	≥3.0	≥41	≤6.3	Variable*

*Difficult to measure unless calipers are used.

†In cases where one side is symptomatic and the other is not, it is often helpful to compare the amplitudes side to side, rather than use normal value tables.

Antidromic Sensory

Nerve	Record	Amplitude (μV)	Conduction Velocity (m/s)	Peak Latency (ms)	Distal Distance (cm)
Sural	Posterior ankle	≥6	≥40	≤4.4	14†
Superficial peroneal	Lateral ankle	≥6	≥40	≤4.4	14†
Saphenous*	Medial/anterior ankle	≥4	≥40	≤4.4	14†
Medial plantar*	Medial ankle	≥2	≥35	–	Variable
Lateral plantar*	Medial ankle	≥1	≥35	–	Variable
Lateral femoral cutaneous‡	Anterior thigh	≥4		≤2.6	12

*In some normal individuals without symptoms, especially those older than age 40, these responses may be very small, requiring electronic averaging, or may be absent. Thus, a low-amplitude or absent potential should not necessarily be interpreted as abnormal. Side-to-side comparisons often are very useful in this regard if one side is symptomatic and the other is not.

†Although the normal values for peak latency are based on the standard distance of 14 cm, in many individuals, it is much easier to stimulate at a shorter distance (typically 10–12 cm). Supramaximal stimulation usually can be achieved with low stimulation intensities (e.g., 5–25 mA). Thus, if the response is not present stimulating at 14 cm or if high currents are needed, try a shorter distance of 10–12 cm. If a good response is obtained, do not use the peak latency to determine if the response is normal, but rather the calculated conduction velocity based on the onset latency and the distance used.

‡Although the normal value for peak latency is based on the standard distance of 12 cm, in some individuals, the nerve may be easier to stimulate at a shorter distance (typically 10 cm). Difficult study to perform in obese individuals. Thus, a low-amplitude or absent potential should not necessarily be interpreted as abnormal unless side-to-side comparisons are done in patients with symptoms limited to one side. Source: from Shin, Y.B., Park, J.H., Kwon, D.R., et al., 2006. Variability in conduction of the lateral femoral cutaneous nerve. Muscle Nerve 33 (5), 645–649. Values based on reported mean minus 2 SD for amplitude, and mean plus 2 SD for peak latency.

Plantar Mixed Nerve Studies

Nerve	Amplitude (μV)	Conduction Velocity (m/s)	Distal Peak Latency (ms)	Distance (cm)
Medial plantar*	≥3	≥45	≤3.7	14
Lateral plantar*	≥3	≥45	≤3.7	14

*In some normal individuals without symptoms, especially those older than age 40, these responses may be very small, requiring electronic averaging, or may be absent. Thus, a low-amplitude or absent potential should not necessarily be interpreted as abnormal. Side-to-side comparisons often are very useful in this regard.

*Late Responses**

Nerve	Minimal F latency (ms)	Minimal H latency (ms)
Peroneal	≤56	N/A
Tibial	≤56	≤34†

*For tall or short patients, F responses and H reflexes must be normalized for height (see Chapter 4).

†Compare side to side. Any difference in latency between sides >1.5 ms is considered abnormal.

Notes:

1. All normal value tables assume controlled temperature and standard distances.
2. All motor and sensory amplitudes are measured from baseline to negative peak.
3. All sensory and mixed nerve distal latencies are peak latencies; however, all sensory and mixed nerve conduction velocities are calculated based on the onset latency.
4. Some values may have to be adjusted for extremes of height or age (see Chapter 8).
5. Comparison between the affected and unaffected limb often is very useful and may be more useful than normal value tables.
6. This is one set of normal values; others exist. Ideally, each laboratory should develop its own set of normal values.

NERVE CONDUCTION STUDIES: NORMAL PEDIATRIC VALUES

Motor Studies

	Median Nerve				Peroneal Nerve			
Age	DML (ms)	CV (m/s)	F (ms)	AMP (mV)	DML (ms)	CV (m/s)	F (ms)	AMP (mV)
7 days–1 month	2.23 (0.29)*	25.43 (3.84)	16.12 (1.5)	3.00 (0.31)	2.43 (0.48)	22.43 (1.22)	22.07 (1.46)	3.06 (1.26)
1–6 months	2.21 (0.34)	34.35 (6.61)	16.89 (1.65)	7.37 (3.24)	2.25 (0.48)	35.18 (3.96)	23.11 (1.89)	5.23 (2.37)
6–12 months	2.13 (0.19)	43.57 (4.78)	17.31 (1.77)	7.67 (4.45)	2.31 (0.62)	43.55 (3.77)	25.86 (1.35)	5.41 (2.01)
1–2 years	2.04 (0.18)	48.23 (4.58)	17.44 (1.29)	8.90 (3.61)	2.29 (0.43)	51.42 (3.02)	25.98 (1.95)	5.80 (2.48)
2–4 years	2.18 (0.43)	53.59 (5.29)	17.91 (1.11)	9.55 (4.34)	2.62 (0.75)	55.73 (4.45)	29.52 (2.15)	6.10 (2.99)
4–6 years	2.27 (0.45)	56.26 (4.61)	19.44 (1.51)	10.37 (3.66)	3.01 (0.43)	56.14 (4.96)	29.98 (2.68)	7.10 (4.76)
6–14 years	2.73 (0.44)	57.32 (3.35)	23.23 (2.57)	12.37 (4.79)	3.25 (0.51)	57.05 (4.54)	34.27 (4.29)	8.15 (4.19)

*Mean (SD). DML = distal motor latency; CV = conduction velocity; F = F latency; AMP = amplitude.

From Parano, E., Uncini, A., DeVivo, D.C., et al., 1993. Electrophysiologic correlates of peripheral nervous system maturation in infancy and childhood. J Child Neurol 8, 336–338.

Antidromic Sensory Studies

	Median Nerve		Sural Nerve	
Age	CV (m/s)	AMP (μV)	CV (m/s)	AMP (μV)
7 days–1 month	22.31 (2.16)*	6.22 (1.30)	20.26 (1.55)	9.12 (3.02)
1–6 month	35.52 (6.59)	15.86 (5.18)	34.63 (5.43)	11.66 (3.57)
6–12 month	40.31 (5.23)	16.00 (5.18)	38.18 (5.00)	15.10 (8.22)
1–2 years	46.93 (5.03)	24.00 (7.36)	49.73 (5.53)	15.41 (9.98)
2–4 years	49.51 (3.34)	24.28 (5.49)	52.63 (2.96)	23.27 (6.84)
4–6 years	51.71 (5.16)	25.12 (5.22)	53.83 (4.34)	22.66 (5.42)
6–14 years	53.84 (3.26)	26.72 (9.43)	53.85 (4.19)	26.75 (6.59)

*Mean (SD); CV = conduction velocity; AMP = amplitude.

From Parano, E., Uncini, A., DeVivo, D.C., et al., 1993. Electrophysiologic correlates of peripheral nervous system maturation in infancy and childhood. J Child Neurol 8, 336–338.

NORMAL MOTOR UNIT ACTION POTENTIAL DURATION

Mean Motor Unit Action Potential Duration Based on Age and Muscle Group

Age of Subjects (yrs)	Arm Muscles (ms)					Leg Muscles (ms)					
	Deltoid	Biceps	Triceps	Thenar	ADM	Quad, BF	Gastroc	Tib Ant	Per Long	EDB	Facial
0–4	7.9–10.1	6.4–8.2	7.2–9.3	7.1–9.1	8.3–10.6	7.2–9.2	6.4–8.2	8.0–10.2	6.8–7.4	6.3–8.1	3.7–4.7
5–9	8.0–10.8	6.5–8.8	7.3–9.9	7.2–9.8	8.4–11.4	7.3–9.9	6.5–8.8	8.1–11.0	5.9–7.9	6.4–8.7	3.8–5.1
10–14	8.1–11.2	6.6–9.1	7.5–10.3	7.3–10.1	8.5–11.7	7.4–10.2	6.6–9.1	8.2–11.3	5.9–8.2	6.5–9.0	3.9–5.3
15–19	8.6–12.2	7.0–9.9	7.9–11.2	7.8–11.0	9.0–12.8	7.8–11.1	7.0–9.9	8.7–12.3	6.3–8.9	6.9–9.8	4.1–5.7
20–29	9.5–13.2	7.7–10.7	8.7–12.1	8.5–11.9	9.9–13.8	8.6–12.0	7.7–10.7	9.6–13.3	6.9–9.6	7.6–10.6	4.4–6.2
30–39	11.1–14.9	9.0–12.1	10.2–13.7	10.0–13.4	11.6–15.6	10.1–13.5	9.0–12.1	11.2–15.1	8.1–10.9	8.9–12.0	5.2–7.1
40–49	11.8–15.7	9.6–12.8	10.9–14.5	10.7–14.2	12.4–16.5	10.7–14.3	9.6–12.8	11.9–15.9	8.6–11.5	9.5–12.7	5.6–7.4
50–59	12.8–16.7	10.4–13.6	11.8–15.4	11.5–15.1	13.4–17.5	11.6–15.2	10.4–13.6	12.9–16.9	9.4–12.2	10.3–13.5	6.0–7.9
60–69	13.3–17.3	10.8–14.1	12.2–15.9	12.0–15.7	13.9–18.2	12.1–15.8	10.8–14.1	13.4–17.5	9.7–12.7	10.7–14.0	6.3–8.2
70–79	13.7–17.7	11.1–14.4	12.5–16.3	12.3–16.0	14.3–18.6	12.4–16.1	11.1–14.4	13.8–17.9	10.0–13.0	11.0–14.3	6.5–8.3

ADM, abductor digiti minimi; BF, biceps femoris; EDB, extensor digitorum brevis; Gastroc, gastrocnemius; Per long, peroneus longus; Quad, quadriceps; Tib ant, tibialis anterior.

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