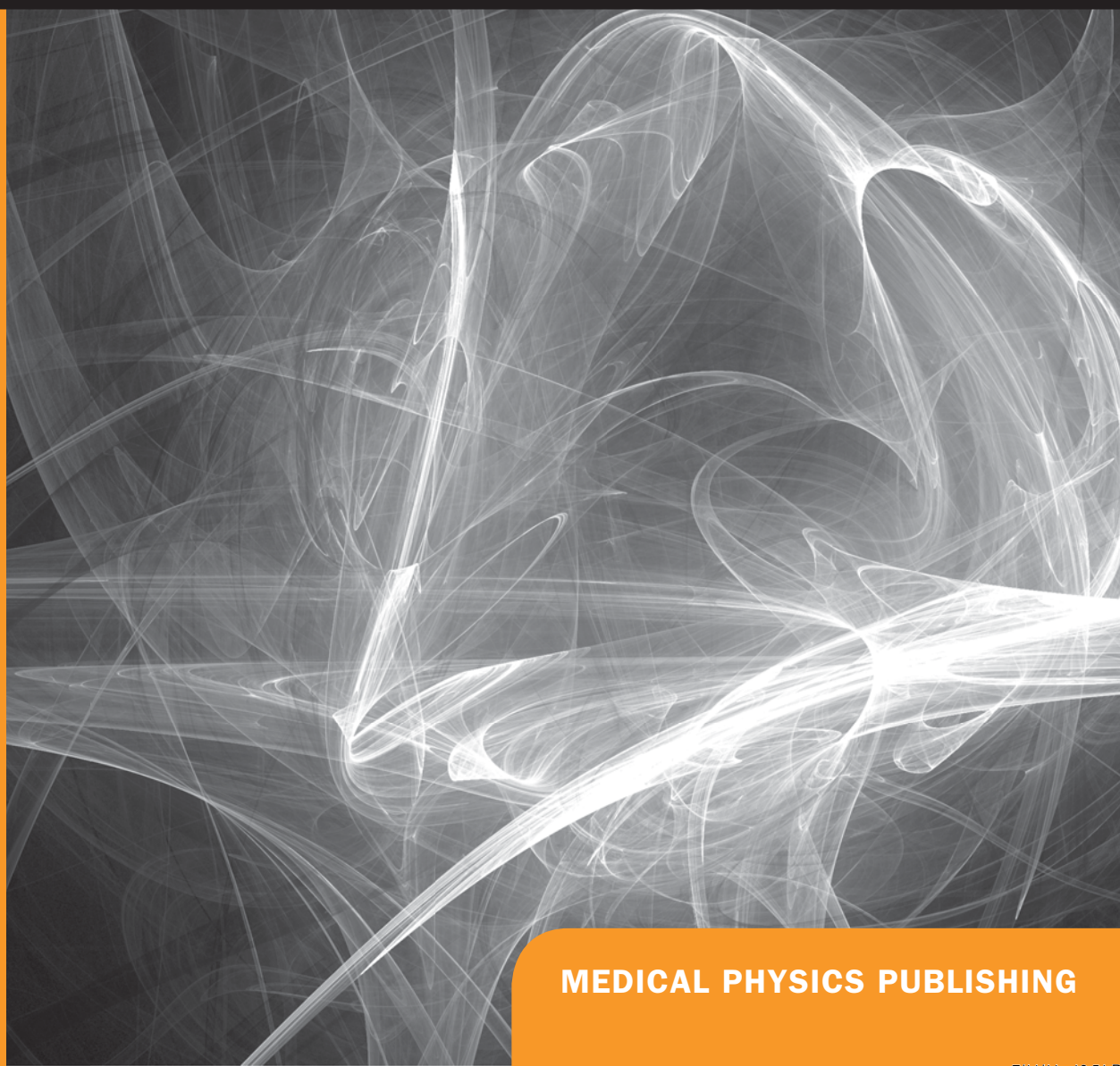
RT X-RAY PHYSICS REVIEW

Walter Huda
Kerry Greene-Donnelly



MEDICAL PHYSICS PUBLISHING

RT X-Ray Physics Review

Walter Huda, Ph.D.

Department of Radiology and Radiological Science
Medical University of South Carolina
Charleston, South Carolina

and

Kerry Greene-Donnelly, R.T.(R)(M)(CT)(QM)

Department of Medical Imaging Sciences
SUNY Upstate Medical University
Syracuse, New York

MEDICAL PHYSICS PUBLISHING
Madison, Wisconsin

15 14 13 12 11 1 2 3 4 5 6

Library of Congress Control No.: 2011933323

ISBN 13: 978-1-930524-54-5

ISBN 13 2014 eBook edition: 978-1-930524-75-0

Medical Physics Publishing
4513 Vernon Boulevard
Madison, WI 53705-4964
Phone: 1-800-442-5778, 608-262-4021
Fax: 608-265-2121
Web: www.medicalphysics.org

Printed in the United States of America

Dedication

Walter Huda dedicates this book to Joyce.

Kerry Greene-Donnelly dedicates this book to Dennis.

Acknowledgments

RT X-Ray Physics Review would not have been possible without the assistance of many colleagues. Kent Ogden, Ph.D., and Marsha Roskopf, R.T.(R) were instrumental in the acquisition of images and creation of graphics, in addition to offering their years of experience and knowledge with the authors. Thank you to the following individuals who offered their clinical expertise and aided in image acquisition: Andrew Smith, Ph.D., Janet Bentley, R.T.(R), Jennifer McBurnie, R.T.(R)(CT), Robyn Ouderkirk, R.T.(R)(CT), Richard Thompson, R.T.(R)(CT), and Donna Fritz.

A special thank you to those who reviewed all or part of the draft manuscript: Dominick DeMichele, R.T.(R)(CT), Charles Drago, R.T.(R)(CT), Colleen Donahue, R.T.(R)(MR), and Rosemary Morin, R.T.(R).

Contents

PART I. BASIC PHYSICS

Preface

I. Radiological Physics

Radiology is an ever-changing field in health care. Since the discovery of x-rays by Roentgen in 1895, many aspects of image production have improved. Advancement in the use of computers and imaging equipment has led to improvement in the detection of disease processes, more efficient patient care, and increased occupational safety. Radiological Physics is involved in every aspect of medical imaging, from image acquisition to display and storage.

Understanding and application of Radiological Physics is essential for the production of quality medical images using Radiography, Fluoroscopy, Mammography, Interventional Radiology, and Computed Tomography. Members of the imaging team include the radiologist, the medical physicist, and the technologist. The imaging team, by working together, provides quality imaging services while maintaining a high level of patient care.

Associated with most imaging modalities is the issue of radiation exposure for both the patient and the operators. Technologists must be aware of the radiation dose to the patient and personnel. One of the most important goals of imaging professionals is to ensure that radiation levels are kept As Low As Reasonably Achievable (i.e., ALARA principle). Exposure levels to operators and patients must also meet regulatory and accreditation limits.

II. Review Book Structure

This review book will assist the student technologist with preparation for the registry/licensing examination. As a review book, it is not intended to cover all Radiological Physics concepts fully, rather, it is to be used as part of a comprehensive registry preparation plan. Use of this review book will complement the student's understanding and application of radiological physics.

This review book is separated in to three units of study. Unit I presents basic concepts in physics, production/interaction of x-rays, and the x-ray tube. Unit II discusses radiographic detectors, the computer in imaging, projection radiography, fluoroscopy, and computed tomography. Unit III concludes the review book with radiation dosimetry, image quality, quality control practices, radiation biology, and protection. Each chapter has 30 questions for content review, and two 100-question comprehensive examinations are included at the end of this book.

The ARRT examination currently uses traditional radiation units, i.e., R, rad, and rem. The radiation quantities provided herein are generally provided using SI units, with traditional units to follow. In the text, the term "exposure" is not used, in favor of "Air Kerma." An Air Kerma of 10 mGy is taken to be approximately equal to an exposure of 1 R.

III. ARRT Exam

The American Registry of Radiologic Technologists (ARRT) oversees imaging-related credentialing examinations in the United States. The ARRT credentialing examinations are available for many modalities, such as Radiography, Mammography, and Computed Tomography. This review book has

been produced for those taking the Radiography credentialing examination. The ARRT examination includes the following content areas: (1) radiation protection, (2) equipment operation and maintenance, (3) image production and evaluation, (4) radiographic procedures, and (5) patient care.

ARRT examinations are computer based and given at secure testing centers across the country. The exam contains 200 questions and must be completed in 3.5 hours. A scientific calculator is provided, as well as a writing surface and a pen. As each ARRT examination is unique, a scaled score exam is used, in that examinations are scaled on their level of difficulty to account for any variation.

A (scaled) test score of 75 is required to pass the ARRT exam. Further information on the American Registry of Radiologic Technologists can be obtained at the ARRT web site (www.arrt.org).

Chapter 11

RADIATION DOSIMETRY

11.1 RADIATION UNITS

A. Air Kerma

- The **International Commission on Radiation Units and Measurements (ICRU)** developed standard units based on the SI system.
- SI units are utilized by all countries except the United States.
- **Air Kerma** is the SI unit that is currently used to quantify the x-ray beam intensity.
- Kerma stands for the ***K*inetic *E*nergy *R*eleased per unit *Ma*ss**.
- Intensity is directly related to the number of x-ray photons in a beam.
- Air Kerma is the kinetic energy transferred from x-ray photons to electrons.
- **Air Kerma** is measured in **joules per kilogram (J/kg):**

1 J/kg is 1 Gray (Gy).

- The Air Kerma value from x-ray sources obeys the inverse square law.

B. Exposure

- **Exposure** is the total charge of electrons liberated per unit mass of air by the x-ray photons.
- Exposure is the non-SI unit used to **quantify the x-ray beam intensity**.
- **One roentgen (R) is equal to the 2.58×10^{-4} C/kg.**

- 1 R is equal to 1000 mR, and is still used in some radiology departments in the United States.
- The roentgen applies to photons (x-rays and gamma rays) but not particles such as electrons.
- An exposure of **1 R corresponds to an Air Kerma of 8.7 mGy**.
- Scientific publications have **replaced exposure (R) with Air Kerma (mGy)**.
- 1 R is often approximated as ~10 mGy Air Kerma, and 10 mGy Air Kerma is approximated as ~1 R.

C. Absorbed dose

- **Absorbed dose (D)** measures the amount of **radiation energy (E)** absorbed per unit **mass (M)** of a tissue (i.e., **D = E/M**).
- Absorbed dose is specified in **gray (Gy)** in SI units.
- **One gray is equal to 1 J of energy deposited per kilogram.**
- In the non-SI system, the **rad** was the unit of absorbed dose.
- The rad was derived from the expression radiation absorbed dose.
- **1 Gy = 100 rad and 1 rad = 10 mGy.**
- It is helpful to specify the absorbing medium explicitly (i.e., absorbed dose to skin entrance, absorbed dose to liver, etc.).

D. Integral dose (energy imparted)

- The **integral dose** is simply the total energy (mJ) that a patient absorbs.
- **Integral dose and energy imparted have the same meaning.**
- A chest x-ray radiograph imparts about 2 mJ of energy to the patient.
- Head radiographs impart about 5 mJ and abdominal radiographs impart about 20 mJ.
- By contrast, a 500-W microwave oven produces 500,000 mJ every second.
- Energy imparted in a microwave oven is much greater than in a radiograph, and increases the food temperature.
- **X-rays deposit very little energy**, but this energy is ionizing, which breaks apart biologically important molecules such as DNA.

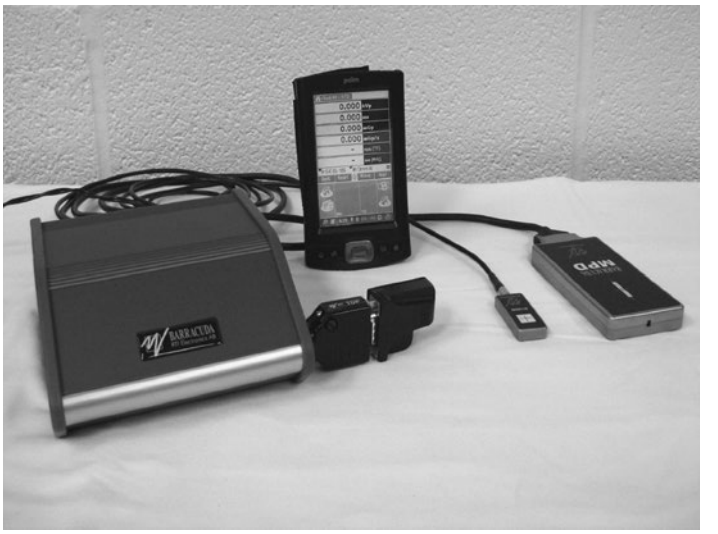
E. Equivalent dose

- **Equivalent dose** quantifies biological damage by *different types* of radiation.
- For the same absorbed dose, alpha particles cause much more biological damage than x-rays.
- The **equivalent dose (H)** is the **absorbed dose (D)** multiplied by a radiation **weighting factor (w_R)**.
- Mathematically, $\mathbf{H = D \times w_R}$.
- **Equivalent dose is expressed in sieverts (Sv).**
- Use of w_R permits comparisons of effects of different types of radiation on a common scale.
- For **x-rays, gamma rays,** and electrons $w_R = 1$.
- An absorbed dose to the skin of 1 Gy (100 rad) from x-rays corresponds to a skin-equivalent dose of 1 Sv (100 rem).
- For **alpha particles** and **neutrons**, w_R may be as high as 20.
- **Equivalent dose** is primarily used for radiation protection purposes as an ***approximate indicator* of biological harm**.
- Dosimetry units are shown in **Table 11.1**. Examples of measurement devices used in dosimetry are shown in **Figure 11.1**.

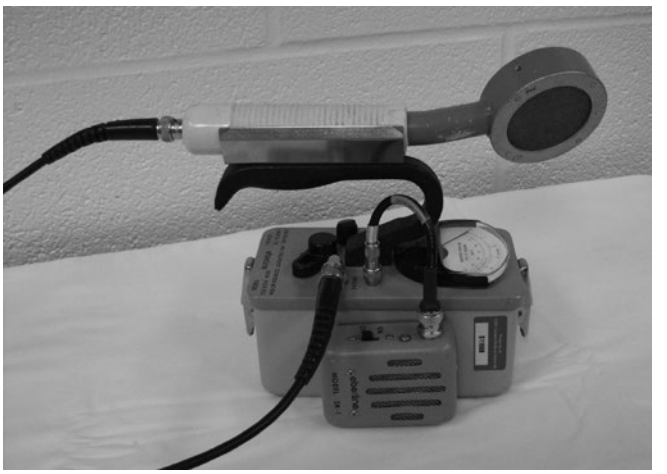
Table 11.1
Summary of dosimetry units used in x-ray imaging

Quantity	Units	Comments
Air Kerma	mGy	Quantifies the intensity of x-ray beams
Exposure	C/kg or roentgen	Has been replaced by Air Kerma
Absorbed dose	mGy or rad	Quantifies how much any tissue absorbs from any incident x-ray beam
Integral dose	mJ	Total energy absorbed by a patient undergoing any x-ray examination
Equivalent dose	mSv or rem	Obtained by multiplying absorbed dose to an organ by radiation weighting factor and used to predict the likelihood of biological harm

(a)



(b)



(c)

Figure 11.1
Examples of radiation measurement/detection devices.
(a) Ionization chamber; (b) Solid-state detector; (a) and (b) are used for the measurement of the primary x-ray beam.
(c) Geiger-Mueller tube used to detect radioactive isotope contamination in nuclear medicine.

11.2 INCIDENT RADIATION

A. Entrance Air Kerma (EAK)

- **Entrance Air Kerma (EAK)** is a measure of the amount of x-ray radiation intensity incident on the patient undergoing an x-ray examination.
- The EAK value is **measured** at the point **where the x-ray beam would enter the patient**, but is obtained in the absence of the patient.
- Values of EAK are thus **measured "free in air"** and do not include backscatter radiation from the patient.
- **The EAK is measured "free in air"** by placing an ionization chamber at the appropriate distance from the x-ray tube and using the patient technique factors (kVp and mAs).
- **Values of the EAK** are easy to measure but **do not quantify the amount of radiation** received by the patient.
- Patient doses (e.g., skin dose, embryo dose, organ dose) can be derived from EAK values via appropriate conversion factors (see below).

B. Radiography

- For a lateral **skull radiograph**, a typical **EAK value is 1.5 mGy**.
- An AP (or PA) skull would likely double the EAK value for a lateral skull.
- For a **PA chest radiograph**, the EAK is generally **0.1 to 0.2 mGy**.
- A lateral chest has EAK values about four times higher than a PA chest radiograph.
- For an **AP abdominal radiograph**, the EAK value is about **3 mGy**.
- EAK values for extremities are very low (< 0.1 mGy).

C. Fluoroscopy

- Because fluoroscopy involves continuous exposure, **Air Kerma rates in mGy/minute** are the units used.
- Entrance Air Kerma rates in fluoroscopy typically range from **10 to 100 mGy/min**.
- An **average-sized patient** entrance skin Air Kerma rate in fluoroscopy is **30 mGy/min**.
- Larger patients require more radiation in fluoroscopy, which is achieved either by increasing the x-ray tube voltage (kV) and/or increasing the tube current (mA).
- **Figure 11.2** shows a typical variation of EAK rates as a function of patient thickness.
- Magnification imaging in fluoroscopy will cause an increase in entrance Air Kerma rate as shown in **Figure 11.3**.

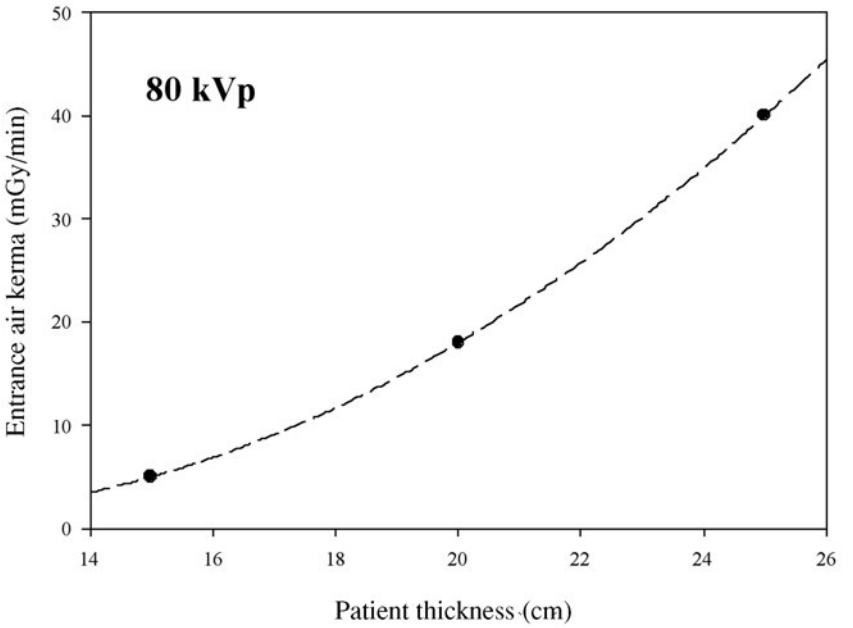


Figure 11.2
Entrance Air Kerma (EAK) rates in fluoroscopy as a function of patient thickness.

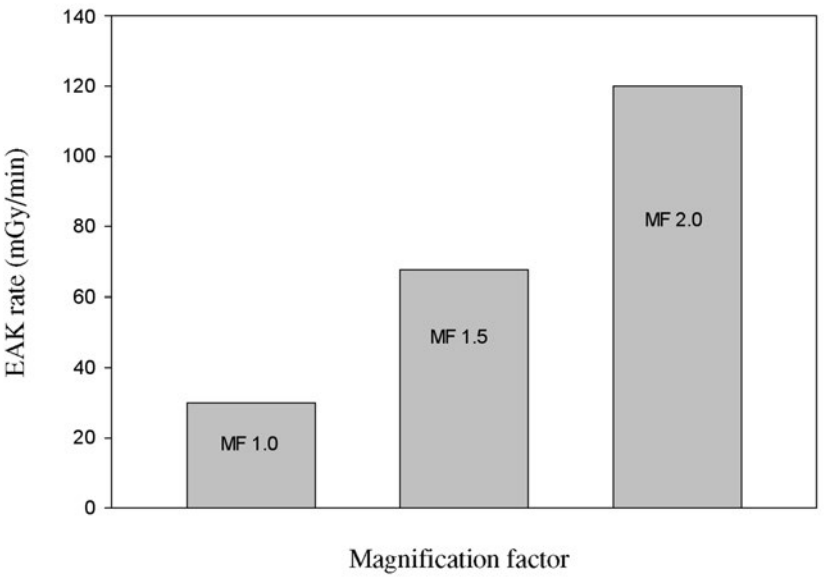


Figure 11.3
Effect of magnification in fluoroscopy on Entrance Air Kerma (EAK) rate. Using a magnification mode of 1.5 and 2.0 increases the EAK by a factor of 2.4 and 4.4, respectively.

D. Regulations

- In the United States, the legal limit for **entrance skin kerma rate is 100 mGy/min (10 R/min)**.
- No regulatory limits apply when a fluoroscopy imaging chain acquires diagnostic images.
- Diagnostic images include cardiac cine, DSA, and photospot.
- **High-dose modes** in fluoroscopy may be activated to maintain image quality in **very large patients**.
- Special activation mechanisms as well as visible/audible indicators are present to indicate when high-dose mode is being used.
- The maximum Air Kerma rate in high-dose mode is **200 mGy/min (20 R/min)**.

E. Kerma Area Product (KAP)

- **The entrance Air Kerma is independent of the x-ray beam area.**
- At constant techniques, a 10 cm × 10 cm beam area and 20 cm × 20 cm beam area have similar EAK values.
- Compared to a 10 cm × 10 cm field, the 20 cm × 20 cm field results in **four times more energy** deposition in the patient.
- The best quantity that takes into account **the *total* amount** of radiation incident on the patient is the **Kerma Area Product (KAP)**.
- KAP is the product of the **entrance Air Kerma** and **cross-sectional area of the x-ray beam**.
- **KAP is independent of the measurement location** because increases in beam area are offset by the reduction of beam intensity **(inverse square law)**.
- KAP can be used to compare doses from different imaging systems (or facilities) for similar types of examinations on similar-sized patients.
- KAP values **indicate relative radiation risks** for similar types of examinations performed on similar-sized patients.
- **Table 11.2** shows typical KAP values in radiography and fluoroscopy.
- Kerma Area Product is also known as the Dose Area Product (DAP), and the terms KAP and DAP are interchangeable.

Table 11.2
Typical KAP values in radiography, fluoroscopy, and IR

Image acquisition	Entrance Air Kerma (mGy)	Kerma Area Product ($Gy\text{-}cm^2$)
Skull radiograph	1.5	0.5
AP chest x-ray	0.2	0.2
Abdominal x-ray	3	3
Fluoroscopy (1 min)	20	10
Spot image (Ba study)	1	0.5
DSA image* (abd)	6	2

*Taking into account that two frames are required to generate one DSA frame

11.3 ABSORBED DOSES

A. Air Kerma (free in air) and doses

- For the same Air Kerma (intensity), **absorbed dose** depends on the **material** or **tissue** that is placed into the x-ray beam.
- The radiation absorbed by a medium is determined by the characteristics of the absorber (density, atomic number, etc.), as well as the x-ray beam energy.
- An Air Kerma of **1 mGy (100 mR)** will result in an absorbed dose in **soft tissue of approximately 1.1 mGy (110 mrad)**.
- An Air Kerma of **1 mGy (100 mR)** will result in a **bone dose of 4 mGy (400 mrad)**.
- **Doses** in radiology also **need to account for backscatter**.
- An x-ray beam incident on a patient will also result in x-ray photons from within the patient being backscattered.
- Backscatter is the ratio of the radiation intensities with and without the patient being present.
- **Values of backscatter in diagnostic radiology are about 1.4.**
- Skin doses will be higher than entrance Air Kerma because tissue absorbs more radiation than air (**×1.1**), and because of backscatter (**×1.4**).
- **An entrance Air Kerma of 1 mGy results in skin doses of about 1.5 mGy.**

B. Skin doses

- **Skin doses** are generally specified at the location **where the x-ray beam enters the patient**.
- Skin doses are numerically about 50% higher than the entrance Air Kerma.
- Skin doses in radiography are generally very low.
- Pediatric skin doses will generally be lower than for adults.
- An **average-sized patient (23 cm)** undergoing fluoroscopy will have a skin dose rate of about **45 mGy per minute**.
- An average-sized patient undergoing 10 minutes of fluoroscopy may result in a skin dose of 450 mGy.
- Skin doses can be substantially increased for larger patients.
- Interventional Radiology (IR) is complex, has long fluoroscopy times, and can generate many images.
- Because of this, IR may result in deterministic effects.
- **Fewer than 1 in 10,000 patients** undergoing IR by qualified personnel **suffer from serious deterministic effects**.

C. Organ (embryo) doses

- **Entrance Air Kerma may be converted into absorbed doses** to any organ located within the patient.
- Organ doses are generally much lower than skin doses.
- If the x-ray beam does not directly irradiate the embryo, the embryo dose may be taken to be very low.
- **Embryo doses** may be estimated from entrance Air Kerma values.
- The **x-ray projection is important** when determining embryo doses.
- **Table 11.3** provides typical values of entrance Air Kerma and the corresponding values of embryo dose in abdominal radiography.

Table 11.3
Entrance Air Kerma (EAK) and embryo doses in abdominal/pelvic radiography when the embryo is directly irradiated

Projection	EAK (mGy)	Embryo dose (mGy)
AP	3	1
PA	3	0.6
Lateral	6	0.3

- **Patient size** is an additional factor that needs to be taken into account when estimating embryo doses.
- Larger patients require more radiation for adequate penetration, but this will also result in more attenuation between the entrance and the location of the embryo.
- **Estimating embryo doses generally requires input from a Qualified Medical Physicist.**

D. Gonad doses

- **Gonad doses** refer to the radiation received by the testes in males and the ovaries in females.
- The genetic risk in any exposed individual is generally deemed to be low and of no direct clinical concern.
- Gonad doses have been used to quantify the **genetically significant dose (GSD),** which is an index of **potential genetic damage in exposed populations**.
- GSD accounts for gonad dose and the number of offspring likely to be produced.
- When a population receives a gonad dose equal to the GSD, the genetic harm equals that from current medical exposures.
- The **National Council on Radiation Protection and Measurements (NCRP) reported the U.S. GSD at about 0.3 mGy in 1980.**
- Gonad doses are now **of little concern in diagnostic radiology**, and GSD values are rarely subject to scientific investigation.
- **Nonetheless, use of gonad shields is still common practice and useful as a precautionary principle.**

E. Mammography

- In mammography, the **average glandular dose (AGD)** is obtained from a measurement of the **entrance Air Kerma using a breast phantom**.
- AGD values depend on x-ray beam techniques (kV and mAs), beam filtration, breast thickness, and composition.
- **AGD are obtained using a phantom simulating a 4.2-cm thick breast with 50% glandularity.**
- Increasing the x-ray tube voltage when the image receptor intensity is kept constant will reduce AGD because of increased x-ray beam penetration.
- **AGD values are about 1.5 mGy (150 mrad) per image.**
- Digital mammography has slightly lower AGD values than screen-film because of the use of higher beam qualities (i.e., increased kV and/or filtration).

- **Patient doses can differ markedly** from the AGD obtained using a breast dosimetry phantom because of differences in breast size and composition.

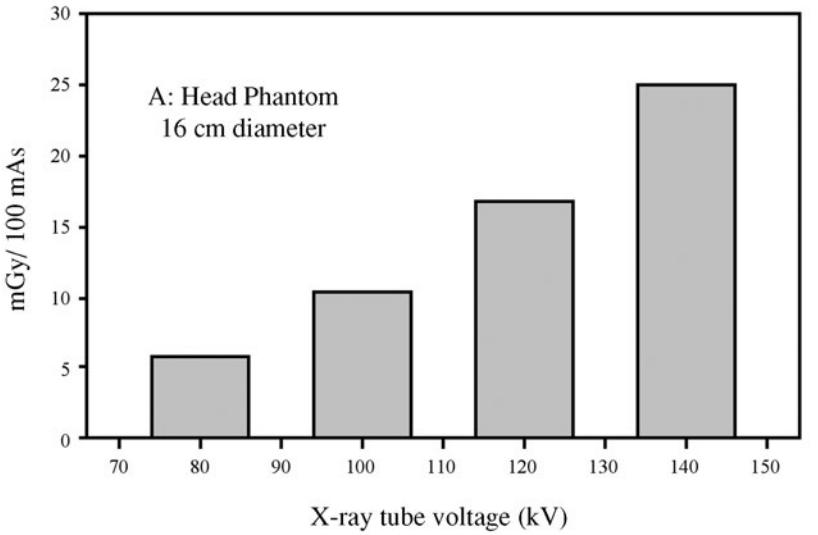
11.4 CT DOSIMETRY

A. Computed Tomography Dose Index (CTDI)

- Manufacturers specify CT doses by the **CT dose index (CTDI)**.
- CTDI is obtained from the dose distribution that occurs when the x-ray tube performs **one single 360° rotation with no table motion**.
- CTDI values are **measured using a pencil-shaped ionization chamber** in terms of Air Kerma, and are specified in **mGy**.
- An **acrylic cylinder** with a 16-cm diameter is normally taken to represent an adult patient head.
- The head CT dosimetry phantom can also represent a pediatric abdomen.
- An acrylic cylinder with a 32 cm diameter is normally taken to represent an adult body.
- Most patients are smaller than a 32 cm acrylic phantom, and dose measurements made in this phantom will underestimate patient doses.

B. Clinical CTDI

- CTDI measurements may be made at the periphery and at the center of the phantom are called $CTDI_p$ and $CTDI_c$, respectively.
- **A weighted CTDI (i.e., $CTDI_w$) is defined as 2/3 $CTDI_p$ + 1/3 $CTDI_c$.**
- Doses in helical scanning modes with a **pitch of 1.0 are similar** to those resulting from contiguous axial scanning.
- When pitch is less than 1.0, doses increase because of overlap. When pitch is greater than 1.0, doses decrease because scan energy is deposited in a larger volume.
- A pitch of 2 will halve dose, and a pitch of 0.5 will double the dose.
- **CTDI is inversely proportional to pitch.**
- To account for different pitch values in helical scanning, the volume **$CTDI_{vol}$** has been introduced as **$CTDI_w$/Pitch**.
- $CTDI_{vol}$ is expressed in mGy.
- **Figure 11.4** shows $CTDI_{vol}$ for head and body phantoms, illustrating that **body doses are about half head CTDI due to increased attenuation**.



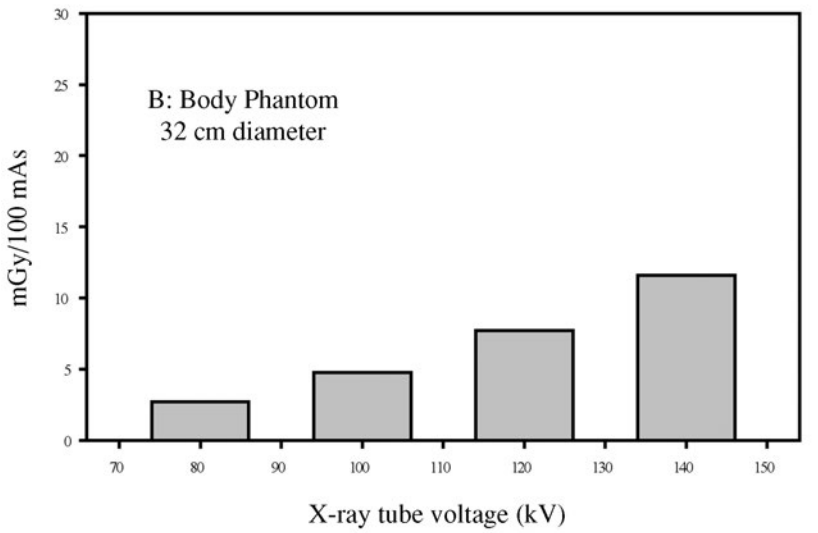


Figure 11.4
Average values of $CTDI_{vol}$ as a function of x-ray tube voltage (per 100 mAs).

C. Dose-Length Product (DLP)

- **$CTDI_{vol}$ is independent of the total scan length.**
- The total amount of radiation received by the patient, however, is directly proportional to the scan length.

- The **Dose-Length Product (DLP)** is the **product of $CTDI_{vol}$ and scan length**.
- The DLP is proportional to the total dose (energy) imparted to the patient.
- **DLP** is a good measure of the total amount of **radiation incident on a patient**.
- A typical **head CT examination has a DLP of 1000 mGy-cm**, where CTDI is measured in 16-cm phantoms.
- A **chest, body, or pelvic CT examination would have a DLP of 600 mGy-cm,** where CTDI is measured in 32-cm phantoms.
- A chest abdomen pelvic CT scan would have a DLP of 1500 mGy-cm.
- CTDI and DLP measures are shown in **Table 11.4**, and it is very important that the phantom size (16 cm or 32 cm) is always specified.

Table 11.4
Common Computed Tomography Dose Index (CTDI) measures used in CT dosimetry

Quantity	Units	Comments
$CTDI_{air}$	mGy	CTDI measured at the CT scanner isocenter in the absence of any patient or dosimetric phantom
$CTDI_{p}$	mGy	CTDI measured at the periphery (i.e., 1 cm from edge) of an acrylic dosimetric phantom
$CTDI_{c}$	mGy	CTDI measured at the center of an acrylic dosimetric phantom
$CTDI_{w}$	mGy	Equal to 1/3 ($CTDI_{c}$) + 2/3 ($CTDI_{p}$), and measured in either 16-cm (head) or 32-cm (body)
$CTDI_{vol}$*	mGy	Equal to $CTDI_{w}$ divided by pitch
Dose-Length Product (DLP)*	mGy-cm	Product of $CTDI_{vol}$ and the scan length L (cm)

*Metrics easily available to the technologist

D. Adult CTDI

- **The American College of Radiology (ACR)** runs a CT Accreditation Program, including CT dosimetry data.
- Mean values of $CTDI_{vol}$ for an adult head are 58 mGy (16-cm phantom), and for an adult abdomen, 18 mGy (32-cm phantom).
- **CT doses are directly proportional to the mA and to the scan rotation time.**
- Increasing the x-ray tube voltage from **80 kV to 140 kV, increases doses fivefold**.

- Performing multi-phase studies can substantially increase patient doses.
- For constant techniques, performing four phase examinations (pre-contrast, arterial, venous, and equilibrium) would quadruple the patient dose.
- **Multi-detector CT (MDCT) has radiation doses similar to those of axial CT for similar image quality.**

E. Pediatric

- Pediatric doses depend on both patient characteristics and selected techniques.
- Doses in infants and young children are much higher than for adults when performed using the same techniques.
- **The Food and Drug Administration (FDA) issued an advisory in 2001 to reduce radiation doses to pediatric patients.**
- Increasing the patient size from 20 to 100 kg reduces x-ray beam penetration by a factor of 30.
- **Reduced techniques** are possible because x-ray penetration is much greater in children than in adults.
- **The American College of Radiology (ACR)** CT Accreditation Program includes specific CT dosimetry requirements for pediatric examinations.
- The ACR provides resources to assist in dose reduction techniques, such as the Image Gently™ web site, www.imagegently.org.
- Pediatric body examinations should be performed with a **reduction in dose by a factor of ~3** compared with adult examinations.

11.5 EFFECTIVE DOSES

A. Effective dose

- Skin doses are poor predictors of patient stochastic radiation risk.
- Problems with skin doses include the fact that they **fail to account for the exposed body region, x-ray beam area, and x-ray penetration**.
- The **effective dose (E)** is obtained by taking into account the equivalent dose to all exposed organs, as well as each organ's relative radiosensitivity.
- **E** is obtained by multiplying **equivalent dose (H)** to an organ by the **organ weighting factor (w)**, and **summed for all irradiated organs**.
- The organ weighting factor (w) is a measure of the relative organ radiosensitivity for the induction of stochastic effects.
- The **most radiosensitive organs** are the red bone marrow, colon, lung, breast, and stomach.

- The **effective dose** is expressed in terms of the **equivalent dose (mSv)**.
- The effective dose (E) is the uniform whole-body dose that results in the same stochastic detriment as any non-uniform pattern of dose.
- A major benefit of the **effective dose** is that it permits all radiological examinations that use ionizing radiations to be directly compared using a single common scale.

B. Computing effective doses

- KAP may be converted to effective dose by taking into account irradiation geometry and x-ray beam quality.
- **PA chest radiographs have E/KAP of ~0.2 mSv/Gy-cm^2.**
- Effective dose per unit skin dose for **AP chest radiographs is ~0.3 mSv/Gy-cm^2**, and for **lateral chest radiographs is ~0.15 mSv/Gy-cm^2**.
- For **AP abdominal** radiographs, the effective dose per unit skin dose is **~0.2 mSv/Gy-cm^2**.
- E/KAP conversion factor for newborns is an order of magnitude higher than for adults.
- CT DLP doses can be converted into an effective dose using E/DLP conversion factors.
- **E/DLP values for 32-cm diameter phantoms are generally twice as high as E/DLP values for 16-cm diameter phantoms.**

C. Radiography

- The **effective dose** of a chest radiographic examination **(PA + lateral views)** is typically **0.05 mSv (5 mrem)**.
- The effective dose of a complete skull radiographic examination is ~0.1 mSv (10 mrem).
- The effective dose of a complete **abdominal radiographic examination is ~0.5 mSv (50 mrem)**.
- Radiation doses in projection radiography are low in comparison to GI studies, Interventional Radiology, and CT.

D. Fluoroscopy and IR

- Effective doses in GI studies depend on total fluoroscopy time as well as the number of photospot images.
- **Table 11.5** summarizes common fluoroscopy examinations, highlighting increased effective dose as fluoroscopy time and spot images increase.

Table 11.5
Common fluoroscopy exam time, images, and dose information

Type of examination	Typical fluoroscopy time (minutes)	Number of spot films	Effective dose (mSv)
Barium swallow	1 to 2	9 to 15	1 to 2
Upper GI	2 to 3	12 to 15	2 to 4
Barium enema	3 to 5	6 to 12	4 to 8

- Effective doses for a **cardiac catheterization** examination are **~7 mSv (700 mrem)**.
- Therapeutic catheterization of the heart vessels is likely to result in higher radiation doses.
- **Cerebral angiography** has effective doses that range from **1 to 10 mSv (100–1000 mrem)**.
- Abdominal interventional radiography includes hepatic, renal, mesenteric studies, as well as those of the aorta.
- Typical effective doses in **abdominal angiography** are **~20 mSv (2000 mrem)**.
- **Peripheral angiography** studies have effective doses of **~5 mSv (500 mrem)**.

E. CT

- Effective doses in **head CT** scans are **1 to 2 mSv (100–200 mrem)**.
- Effective doses in **chest CT** scans are **5 to 10 mSv (500–1000 mrem)**.
- For a single-phase exam, effective doses in pelvis + abdominal CT scans are 5 to 10 mSv.
- A three-phase exam (pre-contrast, arterial phase, venous phase) would likely triple the patient effective dose.
- Effective doses for CT of the **extremities** would be less than **1 mSv (100 mrem)**.
- **Figure 11.5** shows how CT effective doses vary with age when the amount of radiation used (i.e., DLP) is kept constant.

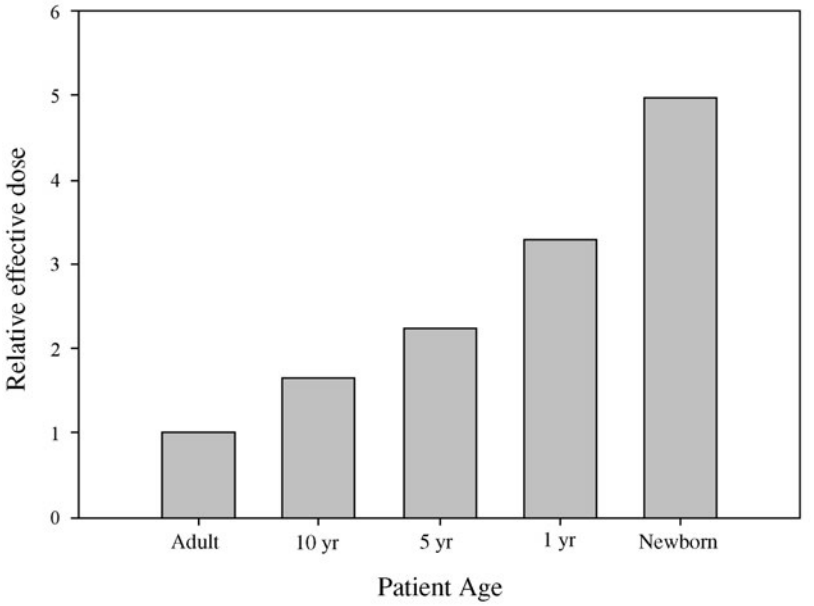


Figure 11.5
Relative effective dose for CT examination as a function of patient age, showing a large increase when CTDI and DLP are kept constant for a small patient size.

QUESTIONS

Chapter 11: Radiation Dosimetry

11.1 In the SI system of units, the intensity of an x-ray beam is best measured as:
A. air kerma.
B. exposure.
C. air dose.
D. equivalent dose.

11.2 An exposure of 1 roentgen may be taken to be an Air Kerma of about _____ mGy.
A. 0.1
B. 1
C. 10
D. 100

11.3 Absorbed dose is the energy absorbed per unit:
A. density.
B. mass.
C. time.
D. power.

11.4 The units of equivalent dose are:
A. C/kg.
B. dimensionless.
C. Gy.
D. Sv.

11.5 The radiation weighting factor for x-rays is _____ .
A. 1
B. 2
C. 10
D. 20

11.6 When the skin dose in an x-ray examination is 10 mGy, the skin equivalent dose is _____ mSv.
A. 1
B. 2
C. 10
D. 20

11.7 The Entrance Air Kerma (EAK) is least affected by the x-ray:
A. tube potential (kV).
B. tube current (mA).
C. exposure time (ms).
D. beam area (cm^2).

11.8 Entrance Air Kerma would most likely be measured using:
A. ionization chambers.
B. Geiger Mueller tubes.
C. NaI crystals.
D. photomultiplier tubes.

11.9 Then entrance Air Kerma for a normal-sized adult undergoing abdominal fluoroscopy (PA) is most likely _____ mGy/min.
A. 0.3
B. 3
C. 30
D. 300

11.10 The maximum Air Kerma rate (mGy/minute) in high-dose fluoroscopy is currently:
A. 50.
B. 100.
C. 200.
D. No limit.

11.11 The units of Kerma Area Product (KAP) are:
A. Gy/cm^2
B. $Gy\text{-}cm^2$
C. Gy-cm
D. Gy

11.12 An Air Kerma of 1 mGy would likely correspond to a soft-tissue dose of _____ mGy.
A. 0.5
B. 0.9
C. 1.1
D. 1.5

11.13 An Air Kerma of 1 mGy would likely correspond to a bone dose of _____ mGy.
A. 0.5
B. 1
C. 2
D. 4

11.14 The backscatter factor in diagnostic radiology is most likely _____ .
A. 0.7
B. 1.1
C. 1.4
D. 2.0

11.15 An entrance Air Kerma (free in air) of 1 mGy will most likely result in a skin dose of _____ mGy.
A. 0.75
B. 1.0
C. 1.25
D. 1.5

11.16 Skin dose for a chest radiograph is most likely _____ mGy.
A. 0.15
B. 1.5
C. 15
D. 150

11.17 For an AP projection, the ratio of the embryo dose to the entrance Air Kerma is most likely _____.
A. 1:1
B. 1:2
C. 1:3
D. 1:4

11.18 In 1980, the Genetically Significant Dose (GSD) in the United States was reported to be _____ mGy.
A. 0.003
B. 0.03
C. 0.3
D. 3

11.19 Mean Glandular Doses per image in mammography are most likely _____ mGy.
A. 0.5
B. 1.5
C. 5
D. 15

11.20 Using Automatic Exposure Control (AEC) increasing which x-ray tube parameter is most likely to reduce the mean glandular dose?
A. Current (mA)
B. Exposure time
C. Voltage (kV)
D. Focus size

11.21 Head CTDI doses are measured using an acrylic cylinder with a diameter of _____ cm.
A. 8
B. 16
C. 24
D. 32

11.22 The volume CTDI ($CTDI_{vol}$) is obtained by dividing the weighted CTDI ($CTDI_w$) by the CT:
A. pitch.
B. table speed.
C. gantry rotation time.
D. beam width.

11.23 Volume CTDI ($CTDI_{vol}$) and weighted CTDI ($CTDI_w$) are equal for a pitch ratio of:
A. 0.5.
B. 1.
C. 2.
D. All pitch values.

11.24 A typical adult head $CTDI_{vol}$ would likely be _____ mGy.
A. 2
B. 6
C. 20
D. 60

11.25 Units of Dose-Length Product (DLP) are:
A. mGy
B. mGy/cm
C. mGy-cm
D. $(mGy\text{-}cm)^2$

11.26 The ACR suggests a dose reduction by a factor of _____ from adult to pediatric body CT protocols.
A. 2
B. 3
C. 4
D. 5

11.27 The typical adult effective dose from a chest examination is most likely _____ mSv.
A. 0.05
B. 0.5
C. 5
D. 50

11.28 The typical adult effective dose from an upper GI examination is most likely _____ mSv.
A. 0.03
B. 0.3
C. 3
D. 30

11.29 The typical adult effective dose from a diagnostic cardiac catheterization is most likely _____ mSv.
A. 0.07
B. 0.7
C. 7
D. 70

11.30 The typical adult effective dose from a head CT examination is most likely _____ mSv.
A. 0.2
B. 2
C. 20
D. 200

ANSWERS[1]

Chapter 11: Radiation Dosimetry

11.1	A	Air Kerma is the SI unit used to measure exposure in air or intensity.	*p. 34 Bushong* *p. 140 Carlton/Adler*
11.2	C	One roentgen of exposure is equivalent to approximately 10 mGy Air Kerma.	*p. 34 Bushong* *p. 140 Carlton/Adler*
11.3	B	Absorbed dose is the amount of energy deposited per unit mass (J/kg).	*p. 34 Bushong* *p. 140 Carlton/Adler*
11.4	D	Equivalent dose is measured in sieverts (Sv).	*p. 618 Bushong* *p. 140 Carlton/Adler*
11.5	A	Radiations used in diagnostic radiology all have a radiation weighting factor of 1.	*p. 34 Bushong* *p. 141 Carlton/Adler*
11.6	C	The skin equivalent dose is equal to the skin dose because the x-ray radiation weighting factor is 1.	*p. 635 Bushong* *p. 141 Carlton/Adler*
11.7	D	Entrance Air Kerma values are measured free in air at the entrance skin distance. Any factor that affects beam quantity or quality would affect the EAK, but not the x-ray beam area.	*p. 34 Bushong* *p. 140 Carlton/Adler*
11.8	A	An ionization chamber would be placed free in air at the same location as the entrance skin.	*p. 589 Bushong* *p. 142 Carlton/Adler*
11.9	C	Entrance Air Kerma in fluoroscopy ~30 mGy/min for an average adult.	*n/a Bushong* *p. 579 Carlton/Adler*
11.10	C	*High-dose mode* fluoroscopy is limited to an Air Kerma of 200 mGy/min in the United States.	*p. 311 Bushong* *p. 202 Carlton/Adler*
11.11	B	Kerma Area Product is given in Gy-cm^2.	*n/a Bushong* *n/a Carlton/Adler*
11.12	C	Tissue doses are slightly higher than air doses, so an Air Kerma of 1 mGy results in a tissue dose of 1.1 mGy.	*p. 35 Bushong* *p. 186 Carlton/Adler*

[1] As a study aid, page numbers for additional study are given for the following references:
Bushong SC: *Radiologic Science for Technologists,* 9th ed. St. Louis, MO: Mosby, 2008.
Carlton RR, Adler AM: *Principles of Radiographic Imaging: An Art and a Science,* 4th ed. Albany, NY: Delmar Publishing Inc., 2005.

11.13	D	Bone doses are much higher than air doses, so an Air Kerma of 1 mGy results in a bone dose of 4 mGy.	*p. 168 Bushong* *p. 186 Carlton/Adler*
11.14	C	Diagnostic radiography has a backscatter factor of ~1.4.	*n/a Bushong* *n/a Carlton/Adler*
11.15	D	Skin doses will be higher than the entrance Air Kerma due to higher absorption in skin and backscatter.	*n/a Bushong* *p. 202 Carlton/Adler*
11.16	A	A skin dose of ~0.15 is typical in chest radiography and an entrance Air Kerma of 1 mGy will result in a skin dose of 1.5 mGy.	*n/a Bushong* *p. 202 Carlton/Adler*
11.17	C	Attenuation in the soft tissues results in the embryo dose that is numerically one-third of the entrance Air Kerma.	*p. 610 Bushong* *n/a Carlton/Adler*
11.18	C	In 1980 the Genetically Significant Dose was estimated at 0.3 mGy by the NCRP.	*p. 601 Bushong* *p. 139 Carlton/Adler*
11.19	B	A mean glandular dose of 1.5 mGy (150 mrad) is common in mammography.	*p. 602 Bushong* *p. 621 Carlton/Adler*
11.20	C	Increasing the kVp allows for a decrease in mAs and an overall dose savings.	*p. 322 Bushong* *p. 614 Carlton/Adler*
11.21	B	A 16-cm acrylic phantom is used for CTDI measurements in adult head protocols.	*n/a Bushong* *n/a Carlton/Adler*
11.22	A	The volume CTDI is obtained by dividing the weighted CTDI by the pitch.	*n/a Bushong* *n/a Carlton/Adler*
11.23	B	A pitch of 1 results in equal values of weighted and volume CTDI.	*n/a Bushong* *n/a Carlton/Adler*
11.24	D	A $CTDI_{vol}$ of ~60 Gy is typical for an adult head CT.	*p. 603 Bushong* *p. 667 Carlton/Adler*
11.25	C	The DLP is calculated by multiplying the $CTDI_{vol}$ by scan length, resulting in a value measured in mGy-cm.	*p. 635 Bushong* *n/a Carlton/Adler*
11.26	B	Pediatric body scans typically use 3 times less radiation than adult scans.	*n/a Bushong* *n/a Carlton/Adler*
11.27	A	A chest exam, PA and lateral, has an effective dose of ~0.05 mSv.	*n/a Bushong* *n/a Carlton/Adler*
11.28	C	An effective dose of ~3 mSv is typical.	*n/a Bushong* *n/a Carlton/Adler*

11.29 C A cardiac catheterization (diagnostic) has an effective dose of ~7 mSv. *n/a Bushong*
n/a Carlton/Adler

11.30 B Head CT scans in adults have effective doses of ~2 mSv. *n/a Bushong*
n/a Carlton/Adler

APPENDIX A

SUMMARY OF PREFIX NAMES AND MAGNITUDES

Prefix Name	Symbol	Magnitude
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecta	h	10^{2}
deca	da	10
deci	d	10^{-1}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}

APPENDIX B

RADIOLOGIC QUANTITIES AND UNITS

Quantity	SI Unit	SI to Non-SI Non-SI Unit	Non-SI to SI Conversion	Conversion
Exposure	C/kg	roentgen	1 C/kg = 3876 R	1 R = 2.58×10^{-4} C/kg
Air Kerma	gray (J/kg)	roentgen	1 Gy = 115 R	1 R = 8.73 mGy
Absorbed dose	gray (J/kg)	rad (100 erg/g)	1 Gy = 100 rad	1 rad = 10 mGy
Equivalent dose	sievert	rem	1 Sv = 100 rem	1 rem = 10 mSv

APPENDIX C

SI AND NON-SI UNITS FOR QUANTITIES USED IN RADIOLOGICAL PHYSICS

Quantity	SI Unit	Non-SI Unit
Length	meter (m)	centimeter (cm)
Mass	kilogram (kg)	gram (g)
Time	second (s)	minute (min)
Electrical current	ampere (A)	electrostatic unit (ESU) per second (s)
Frequency	hertz (Hz)	revolutions per minute (rpm)
Force	newton (N)	dyne
Energy	joule (J)	erg
Power	watt (W)	erg/s
Electrical charge	coulomb (C)	ESU

APPENDIX D

UNITS FOR PHOTOMETRIC QUANTITIES

Quantity	SI Unit	Non-SI Unit	To Convert Non-SI Units to SI Units
Luminance*	cd/m^2 (nit)	foot-lambert	foot-lambert × 3.4261 = cd/m^2
Illuminance**	$lumen/m^2$ (lux)	foot-candle	foot-candle × 10.761 = $lumen/m^2$

*Light scattered or emitted by a surface.
**Light falling on a surface.

APPENDIX E

SELECTED RADIOLOGICAL PHYSICS WEB SITES

American Association of Physicists in Medicine (AAPM)	www.aapm.org
American College of Radiology (ACR)	www.acr.org
American Journal of Roentgenology (AJR)	www.ajronline.org
American Registry of Radiologic Technologists (ARRT)	www.arrt.org
American Roentgen Ray Society (ARRS)	www.arrs.org
American Society of Radiologic Technologists (ASRT)	www.asrt.org
Conference of Radiation Control Program Directors (CRCPD)	www.crcpd.org
CTISUS Advanced Diagnostic Imaging	www.ctisus.com
Health Physics Society (HPS)	www.hps.org
Huda Physics Review	www.HudaPhysicsReview.com
Image Gently	www.imagegently.org
Image Wisely	www.imagewisely.org
International Commission on Radiation Units and Measurements (ICRU)	www.icru.org
International Commission on Radiological Protection (ICRP)	www.icrp.org
Joint Commission for Accreditation of Healthcare Organizations (JCAHO) (now Joint Commission)	www.jcaho.org
National Council on Radiation Protection and Measurements (NCRP)	www.ncrponline.org
Radiological Society of North America (RSNA)	www.rsna.org
Society for Imaging and Informatics in Medicine (SIIM)	www.siim.web.org
U.S. Food and Drug Administration (FDA)	www.fda.gov
U.S. Nuclear Regulatory Commission (NRC)	www.nrc.gov

BIBLIOGRAPHY

GENERAL RADIOLOGIC IMAGING

AAPM Report No. 15: Performance Evaluation and Quality Assurance in Digital Subtraction Angiography. New York: American Institute of Physics, 1985. www.aapm.org/pubs/reports/RPT_15.pdf.

AAPM Report No. 70: Cardiac Catheterization Equipment Performance. Report of AAPM Task Group No. 17. Madison, WI: Medical Physics Publishing, 2001. www.aapm.org/pubs/reports/RPT_70.pdf.

Ball J, Moore AD, Turner S: *Ball and Moore's Essential Physics for Radiographers*, 4th ed. Hoboken, NJ: Wiley-Blackwell, 2008.

Bushong SC: *Radiologic Science for Technologists*, 9th ed. St. Louis, MO: Mosby, 2008.

Carlton RR, Adler AM: *Principles of Radiographic Imaging: An Art and a Science*, 4th ed. Albany, NY: Delmar Publishing Inc., 2005.

Carter C: *Digital Radiography and PACS*. St. Louis, MO: Mosby, 2008.

Cullinan AM, Cullinan JE: *Producing Quality Radiographs*, 2nd ed. Baltimore, MD: Lippincott William & Wilkins, 1994.

Daniels C: Fundamentals of Diagnostic Radiology (CD-ROM). Madison, WI: Medical Physics Publishing, 1996.

Fosbinder R, Kelsey CA: *Essentials of Radiologic Science*. New York: McGraw-Hill, 2011.

Graham TG: *Principles of Radiological Physics*. 5th ed. New York: Churchill Livingstone, 2007.

Papp J: *Quality Management in the Imaging Sciences*, 4th ed. St. Louis, MO: Mosby, 2010.

Samei E, Badano A, Chakraborty D, Compton K, Cornelius C, Corrigan K, Flynn MJ, Hemminger B, Hangiandreou N, Johnson J, Moxley M, Pavlicek W, Roehrig H, Rutz L, Shepard J, Uzenoff R, Wang J, Willis C: Assessment of Display Performance for Medical Imaging Systems. Report of the American Association of Physicists in Medicine (AAPM) Task Group 18, Medical Physics Publishing, Madison, WI, AAPM On-Line Report No. O3, April 2005. www.aapm.org/pubs/reports/OR_03.pdf.

Selman J: *The Fundamentals of Imaging Physics and Radiobiology: For the Radiologic Technologist*, 9th ed. Springfield, IL: Charles C Thomas, 2000.

Stevens AT: *Quality Management for radiographic imaging*. New York: McGraw-Hill, 2001.

EXAMINATION REVIEW BOOKS

Carlton RR: *Delmar's Radiography Exam Review*. Albany, NY: Delmar Cengage Learning, 2010.

Bonsignore K, Maiellaro D, Kudlas M, Thengampallil A, Thengampallil S: *Kaplan's Radiography Exam with CD-ROM*, 2nd ed. New York: Kaplan Publishing, 2009.

Huda W: *Review of Radiologic Physics*, 3rd edition. Philadelphia: Lippincott Williams & Wilkins, 2010.

Leonard WL: *Radiography Examination Review*, 10th ed. Holly Springs, NC: JLW Publications, 2004.

Saia DA: *Appleton and Lange's Review for the Radiography Examination*, 7th ed. New York: McGraw-Hill, 2008.

Saia DA: *Radiography PREP: Program Review and Exam Preparation*, 5th ed. New York: McGraw-Hill, 2008.

BREAST IMAGING

American College of Radiology (ACR). *Mammography Quality Control Manua*l. Reston, VA: ACR, 1999.

Andolina V, Lillé L: *Mammographic Imaging: A Practical Guide*, 3rd ed. Philadelphia: Lippincott Williams & Wilkins, 2010.

Myers CP: *Mammography Quality Control: The Why and How Book.* Madison, WI: Medical Physics Publishing, 1997.

Peart O: *Lange Q&A: Mammography Examination*, 2nd ed. New York: McGraw-Hill, 2008.

Wagner JR, Wight EK: *Mammography Exam Review.* Philadelphia: Lippincott Williams & Wilkins, 2007.

COMPUTED TOMOGRAPHY

Blanck C: *Understanding Helical Scanning.* Baltimore, MD: Williams & Wilkins, 1998.

Phlipot-Scroggins D, Reddinger W Jr, Carlton R, Shappell A: *Lippincott's Computed Tomography Review*. Philadelphia: JB Lippincott, 1995.

Romans LE: *Computed Tomography for Technologists: A Comprehensive Text.* Baltimore, MD: Williams & Wilkins, 2010.

Seeram E: *Computed Tomography: Physical Principles, Clinical Applications, and Quality Control*, 3rd ed. Philadelphia: WB Saunders, 2008.

RADIOBIOLOGY AND RADIATION PROTECTION

American College of Radiology: *Radiation Risk: A primer.* Reston, VA: ACR, 1996.

Bushong SC: *Radiation Protection.* New York: McGraw-Hill, 1998.

Hall EJ, Giaccia AJ: *Radiobiology for the Radiologist*, 6th ed. Philadelphia: Lippincott Williams & Wilkins, 2005.

National Council on Radiation Protection and Measurements (NCRP) Report No. 147. Structural Shielding for Medical X-Ray Imaging Facilities. Bethesda, MD: NCRP, 2004.

Seeram E: *Radiation Protection.* Philadelphia: Lippincott, 1997.

Statkiewicz Sherer MA, Visconti PJ, Ritenour ER: *Radiation Protection in Medical Radiography*, 6th ed. St Louis: Mosby, 2010.

Wagner LK, Lester RG, Saldana LR: *Exposure of the Pregnant Patient to Diagnostic Radiations: A Guide to Medical Management*, 2nd ed. Madison, WI: Medical Physics Publishing, 1997.

About the Authors

Walter Huda studied Physics at Corpus Christi College, Oxford University, in the United Kingdom, followed by a doctorate degree in Medical Physics at the Royal Postgraduate Medical School (Hammersmith Hospital) at the University of London. From 1976 to 1981, Dr. Huda worked as a physicist at Amersham International, a commercial company specializing in radioactive products. In 1982, Dr. Huda moved to the Manitoba Cancer Treatment and Research Foundation in Winnipeg, MB, Canada, where he worked as a medical physicist in the fields of diagnostic imaging and medical radiation dosimetry. Dr. Huda has worked at the University of Florida, Gainesville, FL (1990 to 1997), SUNY Upstate Medical University at Syracuse (1997 to 2007), and the Medical College of South Carolina (MUSC) in Charleston, SC (2007 to present). His research interests are in medical imaging and radiation dosimetry. He has published one other book[1], approximately 200 scientific papers, and is board certified by the Canadian College of Physicists in Medicine and by the American Board of Medical Physics.

Dr. Huda has extensive experience in teaching x-ray physics, including to physicists, radiology residents, and x-ray technologists. Dr. Huda also offers review courses in North America directed at residents and other medical practitioners in Boston, Chicago, Ottawa, and Charleston, attracting over 400 attendees each year.

Kerry Greene-Donnelly holds a Master of Business Administration degree from SUNY Oswego, a Bachelor of Professional Studies degree in Health Service Management from SUNY Institute of Technology at Utica/Rome, and an Associate in Applied Science degree in Medical Radiography from SUNY Health Science Center at Syracuse. Kerry has 16 years of professional experience, with 11 of those years teaching in the Department of Medical Imaging Sciences at SUNY Upstate Medical University Syracuse. Kerry continues to work clinically, consulting on accreditation and CT protocol development.

Kerry teaches a variety of courses including: fundamentals of imaging, fundamentals of computed tomography, quality management, management principles, and imaging in radiation oncology, and coordinates computed tomography clinical rotations. Kerry is nationally certified in the following modalities: Radiography, Mammography, Computed Tomography, and Quality Management. Kerry participates in several professional societies: American Society of Radiologic Technologists (ASRT), Central New York Society of Radiologic Technologists, Western New York Health Physics Society, and the Upstate New York chapter of the American Association of Physicists in Medicine.

[1] Huda W: *Review of Radiologic Physics*, 3rd edition. Philadelphia: Lippincott Williams & Wilkins, 2010.