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Radiation Protection in the Design of Radiotherapy Facilities

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RADIATION PROTECTION IN THE DESIGN OF RADIOTHERAPY FACILITIES

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FOREWORD

The incidence of cancer throughout the world is increasing with the prolonged life expectancy that has resulted from improvements in standards of living. About half of all cancer patients receive radiotherapy, either as part of their primary treatment or in connection with recurrences or palliation. The IAEA has estimated that approximately 2500 teletherapy machines were in use in 1998 in developing countries and that 10 000 such machines may be needed by 2015. This Safety Report was initiated as a result of an expected increase in the construction of radiotherapy facilities, and in response to Member States that have requested practical guidance regarding the design and shielding of such facilities.

The objective of this report is to elaborate on the requirements for the design and shielding of radiotherapy facilities prescribed in Appendix IV of the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation, Safety Series No. 115. This report gives guidance on the design of radiotherapy facilities and describes how the required structural shielding should be determined. Methods for determining the necessary structural shielding for external beam units (^{60}Co units, linear accelerators, superficial and orthovoltage units and simulators) are given as well as shielding for brachytherapy units. Data used for determining the structural shielding necessary for all types of radiotherapy facilities are reproduced in this report, and example calculations are provided for each type of facility. The design of facilities so that security objectives for radioactive sources can be met is also addressed in this publication.

This Safety Report is intended to be used primarily by health physicists, medical physicists and other radiation protection professionals in the planning and design of new radiotherapy facilities and in the remodelling of existing facilities. Sections of the report will also be of interest to architects, civil engineers, hospital administrators and others who are concerned with the design of radiotherapy facilities. In addition, the guidance in this report will be useful to regulatory personnel responsible for the licensing and inspection of these facilities.

The IAEA expresses its gratitude to the two consultants who prepared this report — H.M. Morgan of the Royal United Hospital, Bath, United Kingdom, and R.K. Wu of the Eastern Virginia Medical School, Norfolk, Virginia, and Ohio Health Hospitals, Columbus, Ohio, USA. The IAEA officer responsible for this report was E. Reber of the Division of Radiation, Transport and Waste Safety.

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1. INTRODUCTION

1.1. BACKGROUND

The incidence of cancer throughout the world is increasing with the prolonged life expectancy that has resulted from improvements in standards of living. About half of all cancer patients receive radiotherapy, either as part of their primary treatment or in connection with recurrences or palliation. The IAEA has estimated that approximately 2500 teletherapy machines were in use in 1998 in developing countries and that 10 000 such machines may be needed by 2015. The preparation of this Safety Report was initiated as a result of an expected increase in the construction of radiotherapy facilities, and in response to Member States that have requested practical guidance regarding the design and shielding of such facilities.

1.2. OBJECTIVE

The objective of this report is to elaborate on the requirements for the design and shielding of radiotherapy facilities prescribed in Appendix IV of the International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation, Safety Series No. 115 (the BSS) [1].

1.3. SCOPE

This report is intended to be used primarily by health physicists, medical physicists and other radiation protection professionals in the planning and design of new radiotherapy facilities and in the remodelling of existing facilities. It draws together information from several reports [2, 3] with regard to the requirements of the BSS [1]. It provides guidance on the design of radiotherapy facilities and describes how the required structural shielding should be determined. Methods for determining the necessary structural shielding for external beam units (^{60}Co units, linear accelerators, superficial and orthovoltage units and simulators) are given as well as shielding for brachytherapy units. Data used for determining the structural shielding necessary for all types of radiotherapy facilities are reproduced in this report, and example calculations are provided for each type of facility. The design of facilities so that security objectives for radioactive sources can be met is also addressed in this publication.

Since corrections or additions after facilities are completed can be expensive, it is important that security concerns be addressed and structural shielding be properly designed and installed during the original construction process. It is also advisable that the planning includes consideration of possible future needs for new equipment, higher radiation energies, and increased workloads.[1] Special consideration needs to be given to the fact that workload can increase significantly with many new techniques which require more beam-on time per treatment or which enable many more patients to be treated per unit time.

The BSS [1] define a dose constraint as "…[a] prospective and source related restriction on the individual dose delivered by the source which serves as a bound in the optimization of protection and safety of the source." When planning for the construction of a radiotherapy facility, the dose constraints for occupational and public exposures will be the doses in, respectively, controlled and supervised areas (see Section 2.2) for which the facility is designed. Two principles of radiation protection and safety on which the BSS [1] are based and that must be considered when choosing appropriate dose constraints are optimization of protection and dose limitation.

In ICRP Publication 60 [4], an acceptable level of optimization of protection is described in this way:

> "If the next step of reducing the detriment[2] can be achieved only with a deployment of resources that is seriously out of line with the consequent reduction, it is not in society'sinterest to take that step, provided that individuals have been adequately protected."

Therefore, when considering anticipated dose rates in controlled and supervised areas in radiotherapy facilities, additional shielding can be added to the facility if the costs of the shielding are not significantly more than the resultant dose reduction. Further information on the complex task of cost–benefit analysis is given in ICRP Publication 37 [5].

The BSS [1] provide a simplified rendering of the principle of limitation: "individual doses due to the combination of exposures from all relevant

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[1] The degree of use of an X ray or gamma ray source. For X ray equipment operating below 4 MV, the weekly workload is usually expressed in milliampere minutes. For gamma ray beam therapy sources, and for X ray equipment operating at 4 MV or above, the workload is usually stated in terms of the weekly exposure of the useful beam and is expressed in gray (Gy).

[2] Detriment can be taken to be effective dose as it is considered here.

practices should not exceed specified dose limits." Therefore, dose constraints need to be selected so that, in addition to meeting the requirement for optimization, limits on individual doses from occupational and public exposures are not exceeded. It should be noted that the possibility that public and occupational exposures may result from more than one source must be taken into account.

There is no quantitative international standard with regard to dose constraints for radiotherapy facilities. However, two examples of dose constraints that are presented in this Safety Report are those used in the United Kingdom [6, 7] and the USA [8–10]. These dose constraints are based on the principles of optimization and limitation of doses and have been supported by many years of operational experience. Therefore, the use of the methods and data presented in this report should result in a cost effective room design consistent with radiation protection principles and requirements.

Shielding should be designed by a qualified expert, as defined in the Glossary of the BSS [1], to ensure that the required degree of radiation protection is achieved. The expert should be consulted during the early planning stages. Often, the shielding requirements affect the choice of location of radiation facilities and type of building construction. It is strongly recommended that a qualified expert approves the final shielding drawings and specifications before beginning construction. Other aspects of X and gamma ray facilities, such as interlocks, warning signs and lights, and room lighting, are mentioned in this Safety Report.

While specific calculational methods are used in the examples in this publication, alternative methods may prove equally satisfactory in providing radiation protection. The final assessment of the adequacy of the design and construction of structural shielding should be based on the radiation survey of the completed installation. If the radiation survey shows deficiencies, additional shielding or modifications of equipment and procedures will be required.

1.4. STRUCTURE

After a brief review of terminology in Section 2, the design features of radiotherapy facilities are described in Section 3, while Section 4 describes the materials used for shielding such facilities. Section 5 reviews the methods for calculating radiation barriers at radiotherapy facilities. Sections 6–9 provide examples of external beam facilities, simulators and orthovoltage units, brachytherapy facilities, and special radiotherapy procedures. Finally, Section 10 .provides guidance on how to conduct a radiation survey of facilities.

2. TERMINOLOGY

2.1. RADIATION BARRIERS AND MAZES

Radiation treatment facilities are comprised of primary and secondary barriers. Where the main radiation beam can strike the wall and roof, a primary barrier is required. If the facility is located above any accessible area, the floor will need to be a primary barrier. Primary barriers will be much thicker than the remaining walls, which are called secondary barriers. The secondary barriers will protect against scattered and leakage radiation.

For external beam therapy units the extent of the primary barrier will be determined by the divergence of the primary beam (as defined by the primary cone) to the outside of the barrier. The primary barrier is then extended further by 300 mm on each side to allow for small angle scatter (also termed the plume effect[3]).

The usual materials for radiation shielding are (normal or high density) concrete, steel, or lead. Concrete is usually the cheapest material as it is easier to bring to the site and use for construction. However, concrete densities are not as consistent as steel or lead, and they are therefore more difficult to monitor and control. More effort is needed on the part of the contractor and the structural engineer with regard to the quality control of concrete, avoiding the possibility of voids, and the sequence of pouring. It is recommended that during the pouring phase, an on-site concrete testing service be used. In new construction, standard concrete of density 2350 $kg \cdot m^{-3}$ should be used, although there may be local variations in density. If there are space restrictions, then it may be necessary to use higher density materials such as steel or lead. Further considerations regarding the choice of building materials are also given in Section 4.

2.2. CONTROLLED AND SUPERVISED AREAS

The glossary of the BSS [1] defines a controlled area as any area in which specific protection measures and safety provisions are or could be required for:

(a) Controlling normal exposures or preventing the spread of contamination during normal working conditions;
(b) Preventing or limiting the extent of potential exposures.

[3] The broadening of a radiation beam beyond geometrical divergence due to the accumulation of lateral scattering with depth.

A supervised area is defined in the BSS Glossary as any area not designated as a controlled area, but for which occupational exposure conditions are kept under review even though specific protective measures and safety provisions are not normally needed.

The designation of areas as controlled or supervised areas may sometimes be defined in terms of the dose rate at the boundary. Such an approach may be appropriate, but it should not be used without careful evaluation. For instance, account needs to be taken of variations in dose rate and occupancy over time as discussed in this Safety Report.

Paragraph I.29 of the BSS [1] requires that facilities be designed to "…minimize the need for relying on administrative controls and personal protective equipment for protection and safety during normal operations…" Therefore, facilities need to be designed with the goal that the number and extent of controlled areas will be as limited as possible, economic and social factors being taken into account.

Under the BSS [1] classification system, the treatment room will normally be designated as a controlled area. The treatment control area and other areas adjacent to the treatment room may also be designated as controlled areas if the facility cannot be designed such that dose levels in these areas are sufficiently low that they could be considered to be supervised areas. Controlled areas should have restricted access and be labelled appropriately.

2.3. WORKLOADS, USE AND OCCUPANCY FACTORS

The term workload (W) is used to provide some indication of the radiation output per week of external beam X ray and gamma ray sources. For a linear accelerator the typical number of patients treated in an eight hour day is 50. NCRP Report 49 [2] suggests a workload figure of 1000 Gy/week based on a dose of 4 Gy at 1 m per patient, assuming a five day week for megavoltage facilities. For dual energy machines the same workload figure of 1000 Gy/week may be used. NCRP Report 51 [11] suggests an assumed workload of 500 Gy/week for the higher energy, with the remainder of the workload being attributed to lower energy X rays or electrons. If the workload is greater, the figures used for Gy/week should reflect this.

A use factor[4] (U) describes the different beam orientations used for treatment when calculating the required barrier thickness for each beam

[4] Fraction of the time during which the radiation under consideration is directed at a particular barrier.

orientation. If conventional treatment techniques are to be used, NCRP Report 49 [2] suggests a use factor of 1 for the floor with the beam pointing vertically down, and 0.25 for each wall and ceiling if specific values are not available. These use factors may depend on the particular use of the facility and also on the energy used. For example, a facility performing a large number of total body irradiations may have a use factor greater than 0.25 for one wall, and lower for other walls.

The occupancy factor (T) relates to the amount of time rooms adjacent to the treatment room are occupied. An area below ground would have no occupancy at all and therefore T would equal zero. Areas that are intermittently occupied, such as corridors, would have a slightly greater occupancy and an area such as an office even greater. All things being equal, an adjacent area that is occupied more often will require more shielding. The occupancy factor for an area should be considered as the fraction of time spent by a single person who is there the longest. It is most likely that the target group for shielding purposes will be non-radiation workers employed by the hospital. The occupancy factor is best defined as the fraction of an 8 h day or 2000 h year for which a single individual may occupy a particular area. Examples of occupancy factors are given in different publications [2, 12] and these are shown in Table 3. Occupancy factors for the local situations should be based on these figures, any local regulations and the specific conditions at the facility under consideration.

2.4. INSTANTANEOUS DOSE RATES AND TIME AVERAGED DOSE RATES

When designing radiation shielding barriers it is usual to assume that the workload will be evenly distributed throughout the year. Therefore, it is reasonable to design a barrier to meet a weekly dose limit equal to one-fiftieth of the annual limit [1]. However, further scaling of the dose limit down to shorter time intervals may result in a significantly greater shielding requirement. In the United Kingdom, the shielding design for therapy installations may take account of the instantaneous dose rate[5] (IDR) limit (see Table 2). This is the direct reading of the dosemeter that gives a reading in dose per hour, averaged over one minute. When calculating the required barrier shielding it is useful to calculate the expected IDR for comparison with direct measurement after the facility has been built and the treatment unit installed. The time averaged

[5] The direct reading of a dosimeter in dose per hour averaged over one minute.

dose rate[6] (TADR) is the barrier attenuated dose rate averaged over a specified time. TADR is proportional to IDR, and incorporates the *W*, *U* and dose output rate (DR_0) of the unit (for secondary barriers *U* will be unity).

The TADR is estimated over 8 h (R_8), taking use and workload into account, for the typical worst-case scenario, i.e. an occupancy factor of unity. For megavoltage treatment units, although the unit may be in use for 8 h per day, it is likely that the total beam-on time per day will be much less. The TADR, or R_8, is then determined from the IDR multiplied by the daily beam-on time and then divided by the length of the working day:

$$\text{TADR} = \text{IDR} \quad \frac{\text{Daily beam-on time}}{\text{Length of working day}} \tag{1}$$

or, expressed another way:

$$R_8 = \text{IDR} \times \frac{W_d U}{8 \times \text{DR}_0} \tag{2}$$

where

R_8 is the TADR averaged over an 8 h day, in $\mu Sv \cdot h^{-1}$;
IDR is IDR in $\mu Sv \cdot h^{-1}$ averaged over 1 min at a point 0.3 m beyond the barrier, with the machine operating at the dose output rate DR_0;
W_d is the daily workload defined at 1 m, in Gy for an 8 h day;
U is the use factor (=1 for secondary barriers or the maze entrance);
DR_0 is the dose output rate at 1 m, in $Gy \cdot h^{-1}$ or $Sv \cdot h^{-1}$.

The TADR2000 [6] is the time averaged dose rate estimated over 2000 h. This takes into account the workload, use and occupancy. According to guidance from the United Kingdom [6], if the IDR is less than 7.5 $\mu Sv \cdot h^{-1}$ and the TADR is less than 0.5 $\mu Sv \cdot h^{-1}$ or the TADR2000 is less than 0.15 $\mu Sv \cdot h^{-1}$, the area does not need to be supervised. The dose rate of 0.15 $\mu Sv \cdot h^{-1}$ is equivalent to 3/10 of 0.5 $\mu Sv \cdot h^{-1}$ or 0.3 $mSv \cdot a^{-1}$ that is the dose constraint for an office worker.

[6] The IDR multiplied by the expected daily beam-on time and then averaged over the time under consideration. (e.g. eight working hours in a day or 40 working hours in a week).

Other average dose rates may be specified:

2.4.1. Weekly TADR (R_w)

If R_w is the TADR averaged over a 40 hour week, it can be derived that

$$R_W = \text{IDR} \times \frac{WU}{\text{DR}_0} \tag{3}$$

where

R_w is the TADR averaged over one week, in Sv·week^{-1};
IDR is in Sv·h^{-1} when the machine is operating at the dose output rate DR_0;
W is the weekly workload defined at 1 m in Gy;
DR_0 is the dose output rate at 1 m, in Gy·h^{-1}.

The concept of R_w is useful in the evaluation of barrier adequacy as described in the examples later in this report (Section 10.1.).

2.4.2. Dose limit in any hour TADR (R_h)

In some places (for instance in the USA), radiation safety regulations specify a TADR (R_h) limit of 20 μSv in any hour in public places. For example, the United States Nuclear Regulatory Commission specifies: "The dose in any unrestricted area from external sources shall not exceed 0.02 millisievert in any one hour" [8]. This requirement considers the maximum number of normal patient procedures that could be performed in any hour. For shielding design purposes it may be assumed that the maximum dose in one hour is no larger than the weekly workload.

The barrier should be evaluated in a two step process for TADR (R_h) compliance. First, consider the time involved to perform a normal procedure, which usually includes setting up the patient, making the required field alignments and turning on the radiation beam. The maximum number of normal patient procedures that could be delivered in one hour is determined. The workload corresponding to this, expressed in Gy·h^{-1}, is then compared with the *numerical value* of the weekly workload, but expressed in Gy·week^{-1}, and the smaller value is the workload W_h to be used for the next step. Note that

W_h is in units of gray or sievert in any hour. The TADR R_h is then obtained using the following equation:

$$R_h = \text{IDR} \times \frac{W_h U}{\text{DR}_0} \tag{4}$$

where

R_h is in units of Sv in any hour;
IDR is in units of $\text{Sv}\cdot\text{h}^{-1}$ at the machine dose output rate DR_0 ;
W_h is in units of Sv in any hour;
DR_0 is in units of $\text{Sv}\cdot\text{h}^{-1}$.

Note that W_h is not always directly related to W, nor is R_h directly related to R_w. Although the numerical value of R_h is always less than or equal to the numerical value of R_w, the numerical value of W_h is always less than or equal to the numerical value of W.

3. DESIGN FEATURES

3.1. LOCATION

Radiotherapy departments are usually located on the periphery of the hospital complex to avoid radiation protection problems arising from therapy rooms being adjacent to high occupancy areas. As pointed out in NCRP 49 [2], operational efficiency, initial cost, as well as provision for future expansion and/or increased workload, should be considered when locating a therapy installation. Proximity to adjunct facilities, ready access for in-patients and outpatients, and consolidation of all therapeutic radiological services, however, may be more important than construction cost. For rooms below ground level, the reduction in shielding costs for floors and outside walls should be weighed against the expense of excavation, watertight sealing and of providing access. For rooms on or above ground level, the outside walls always require shielding; and additional structural support may be required for heavy equipment and for the additional weight of the shielding barriers.

The amount of shielding required in each of the barriers of the treatment bunker will depend to some extent on the use of the surrounding areas. Areas with high occupancy levels will require greater shielding. Wherever possible the treatment bunker should be surrounded with rooms that have low or controlled occupancy. For example locks or signs prohibiting unauthorized entry could control access to the roof space above a bunker.

3.2. ACCESS

Access to the room for the delivery and replacement of the treatment unit and subsequently by patients must be considered. Patients may arrive in wheelchairs or on trolleys or beds. Entrance to the room may be through a shielded door or via a maze (see Section 3.4). It is necessary to include in the room design an open access conduit for dosimetry equipment cables. This dosimetry duct should always be through a secondary barrier so that the primary beam can never strike it. Ideally it should run at an angle through the barrier to the treatment control area (see Section 3.8).

Also, for security purposes, radiotherapy facilities using radioactive sources should be located in areas where access by members of the public to the rooms where sources are used and stored can be restricted. Further, the proximity of source storage facilities to personnel that may respond in the event of a security breach should also be considered.

3.3. ROOM SIZE

The machine manufacturer's pre-installation manual should provide the minimum room dimensions (length, width and height). The room should be large enough to allow full extension of the couch in any direction, with room for an operator to walk around it. The desirable size depends upon the type of treatments; for example, a total body irradiation (TBI) procedure will require a larger treatment distance to one wall. For intra-operative procedures (IORT) that require extensive support staff and equipment, the room may need to be larger. The accessory equipment such as electron applicators, breast positioning boards, etc., are usually stored within the room, and should be located to minimize the walking distance for each patient set-up.

3.4. MAZES

In order to reduce the radiation dose near the entrance, a restricted access passageway leading to the room may be incorporated in the design. This passageway is termed the maze. Ideally this should be as long and with as small a cross-section as possible. The minimum width may be determined by the dimensions of the treatment unit to be delivered by this route or by access for a hospital bed. A maze ensures that photon radiation can only exit the room after scattering has attenuated it. A maze reduces the need for a heavy shielding door. If the length of the maze is sufficient, or if there are enough bends, there may be no need for a radiation protection door at the maze entrance. However, it is recommended that a physical barrier such as a normal door(s) or gate be installed to discourage entry to the maze during patient treatment if a shielded door is not required. Linear accelerators normally only require a gate to prohibit entry during treatment times and/or motion detectors to detect unauthorized entry if a shielded door is not required to reduce dose rates. Another advantage of a maze is a route for ventilation ducts and electrical conduits without compromising the shielding.

3.5. DOORS AND INTERLOCKS

The treatment room containing the radiotherapy equipment will be a controlled area according to the BSS [1] (see Section 2.2) and, in general, it is recommended that a barrier be installed at the entrance to the maze or treatment room to restrict access during exposures. If a shielded barrier is required to reduce dose rates, a motorized door may be necessary. A motorized door must have a manual means of opening the door in the event of a power or mechanical failure. There should also be an emergency means by which the motion of the door is stopped. Additionally, any motorized door that is too heavy to be stopped manually should have sensors that stop the motion of the door to prevent injury to personnel and patients.

All doors, gates, photoelectric beams and motion detectors must be interlocked to the treatment unit to prevent an exposure if a door is open. The interlock must also ensure that when the door is opened the irradiation will be terminated. The radiation output of the device should not be resumed automatically after the door is closed again. The interlock should be fail-safe so that safety is not jeopardized in the event of failure of any one component of the system. In certain countries (such as the United Kingdom), it is advised that a door-reset switch be situated near the exit from the treatment room at the position where the person leaving the room has a clear view of the room. Only

after activation of the reset switch can the radiation be turned on. If there is a maze, this switch should have a delayed action to allow the person time to leave the room and maze after resetting the switch. This switch should be connected in series with a second switch just outside the door. The same person should operate both switches. In cases where the door is clearly visible from the control panel, closing the door may activate the second switch. Only after activation of both switches can the radiation be turned on. For more information IPEM Report 75 [3] should be consulted.

In facilities using radioactive sources, a barrier that restricts access to the treatment room outside normal working hours may also be used to meet security performance objectives for radioactive sources (see Section 3.11). The characteristics of the barrier for security purposes should be determined as a result of an analysis of security threats.

Facilities that use radioactive sources should implement provisions so that unauthorized access to the source can be detected in a timely fashion (see Section 3.11) To achieve this provision, certain technical measures may be incorporated into a facility such as a video camera that provides continuous remote surveillance of the device, a photoelectric beam or motion detector system installed in the maze and/or treatment room, or a door interlock. If these devices indicate the potential presence of an unauthorized person, an alarm should indicate this locally and remotely so that so that personnel can respond in a timely fashion. These technical measures will be independent of any interlocks that terminate the radiation beam during normal operation because they will not be operational when the treatment unit is powered off outside operational times.

3.6. TREATMENT CONTROL AREA

The treatment control area is where the operators control the machine. This area should be close to the entrance to the treatment bunker so that the operators can view the entrance area. The control area should be sufficiently large to accommodate the treatment unit control console and associated equipment. There may be computer terminals for record and verification, electronic portal imaging, hospital information system and dosimetry equipment, as well as closed circuit TV monitors for patient observation. There should be clear access to any dosimetry ducts.

3.7. PATIENT OBSERVATION AND COMMUNICATION

The operator should be able to visually monitor the patient during treatment with closed circuit TV. Two cameras are recommended [13]. These should be situated 15° off and above the gantry rotation axis for optimum observation of the patient on the treatment couch. The cameras should be located far away from the radiation source, consistent with tele-zoom capabilities, to minimize degradation of the image receptor by scatter radiation. There should also be provision for two way audio communication between the treatment control area and the room. A patient activated alarm may be required for patients unable to give an audible call.

3.8. PENETRATION OF DUCTS

Ducts and conduits between the treatment room and the outside must be adequately shielded. This includes ducts for cables necessary to control the treatment unit, heating and ventilation ducts, ducts for physics equipment and other service ducts. It is recommended that ducts should only penetrate the treatment room through secondary barriers. No duct with a diameter greater than 30 mm should penetrate the primary shielding.

The ducts should be placed in such a way that radiation passing through them will require the least amount of compensation for the barrier material it displaces. No duct should run orthogonally through a radiation barrier. It could either run at an angle through the barrier or have one or more bends in it so that the total length of the duct is greater than the thickness of the radiation barrier.

If required, lead or steel plates are suitable materials to compensate for the displaced shielding. To shield the scattered radiation that passes along the duct, it is better to place the additional shielding outside the treatment room, where the radiation has a lower average energy and therefore, less shielding material is needed.

Treatment machine cables are usually run below the floor level under the primary or secondary barriers, before bending up to reach the treatment control area. Provided there are no rooms below, additional shielding is not usually required unless the treatment control area is directly behind a primary barrier, and the cable passes beneath the same primary barrier.

Water pipes and narrow electrical conduits are usually placed in groups inside a larger duct. It is recommended that they also should not penetrate through barriers, but follow the maze to exit the treatment room as described above or follow a route beneath the shielding barrier.

Heating and ventilation ducts should not penetrate through primary barriers because of their large cross-sectional area, which makes it costly to compensate for the shielding material they displace. If the ducts must pass through a secondary barrier, the cross-section of the duct should have a high aspect ratio to decrease the radiation passing through the duct as a result of multiple scattering interactions with the duct/shielding walls. The axis of the duct and the longer side of the duct cross-section should be as orthogonal as possible to the direction of the leakage radiation from the target towards the duct.

The amount of additional shielding required to shield penetrations in shielding walls depends on the energy of the radiation beam, the room layout and the route of the duct(s). The shielding must be evaluated carefully if the ducts must penetrate the primary barrier. The recommended placement of these ducts is above a false ceiling along the path of the maze, to exit the maze at or near the external maze door where the photon and/or neutron fluence are lowest. For accelerators of energies up to 10 MV, usually no additional shielding around the duct is required. For higher energies, an additional shielding recommendation is described in Section 3.8.1. If it is necessary for the ducts to pass through the secondary barrier, they should be placed as high as possible to minimize the scattered radiation to personnel outside the room.

Conduits are required for dosimetry cables, beam data acquisition system control cables, quality assurance (QA) equipment cables, and in vivo dosimetry equipment cables. The conduits are usually PVC pipes of 80–100 mm diameter included in the concrete formwork. They should be inclined at an angle (in the vertical and horizontal planes), and penetrate through the secondary barrier but not through the primary barrier. If the openings are at least 300 mm above floor level they are more convenient to use. Ideally, the opening in the treatment control area should be at the counter top level and the opening in the treatment room side should be at a different level but within easy reach. Conduits as described above usually do not need additional shielding unless the barrier is constructed of material with a much higher density than 2350 $kg \cdot m^{-3}$.

3.8.1. Shielding around ducts above the maze entrance for high energy machines

The photon and neutron dose equivalent rates at the maze door where the ducts penetrate the barrier may be estimated using the method described in Sections 5.7.1 and 5.7.2. Since the penetration area should be located about 3 m or more above the floor, the scattered radiation to a person is further reduced. McGinley [14] has shown that for 18 MV photons, the need for additional shielding depends strongly on the length of the maze. For a maze 5 m in length,

the total dose at the outer maze entrance is low and it usually requires no additional shielding around the duct. However, for a maze less than 3 m long, a shielding baffle may be needed to reduce the dose. McGinley [14] reports that for an 18 MV primary beam, a dose equivalent reduction of ¼ for neutrons and ½ for photons will be produced by a 1.2 m long duct wrapped with 10 mm thick lead and 25 mm thick polyethylene in a 3.6 m long maze. The lead should be wrapped around the outside of the duct first, followed by the polyethylene layer on the outside [14]. For rooms that include more than one bend in the maze, duct shielding is usually unnecessary.

3.9. WARNING SIGNS AND LIGHTS

Paragraph I.23 of the BSS [1] requires registrants and licensees to "display a warning symbol, such as that recommended by the International Organization for Standardization (ISO) [15] …at access points and other appropriate locations within controlled areas." It is recommended that an illuminated warning sign be displayed at the entrance to the maze or treatment bunker as well as several inside the treatment bunker. It should be possible to see a warning sign from any position within the treatment bunker. These signs should be mounted at eye level (1650 mm above finished floor level) and interlocked with the treatment unit control. The illuminated signs may have two or three stages. For a two stage sign, the first stage will be illuminated when there is power to the treatment unit, and the second stage will illuminate when the beam is turned on. For a three stage sign, stage one will be illuminated when there is power to the treatment unit, stage two will light when the treatment unit is programmed to deliver a radiation beam and stage three will illuminate when the beam is turned on. A warning sign should indicate the nature of the hazard. If there are controlled areas with restricted access outside the treatment bunker these should be labelled appropriately. The radiation warning sign is that recommended by the ISO [15].

3.10. ROOM LIGHTING AND ALIGNMENT LASERS

To set up a patient for radiotherapy treatment, the room lights should be dimmable so that the field light of the treatment unit and the alignment lasers can be seen easily. It is useful to be able to control the room lights and lasers from the treatment unit control pendant in the treatment bunker. When the field light is switched on the room lights should dim to a pre-set (but variable) level, and the alignment lasers should also be switched on. Since fluorescent

lights do not dim very satisfactorily, it is recommended that incandescent lights be used for the dim level. The main room lighting can be fluorescent lights that extinguish when the field light is turned on and the incandescent room lights are used for the dim level. When the field light is switched off, the main room lighting is switched on and the lasers switched off. The dimmable lights may remain on at all times.

Karzmark et al. [13] recommend that if junction boxes or alignment lasers are to be inset in the walls, then the voids need to be backed with 40 mm thick steel plate with a 30 mm margin all around. Depending on the occupancy of the adjacent area, it may be acceptable to have a reduction in the shielding over a small area, especially in a secondary barrier.

Four alignment lasers are recommended in total. Three lasers projecting a cross: two aligned with the gantry positions of 90° and 270°, and one mounted in the ceiling directly above the isocentre[7]. The fourth laser should project a sagittal line along the gantry axis. This laser is usually mounted on an angled bracket on the wall opposite the gantry. The laser switching should be controlled from the hand pendant, but it is also useful to be able to switch them off independently for QA tests.

3.11. SECURITY OF RADIOACTIVE SOURCES

Ensuring the safety of radioactive sources requires controlling exposure to radiation from the sources during normal operating conditions and during incidents, including those resulting from compromises to the security of a source. To this end, the licensee's facilities should include security measures to prevent loss, theft or unauthorized access to radioactive sources. Further, because the safety and security aspects of sources are intimately linked, many of the measures designed to address one will also address the other. For this reason, some of the previously described items (doors, walls, interlocks, etc.) that are intended to limit exposure to radiation will also contribute to the security of sources.

Guidance on determining which security measures are needed to ensure consistency with the provisions of the BSS [1] and the Code of Conduct [16] is provided in Ref. [17].

[7] The common point of intersection of the axes of radiation of the treatment unit gantry, field size collimators and patient couch. Normally the treatment head is made to rotate about it.

Reference [17] provides security objectives developed in four different security groups (A through D). The assignment of sources to these groups is the responsibility of the State and is based on Ref. [18].

3.11.1. Security provisions for radioactive teletherapy sources

Radioactive teletherapy sources are usually Category 1 sources and are therefore included in Security Group A, whose security objectives are to deter unauthorized access and to detect unauthorized access and acquisition of the source in a timely manner. Also, security measures should delay acquisition until a response is possible.

To achieve Security Group A objectives, Ref. [17] suggests that the following provisions be implemented:

Sources in storage:

— A locked and fixed source storage container such as a teletherapy head or transport container;
— A locked storage room separating the container from unauthorized personnel;
— Access control to the storage room;
— Detection of unauthorized access or removal of the sources;
— Ability to respond in a timely manner to such detection.
— Sources in use:
— A locked teletherapy head in an area to which access can be controlled;
— Access control to the area;
— Continuous monitoring for unauthorized intrusion attempts, either by personal surveillance or electronic equipment;
— Security guards capable of providing a timely response.

In order to implement these provisions, certain technical measures will have to be incorporated into the design of a radiotherapy facility. These include the possible inclusion of a means to lock the teletherapy head so that the source cannot be removed, a means of locking the treatment/storage room and the inclusion of an intrusion alarm that notifies personnel that the security of the source may have been compromised.

3.11.2. Security provisions for high dose rate and medium dose rate brachytherapy sources

High dose rate (HDR) and medium dose rate (MDR) brachytherapy sources are usually assigned to Security Group B. Associated security

measures should be established to deter unauthorized access, and to detect unauthorized access and acquisition of the source in a timely manner.

For Security Group B sources, Ref. [17] suggests the implementation of the following provisions:

Sources in storage:

— A locked and fixed container or device holding the source;
— A locked room to separate the container from unauthorized access;
— Access control to the room;
— Capability to detect unauthorized access to, or removal of, the source.

Sources in use*:*

— Use of the source in a locked room or controlled area;
— Continuous surveillance of the source;
— Access control to the room or controlled area.

3.11.3. Security provisions for low dose rate brachytherapy sources

Low dose rate (LDR) brachytherapy sources are usually assigned to Security Group C. Associated security measures should be established to deter unauthorized access and to verify the presence of the source at set intervals.

For Security Group C sources in storage, Ref. [17] suggests that the source(s) should be stored in a locked, fixed container and in a room with access control.

For Security Group C sources in use, Ref. [17] suggests that the appropriate control could be to make sure that an authorized person uses the source only in an area that has controlled access, or that the source is in a secure containment in an area where there are personnel to detect any interference with the source.

4. MATERIALS FOR SHIELDING

For new buildings to house radiation treatment facilities, concrete will usually be the material of choice since it is the least expensive. However, if space is at a premium it may be necessary to use a higher density building material. Table 1 lists a range of typical building materials with their densities.

TABLE 1. BUILDING MATERIALS AND THEIR DENSITIES

Building material	Density (kg·m^{-3})	Comment
Concrete	2350	Will vary with mineral content
Barytes concrete	3400–3500	Most commonly used for dense concrete but expensive
Iron ore with ferrosilicone	4000–5400	Range of densities which depend on proportions of ore mixture to sand
Ledite®	3844 and 4613	Pre-moulded high density interlocking blocks from Atomic International, Inc.
Clay bricks	1600	May be used for installations up to 500 kV with supplementary lead or steel shielding
Breeze blocks	1100–1400	
Earth fill	1600	May be useful if bunker is below ground level
Steel	7900	Normally used as supplementary shielding on an existing treatment room.
Lead (solid)	11 340	

Concrete density will vary according to the aggregate used. Most published data assume a density for concrete of 2350 kg·m^{-3}. For concrete of different density an adjustment will be needed to determine the required barrier thickness. For therapy installations operating over 500 kV, Compton absorption dominates and the shielding material will absorb the radiation according to the density of material.

The density of concrete varies according to the local aggregate that has been used. For example, in the United Kingdom, the normal density is 2300 kg·m^{-3}, but this will vary over the country from 2250 kg·m^{-3} (gravel) up to 2450 kg·m^{-3} (dense limestone or granite). If a design density is specified that cannot be made locally, then the cost will go up. The increase in cost is due mainly to the cost of transporting large volumes of aggregates. Concrete density can usually be achieved to within 50 kg·m^{-3} of that specified. It is most cost effective to determine the density of concrete that can be produced locally and determine the necessary barrier thicknesses accordingly, working on the lower limit of the density range specified [3].

Concrete is normally specified by strength, with density being of secondary importance. Strength is increased by increasing the proportion of cement in the mix, while increasing the proportion of aggregate increases

density. Increasing the amount of water in the mix will reduce the overall density as air pockets may be left as the mix dries out [3]. To guard against air pockets it is customary to vibrate the concrete mix as it is poured. Each barrier should be formed in one pour to avoid seams between different layers.

Pre-formed concrete blocks only have a density of 2000 $kg \cdot m^{-3}$, but some special dense building bricks are available. Examples of such bricks are barites, or barium and magnetite bricks, which have a density of around 3000 $kg \cdot m^{-3}$. If using dense bricks, it is important to use heavy mortars to avoid shine paths between the bricks. Ordinary sand mortar only has a density of 2000 $kg \cdot m^{-3}$.

If space is at a premium, then special high density concretes or high density materials such as steel or lead can be used. Steel plate is often used in existing rooms that need to be upgraded. The steel plate is usually formed in 10 mm thick sheets and fixed one layer at a time to the existing wall, taking care that the fixings do not overlie each other.

For therapy installations operating above 10 MV, shielding against neutrons must be considered. Concrete contains a relatively high hydrogen content and is therefore efficient at shielding against fast neutrons. The tenth value layer (TVL) for the primary X ray beam is approximately double that for the photoneutrons produced by medical linear accelerators, so any shield designed as a primary barrier against X rays will be more than adequate against photoneutrons.

The fast neutrons are reduced in energy by elastic scattering interactions with hydrogen. After a number of collisions they become slow neutrons, which undergo capture reactions with many materials and penetrating capture gamma rays are emitted. The capture gamma ray spectrum in concrete extends to greater than 8.0 MeV and the average energy is 3.6 MeV. The capture of slow neutrons by hydrogen in concrete results in a pronounced peak in the photon spectrum at 2.21 MeV.

Boron and cadmium have large cross-sections for the capture of slow neutrons. Boron is incorporated into polyethylene, which has high hydrogen content to form an efficient neutron shield. Slow neutron capture in the boron results in the production of a low energy gamma ray of 0.473 MeV. A 5% composition by weight of boron in polyethylene is commonly used in neutron shielding doors in treatment rooms.

5. CALCULATIONAL METHODS

The design philosophy for the radiation barriers will depend on the legal dose limits in force. At the present time the BSS [1] prescribe the dose limits. Government bodies have incorporated these standards in legislation. The dose limits set by the BSS [1], the USA [8], NCRP [9, 10] and the United Kingdom [7] relevant to barrier design for radiation treatment units are summarized in Table 2.

To determine the barrier thickness required to achieve the dose limits it is necessary to estimate the workload of the radiation unit and to know the dose rate at which the treatment unit will operate. The required barrier thicknesses will depend on achieving the dose limits and also the instantaneous dose rates. It is useful to determine the IDR at each point of interest (i.e. outside all primary and secondary barriers and the entrance), since these values can be compared with direct measurement at the radiation survey following the installation of the treatment unit.

5.1. PRIMARY BARRIERS

5.1.1. Weekly dose rate

The required attenuation of the barrier B may be determined according to a desired dose constraint (design limit) that is derived from an occupational or public dose limit. Reference [2] uses the following expression to determine the attenuation required by the barrier:

$$B = \frac{P(d + \mathrm{SAD})^2}{WUT} \tag{5}$$

where

- P is the allowed dose per week (Sv·week^{-1}) outside the barrier;
- d is the distance from the isocentre to the outside of the barrier, in m;
- SAD is the source–axis (isocentre) distance, in m;
- W is the workload, in Gy·week^{-1} at 1 m;
- U is the use factor or fraction of time that the beam is likely to be incident on the barrier;
- T is the occupancy factor or the fraction of time that the area outside the barrier is likely to be occupied (see Table 3).

The thickness of concrete required can be determined from attenuation graphs, or by the use of TVLs. The number of TVLs required to produce this attenuation is determined from:

$$\text{No. of TVLs} = \log_{10}\left(\frac{1}{B}\right) \tag{6}$$

Table 4 [2, 22] gives the TVLs for a range of megavoltage X ray energies in concrete (density 2350 kg·m^{-3})

5.1.2. Instantaneous dose rate

The barrier thickness required to reduce the IDR to an acceptable level on the far side of the barrier is determined as follows.

The attenuation required B_{IDR} is given by:

$$B_{\text{IDR}} = \frac{P_{\text{IDR}}\left(d + \text{SAD}\right)^2}{\text{DR}_0} \tag{7}$$

where

P_{IDR} is the instantaneous design dose limit, in Sv·h^{-1};
d is the distance from the isocentre to the point of interest on the far side of the barrier, in metres;
SAD is the source–axis (isocentre) distance (usually 1 m for linear accelerators);
DR_0 is the dose rate at the isocentre (1 m), in Gy·h^{-1}.

The number of TVLs of concrete is then determined from Eq. (6) in the same way as for the annual dose limit method.

Wall thicknesses determined for primary barriers will be more than adequate to shield against leakage and scattered radiation and no further calculations are required.

5.2. SECONDARY BARRIERS

These are the barriers that are not in the direct line of the radiation beam but are necessary to shield from leakage radiation from the treatment head and scatter from the patient (or phantom) and the treatment room walls.

5.2.1. Leakage radiation

For a linear accelerator, national and international protocols state that the leakage from the treatment head must not exceed 0.5% of the primary beam, outside the useful beam[8] at 1 m from the path of the electrons between the gun and target window and averaged over 100 cm^2. In the plane of the patient, the leakage must not exceed an average of 0.1% and a maximum of 0.2% over a 2 m radius measured from the beam central axis [19]. In general, manufacturers have protected their machines to better than 0.1%, and it would be reasonable to assume this value when determining the required secondary barrier thickness.

The required attenuation (B_L) to shield against leakage radiation is as follows:

$$B_L = \frac{1000 P d_s^{\,2}}{WT} \tag{8}$$

where

P is the design dose limit;
d_s is the distance from the isocentre to the point of interest in m;
W is the workload;
T is the occupancy factor.

Note that in determining protection against leakage radiation, the use factor (U) is always equal to unity and therefore does not appear in the equation. Since the use factor is unity the average position of the treatment head is taken to be at the isocentre so the distance d_s is measured from the isocentre. However, McGinley [14] has suggested a special case for d_s, for a linear accelerator with a horizontal wave guide for the barrier behind the

[8] Radiation which passes through the window, aperture, cone or other collimating device of the source housing. Sometimes called the “primary beam”.

accelerator. In this case, d_s should be measured from the gun end of the wave guide to the point just outside this secondary barrier since this barrier will be subjected to leakage radiation from the vicinity of the gun. In this example, it is assumed that the protection in the treatment head reduces the leakage radiation to 1/1000 of the useful beam (0.1%).

Leakage radiation has significantly lower energy than that of the primary beam due to scattering inside the treatment head, as demonstrated by the TVL data in Table 4.

5.2.2. Scattered radiation

The required barrier transmission (B_p) needed to shield against radiation scattered by the patient is given in Ref. [2] and in Eq. (9):

$$B_p = \frac{P d_{\text{sca}}^2 d_{\text{sec}}^2}{aWT\left(F/400\right)} \tag{9}$$

where

P, W and T have the same meaning as in Eq. (8).
d_{sca} is the distance from the radiation source to the patient, in m.
d_{sec} is the distance from the patient to the point of interest, in m.
a is the scatter fraction defined at d_{sca}. The scatter primary ratio (a) is dependent on the energy of the X ray beam and the scattering angle. These data are tabulated per 400 cm^2 of irradiated field area for ^{60}Co, 6, 10, 18 and 24 MV X ray beams in Table 5 [2, 20].
F is the field area incident on the patient, in cm^2.

Radiation scattered by a patient or phantom is usually less than 0.1% of the incident radiation per 0.1 m^2 area irradiated. For large scatter angles, the energy of the scattered radiation will be degraded and the protection designed against leakage radiation should provide adequate protection against scattered radiation from the patient. However, when the scatter angle is small, patient scatter should not be ignored. For small scatter angles (10°), the value of the scatter fraction a may be as high as 0.0178 for 24 MV X rays (Table 5) and the scattered photons have energies close to that of the incident beam.

The barrier transmission factor (B_w) needed to shield against scattered radiation when the primary beam strikes a wall is given by the following equation:

$$B_w = \frac{P d_w^2 d_r^2}{\alpha A W U T} \quad (10)$$

where

d_w is the distance from the radiation source to the scattering surface (wall), in m;
d_r is the distance from the scattering surface (wall) to the point of interest, in m;
α is the wall reflection coefficient, which depends on the wall material, scattering angle, and beam energy (Tables 6 and 7 give reflection coefficients from concrete);
A is the field area projected on the scattering surface (wall), in m^2.

The photons scattered by the wall and by the patient are of about the same energy. If the thickness required to shield from patient scatter is different from that needed to shield from wall scatter by one TVL or more, use the larger thickness, otherwise, use the larger thickness and add one-half value layer (HVL).

If the thickness required to protect from leakage differs from that required to protect from scatter by less than one TVL, use the greater thickness and add one HVL of shielding material for the energy of the leakage radiation. If the two thicknesses for leakage and scatter protection differ by more than one TVL use the greater thickness.

5.3. ROOFS

The roof section that can be struck directly by the radiation beam must be a primary barrier and the formulas used to determine the required thickness are the same as those in Section 5.1 (Eqs (5)–(7)). The design dose limit for the roof will depend on the location of the bunker. If it is a single storey building, then the only consideration may be the limitation of access to the roof space. However, if the building is overlooked, then the effect of skyshine must be considered which may result in the irradiation of nearby buildings. If there is a nuclear medicine department nearby, then it should be noted that gamma cameras and possibly other imaging equipment are particularly sensitive to low levels of radiation that can affect certain patient investigations. If the building has further floors above the bunker, then consideration should be given to locating a storage room or plant room immediately above the bunker. (A plant room is used to house the chiller unit for the linear accelerator or heating and

ventilation system plant.) A storage room or plant room will have limited occupancy and access can be restricted, thus allowing a greater design dose limit than if an office was placed directly above the bunker.

5.4. MAZES

A knowledge of the scattering characteristics of X rays (and gamma rays for ^{60}Co sources) by the patient and walls of the room is required when designing a maze or duct. For X ray units operating below 10 MV and ^{60}Co units, the scatter and transmission of primary, leakage and scattered radiation must be considered. For units operating above 10 MV the neutron fluence must be considered (see Section 5.6).

For the equipment arrangement in Fig. 1, where the gantry rotation axis is perpendicular to the maze axis, the total dose at the maze entrance D_d will be given by:

$$D_d = \sum_G D_p + \sum_G f \times D_w + \sum_G D_L + \sum_G D_T \qquad (11)$$

where

$\sum_G$ integrates through all gantry angles;
D_p is the dose arising from patient scatter;
f is the primary radiation transmitted through the patient;
D_w is the primary radiation scattered by the wall into the maze;
D_L is the leakage radiation scattered down the maze;
D_T is the leakage radiation transmitted through the maze wall.

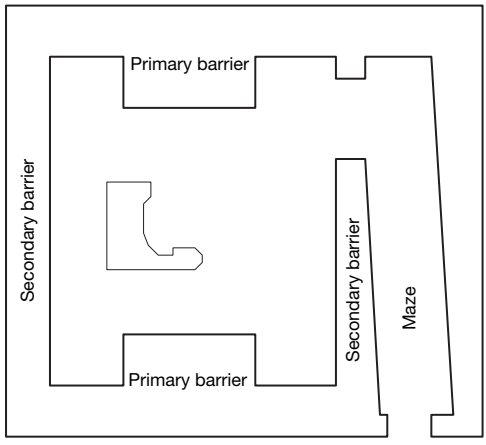

FIG. 1. Typical room layout where the gantry rotation axis is perpendicular to the maze axis.

When the gantry rotation axis is parallel to the maze axis (Fig. 2) the expression will take the form:

$$D_d = \sum_G D_p + \sum_G f \times D_{wT} + \sum_G D_L + \sum_G D_T \quad (12)$$

where the symbols have the same meaning as those in Eq. (11) except that in this instance D_{wT} will be the primary radiation transmitted through the maze wall and further scattered to the maze entrance.

Equations (11) and (12) are used to determine the total dose at the maze entrance. However, they may also be used to determine the IDR. The equations that follow are used to determine the dose contributions from the different components. If the values of the workload (W) and the use factor (U) in these equations are replaced with DR_0 (the absorbed dose rate in $Gy \cdot h^{-1}$ at 1 m from the radiation source), then the result is the IDR at the maze entrance.

5.4.1. Dose arising from scatter by patient D_p

Report NCRP 51 [11] gives an approximate expression to calculate the scatter at the end of the maze for X rays below 10 MV. Figure 3 shows the scatter path along the maze (denoted by the solid lines), with normal incidence on five reflecting walls with 90° reflection from each surface. The maze funnels the scatter along each leg of the maze. It is also possible to draw the scatter path shown by the dashed lines in the figure, which has only two scatters along the maze with the angle of incidence and reflection at each surface being nominally 45°. (For the dashed scatter path the areas of the reflecting surfaces will be

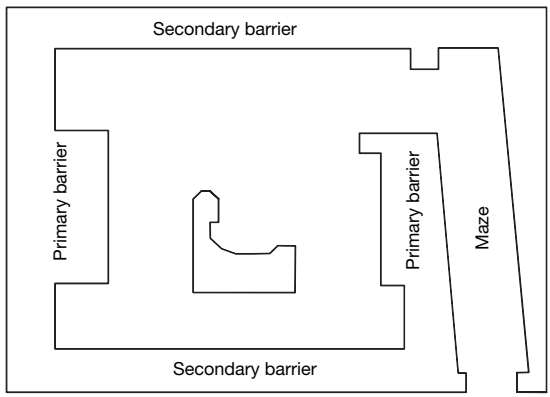

FIG. 2. Typical room layout where the gantry rotation axis is parallel to the maze axis.

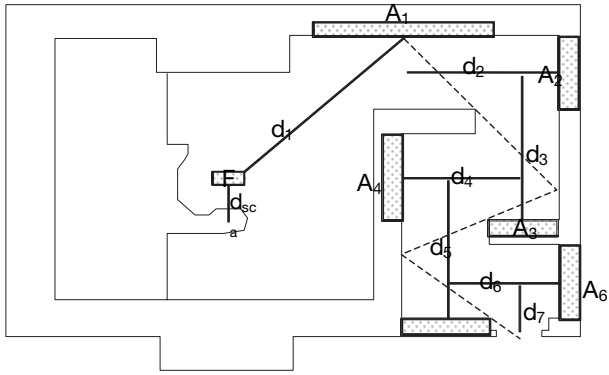

FIG. 3. Schematic diagram to show the scatter paths to the maze entrance.

different from those indicated in Fig. 3). In practice, it has been demonstrated that the measured dose lies between the answers given by these two methods.

In the NCRP [11] formalism, the first scatterer is taken to be the wall but a better approximation is obtained if the patient is taken to be the first scatterer. The dose D_p at the maze entrance due to patient scatter may be determined from Eq. (13). This equation is valid for any placement of the machine within the treatment room, i.e. the gantry rotation axis either perpendicular or parallel to the maze axis:

$$D_p = \frac{WU_0 a(F/400)(\alpha_1 A_1)\cdots(\alpha_{n-1}A_{n-1})}{(d_{\text{sca}} \times d_1 \cdots d_n)^2} \tag{13}$$

where

W is the workload, in Gy·week^{-1};

U_0 is the use factor (usually assumed to be 0.25 for each of the four cardinal beam directions).

a is the scatter primary ratio at the patient (phantom). These values are tabulated per 400 cm^2 incident field area on the patient (Table 5).

α_1, etc., are the wall reflection coefficients for 0.5 MeV X rays (assumed to be the same energy for all subsequent scattering processes) (Tables 6 and 7).

F is the field area incident on the patient, in cm^2.

A_1, etc., are the areas of wall that scattered radiation can strike and be reflected down the maze. Subsequent areas are taken to be the cross-sectional area of the maze.

d_{sca} is the distance of the radiation source from the patient, in metres.
$d_1 \ldots d_n$ are the distances to the next scattering surface, and subsequently the length of each leg of the maze, in m.

5.4.2. Dose arising from the primary beam scattered by the wall D_w

When the gantry rotation axis is perpendicular to the maze, the dose D_w will result from the primary beam being scattered from wall H into the maze.

In Fig. 4, the dose arising from the primary beam scattered by wall H down the maze D_w is given by:

$$D_w = \frac{WU_H}{d_H^2} \times \frac{\alpha_H A_H \alpha_r A_r}{d_r^2 \times d_z^2} \tag{14}$$

where

W is the workload, in Gy·m^2 per week;
U_H is the use factor for wall H, usually assumed to be 0.25;
α_H is the reflection coefficient from wall H;
A_H is the area of the maximum field size projected onto wall H, in m^2;
α_r is the wall reflection coefficient at r;
A_r is the cross-sectional area of the inner maze opening, in m^2;

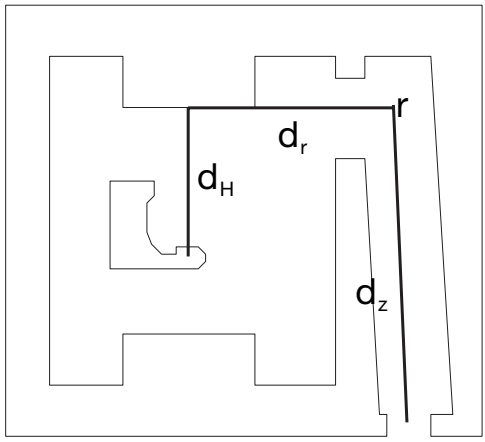

FIG. 4. Schematic diagram showing the scatter path for the primary radiation beam to the maze entrance (gantry rotation axis perpendicular to the maze axis).

d_H is the distance from the radiation source to wall H, in m;
d_r is the distance from where the central axis of the radiation beam strikes wall H to the centre of the maze opening r, in m;
d_z is the distance from point r to the maze entrance, in m.

When the gantry rotation axis is parallel to the maze axis the dose D_{wT} will arise from the primary beam transmitted through the maze wall to the maze entrance, as shown in Fig. 5.

$$D_{wT} = \frac{WU_m B_{pr} \alpha_P A_P}{\left(d_P d''\right)^2} \tag{15}$$

where

W is the workload, in Gy·m^2 per week;
U_m is the use factor for the beam directed at the maze wall (usually 0.25);
B_{pr} is the transmission of the primary through the maze wall;
d_P is the distance from the source to the centre of wall P;
d is the distance from the centre of wall P to the maze entrance;
α_P is the wall reflection coefficient at P;
A_P is the area of maximum field size projected to wall P, in m^2.

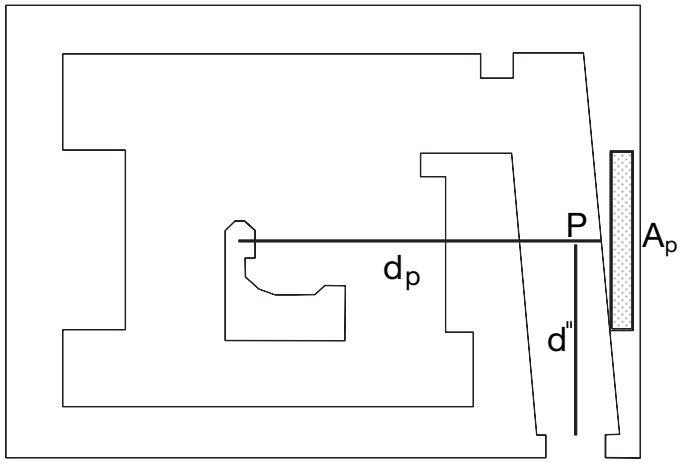

FIG. 5. Schematic diagram showing the scatter path for the primary radiation beam to the maze entrance (gantry rotation axis parallel to the maze axis).

For either orientation of the gantry rotation axis only a fraction of the primary radiation will be transmitted through the patient. The patient transmission f is taken as the percentage depth dose for a 10 cm × 10 cm field at a depth of 30 cm. These values are tabulated in Table 8 [21].

For a multi-leg maze as shown in Fig. 3, Eqs (14) and (15) may be modified by multiplying them with factors $(\alpha_j A_j / d_j^2)$ for legs j = 3 to 6 similar to Eq. (13).

5.4.3. Dose arising from head leakage scatter to the maze entrance D_L

The dose at the maze door in Fig. 6 due to scattered head leakage D_L is given by:

$$D_L = \frac{L_0 W \alpha_1 A_1}{\left(d_i d_m\right)^2} \tag{16}$$

where

L_0 is the fraction of the dose due to head leakage at 1.0 m from the radiation source relative to the dose on the beam axis at one metre (this is usually at the isocentre);

W is the workload, in Gy·m^2 per week;

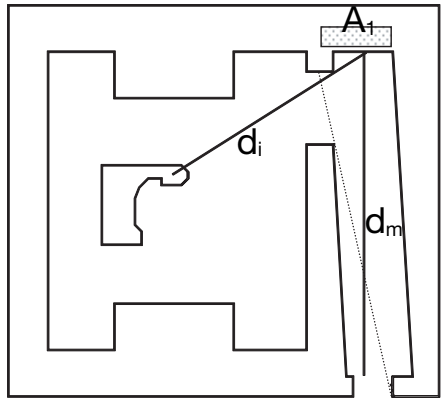

FIG. 6. Schematic diagram showing the path of scattered head leakage to the maze entrance.

α_1 is the wall reflection coefficient;
A_1 is the area of wall that can be seen from the maze entrance;
d_i is the distance from the radiation source to the maze centreline;
d_m is the centreline distance along the maze.

As with Eq. (13), this equation is valid for any machine placement within the treatment room. The fraction of dose due to head leakage is assumed to be 0.001 (0.1 %), and the energy of the head leakage radiation may be taken as 1.4 MeV for 6 MV X rays and 1.5 MeV for 10 MV X rays [22].

Again, for a multi-leg maze as shown in Fig. 3, Eq. (16) may be modified by multiplying with factors ($\alpha_j A_j / d_j^2$) for legs j = 3 to 6 similar to Eq. (13).

5.4.4. Head leakage transmission to the maze entrance D_T

In Fig. 7, the radiation dose at the maze entrance due to head leakage transmitted through the maze wall will be given by:

$$D_T = \frac{L_0 WB}{\left(d_t\right)^2} \tag{17}$$

where

d_t is the distance from the radiation source to the maze entrance;
B is the transmission through the maze wall.

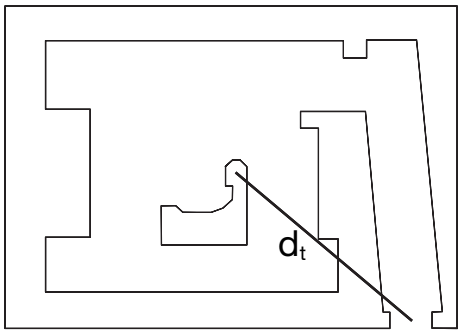

FIG. 7. Schematic diagram showing the path of head leakage radiation transmitted through the maze wall to maze entrance.

This equation is applicable whether the gantry rotation axis is parallel or perpendicular to the maze axis (see Eqs (13) and (16)). Where the maze wall is a primary barrier this contribution should be negligible.

There is a special case when the gantry rotation axis is perpendicular to the maze axis, the room has a moderately long maze and the use factor can be assumed as 0.25 for the four major beam directions. The total photon dose at the maze entrance will be the product of 2.64 and the sum of the doses for the worst case scenario. In Fig. 4, this will be when the beam is directed at wall *H*. (Note that the use factor 0.25 should be applied to all four components, including the leakage dose D_{LH}.)

$$D_d = 2.64\left(D_{pH} + f \times D_{wH} + D_{LH} + D_{TH}\right) \tag{18}$$

where

f is the patient transmission factor described earlier in this section and tabulated in Table 8.

In the United Kingdom, the IDR at the maze entrance for each gantry angle would be calculated. This is achieved by substituting the dose rate DR_0 at 1 m (usually the isocentre) for the workload (*W*), use factor (*U*) and occupancy (*T*) in the above equations. The suitability of the maze design would be assessed on the IDR for the worst case scenario. The aim would be to reduce the IDR at the maze entrance to 7.5 $\mu\mathrm{Sv}\cdot\mathrm{h}^{-1}$or less for the worst case.

The methods described in this section are also valid for accelerators with energies greater than 10 MV. However, the presence of photoneutrons and capture gammas must also be taken into account and this is described in Section 5.7.

5.5. DOORS

Once the dose at the end of the maze has been calculated the necessity or otherwise of a door for radiation safety purposes can be ascertained. This will depend on the design dose limit in force. In the United Kingdom the guidance [6] is to designate the area as controlled if the IDR exceeds 7.5 $\mu\mathrm{Sv}\cdot\mathrm{h}^{-1}$, and as supervised if the TADR is less than 7.5 $\mu\mathrm{Sv}\cdot\mathrm{h}^{-1}$ with a maximum IDR of 500 $\mu\mathrm{Sv}\cdot\mathrm{h}^{-1}$. For a controlled area the annual design dose limit is 6 mSv per year in the United Kingdom [7] or, in the USA, the NCRP recommends a fraction of 10 mSv per year [9]. For a public area the design dose limit is 0.3 mSv per year in the United Kingdom and the NCRP recommends 1 mSv per year in the USA [10].

In the United Kingdom an unsupervised or public area should have a TADR of less than 0.5 μSv·h^{-1} with a maximum IDR of 7.5 μSv·h^{-1} [6]. Dividing the chosen design dose limit by the calculated value of dose at the end of the maze will give the attenuation required in a door. The data to determine the required TVL of lead are tabulated in Table 4. If a protected door is not required it is still recommended to have a physical barrier at the maze entrance such as a gate to discourage entry. Also, it is recommended that ^{60}Co unit installations should have lockable doors so that access may be restricted outside normal hours of use (see also Section 3.11).

5.6. NEUTRONS IN HIGH ENERGY LINEAR ACCELERATOR ROOMS

Neutron production becomes important in high energy medical linear accelerators (linacs) above 10 MV. Photoneutrons are produced when photons interact with the collimators, the target, the flattening filter and other material along the path of the electron and the photon beam. The lead, tungsten, and other high atomic number (Z) materials in the head are effective photon shields, but not for neutrons. Although, due to (n, $2n$) and (n, p) interactions, and other inelastic scattering, the heavy metals do provide shielding effects by lowering the average energy of the neutrons.

The neutron fluence at any point in the room is composed of direct neutrons φ_d, scattered neutrons φ_{sc}, and thermal neutrons φ_{th}. McCall et al. [23] have shown that the direct neutron fluence is given by:

$$\varphi_d = \frac{Q_N}{4\pi d^2} \tag{19}$$

where

d is the distance from the source to the point of interest.

Q_N is the apparent neutron source strength in number of neutrons emitted from the shielded accelerator head per unit dose of photon delivered to the isocentre. Q_N is related to the neutron source strength Q, and is equal to Q for head shielded with lead, and $0.85Q$ for the head shielded with tungsten.

The scatter neutron fluence is given by:

$$\varphi_{sc} = \frac{5.4 Q_N}{S} \tag{20}$$

where

S is the surface area of the treatment room excluding the maze area.

The surface area S is the sum of all wall areas visible from the isocentre. Where primary barriers protrude into the treatment bunker, they will reduce the wall area exposed to neutrons. In these cases the surface area is better approximated by using the average of the maximum and minimum room dimensions to determine the surface area. Example 10 in Section 6.3 illustrates the method used in obtaining S.

McCall [24] reported that in a concrete room where an accelerator is located, the thermal neutron fluence is given by:

$$\varphi_{th} = \frac{1.26\, Q_N}{S} \tag{21}$$

Combining all three components, the total neutron fluence at a distance d per unit photon dose at isocentre is given by:

$$\varphi = \varphi_d + \varphi_{sc} + \varphi_{th} \tag{22}$$

For medical linear accelerators with energy range of 10–25 MV, values of the neutron source strength are available in the published literature, and are tabulated in Table 9 [14, 29].

The neutron fluence is related to the neutron dose equivalent (rem),[9] but the conversion factor is dependent on the neutron energy. McCall et al. [28] provided a 'cookbook method' to obtain the average neutron energy. The dose equivalent can then be obtained from the neutron fluence, using tabulated conversion factors. A method for determining the average neutron energy is described in Ref. [26]. However, for linear accelerators in the energy range between 10 MV and 25 MV, the average energy of direct neutrons exiting the shielded head is never much above 1 MeV, and the average energy of neutrons scattered by the room is about 0.24 MeV [26]. Based on the method described in Ref. [26] the average neutron energy excluding thermal neutrons is about 0.34 MeV.

[9] 1 rem = 1.00×10^{-2} Sv.

Fast neutrons are attenuated efficiently by materials with high hydrogen content. Concrete has a relatively high hydrogen content (water content is 4–5% by weight) and the TVL of 0.34 MeV photoneutrons in concrete is about 210 mm. This is about half the value of TVL in concrete for high energy X rays (10–25 MeV), which is 400–500 mm. Therefore, if the shielding is adequate for photons it will also be adequate for neutrons. However, although different densities of concrete affect the photon transmission they do not affect the transmission of neutrons so a TVL of 210 mm in concrete must be used regardless of its density. The neutron leakage specifications of all major medical linear accelerators are below 2–3 mSv per isocentre photon Gy, and the photon leakage specification used in room shielding calculations is 1 mGy per isocentre photon Gy (0.1%). Therefore, as long as the concrete shielding designed for photon leakage protection is at least one TVL, the same shielding will attenuate the neutron leakage to below the level of photon leakage.

If heavy metal or high atomic number (Z) materials are used for room shielding, adequate photon shielding does not automatically imply adequate neutron shielding. If lead or iron are incorporated in all or part of the shielding, a moderator material will be necessary to capture the neutrons slowed down in the metal. Careful evaluation for neutron shielding must be performed to ensure safety. This evaluation may be complex and is outside the scope of this report. The reader should seek expert advice.

5.7. CAPTURE GAMMA AND NEUTRON DOSES AT THE MAZE ENTRANCE

A typical linear accelerator treatment room utilizes a maze design to reduce the dose at the outer entrance so that heavy door shielding is not necessary. This is particularly important for high energy accelerators above 10 MV because of scatter neutrons and the capture gamma photons generated by neutrons interacting with the maze door and the maze walls.

The dose at the outer maze entrance may be obtained by evaluating the three major components: the scatter and leakage photon dose, the capture gamma dose, and the neutron dose.

The scatter and leakage photon dose may be estimated using methods described in Section 5.4. This is the most significant component for accelerators with energy lower than 10 MV. For higher accelerator energies the capture gamma and neutron dose components dominate as they increase rapidly with accelerator energy.

McGinley [14] developed methods to estimate the capture gamma and neutron dose component for a typical accelerator room shown in Fig. 8 and these are described in Sections 5.7.1 and 5.7.2.

5.7.1. Capture gamma dose

In Fig. 8, the capture gamma dose in the maze D_{φ} is dependent on the maze length d_2 and the total neutron fluence φ_A at the inner maze point A. The inner maze point A is the point of intersection of the centreline of the maze, and the line joining the isocentre and the end of the maze wall, at 1 m above floor level. Figure 8 shows the location of point A.

The total neutron fluence φ_A at the inner maze point A may be estimated from the apparent neutron source strength Q_N, the distance d_1 (in m) from the average position of the source to the inner maze point A, and the surface area of the treatment room S (in m^2). The total neutron fluence is the sum of the direct neutrons from the head of the accelerator, the scatter neutrons and the thermal neutrons, as shown in Eq. 23 [27]:

$$\varphi_{\mathrm{A}} = \frac{Q_N}{4\pi d_1^{\,2}} + \frac{5.4Q_N}{2\pi S} + \frac{1.26Q_N}{2\pi S} \tag{23}$$

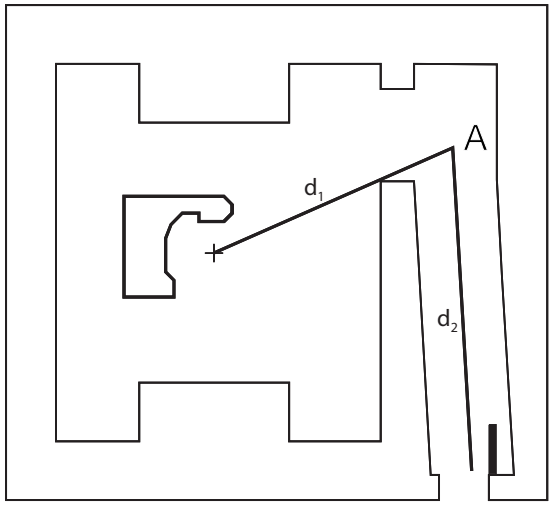

FIG. 8. A typical accelerator room with a maze, showing the distances used to determine the capture gamma dose.

where

φ_A is the total neutron fluence at the inner maze point *A,* in $n \cdot m^{-2}$ per X ray·Gy at 1 m (for high energy machines the isocentre is assumed to be at 1 m in the following formalism);
Q_N is the neutron source strength as given in Table 9;
d_1 is the distance from the isocentre to the inner maze point *A,* in m;
S is the surface area of the treatment room, in m^2.

The fraction ½π in the second and third term is necessary to account for the fact that only a fraction of the room surface can contribute to the neutron fluence at point *A* [28].

Once the total neutron fluence φ_A at the inner maze point has been determined, the capture gamma dose D_φ is determined as follows:

$$D_\varphi = 5.7 \times 10^{-16} \times \varphi_A \times 10^{-\frac{d_2}{6.2}} \tag{24}$$

where D_φ is the capture gamma dose, in Gy per isocentre photon·Gy for a maze length of d_2 in m [29].

The weekly dose equivalent due to capture gamma, in $Sv \cdot week^{-1}$, is the product of the workload and D_φ:

$$D_c = W \times D_\varphi \tag{25}$$

where W is the weekly workload, in $Gy \cdot m^2$.

5.7.2. Neutron dose

At the maze entrance, the neutron dose equivalent is usually the dominant component for high energy accelerators above 10 MV. The neutron dose at any point in the maze depends on several factors, including the distance from the inner maze point A to the isocentre (d_1), the surface area S of the treatment room, the inner maze entrance cross-sectional area (A_r) and the cross-sectional area of the maze (S_1). It is also a function of the energy, the gantry angle and the field size of the photon beam.

At the inner maze point A (shown in Fig. 8), Eq. (23) gives the total neutron fluence, which is a function of d_1, S and Q_N. To reduce the neutron fluence at A, a longer distance d_1, or a smaller inner maze entrance area A_r, may be chosen when designing the room. A larger room size will also reduce the neutron dose at A.

Neutron dose decreases along the maze with a tenth value length (T_N) of 5–7.5 m for many medical accelerator rooms. The value of T_N depends on the cross-sectional area of the maze. A smaller cross-sectional area will allow more interactions between the neutron and the wall, and thus reduces the dose measured at the maze entrance, and the tenth value length.

The neutron dose in the maze is highest at the gantry angle when the head of the accelerator is closest to the inner maze entrance. This is because the neutrons produced leave the head in all directions as the high Z head shielding material has little effect in stopping them. The lowest dose is found when the gantry head is farthest away, even when the photon beam may be pointing at the direction of the inner maze entrance. It is not unusual to see a difference of a factor of 2 in dose between the two gantry angles. When the beam is pointing downward, the dose is slightly higher than the average of the two extreme cases [29]. For shielding calculation purposes, it is considered appropriate to use the neutron dose data with the beam pointing down.

Smaller field sizes will result in a higher neutron dose at any point down the maze at a distance more than 1 m from point A. Comparing the doses at the same point with the beam set at the largest and smallest field sizes, the difference is about 10–20% for a maze of the design described in this publication [29]. Therefore, for conservative reasons, collimators are assumed to be at the fully closed position when making neutron dose estimates.

McGinley and Butker [30] evaluated the neutron dose equivalent at the maze entrance of a number of high energy medical accelerator facilities, and compared their results with the empirical method developed by Kersey [31]. They found that Kersey's method in general produced higher dose estimates, and therefore it is conservative in nature for purposes of shielding requirement calculations. Kersey's method gives the neutron dose equivalent at the maze entrance as follows:

$$D_n = H_1 \times 10^{-3} \times (A_r / S_1) \times (1/d_1)^2 \times 10^{-d_2/5} \tag{26}$$

where

- D_n is the neutron dose equivalent at the maze entrance, in Sv per X ray·Gy at the isocentre.
- H_1 is the neutron dose equivalent at 1 m from the X ray source (target) in mSv per X ray·Gy at the isocentre. Values of H_1 are tabulated in Table 10.
- A_r and S_1 are cross-sectional areas, in m^2, of the inner maze entrance and the maze, respectively.

d_1 is the distance, in m, from the isocentre to the inner maze point A as defined above.
d_2 is the distance, in m, from the inner maze point A to the outer entrance of the maze.

For a maze with an additional bend as shown in Fig. 9, the dose at the maze entrance is given by the equation below [14]:

$$D_n = H_1 \times 10^{-3} \times (A_r / S_l) \times (1/d_2)^2 \times (10^{-d_2/5}) \times (10^{-d_3/5}) \times (1/3) \qquad (27)$$

where

d_2 is the distance, in m, from point A to point B in Fig. 9;
d_3 is the distance, in m, from point B to the maze entrance.

From this equation it is evident that the addition of a bend in the maze design reduces the neutron dose at the maze entrance by a factor of 1/3 for the same total maze length. This is because the majority of the neutrons will encounter more collision interactions with the maze wall before exiting the maze entrance. This reduction will not hold if one of the maze bends is too short, or the cross-sectional area of the maze or the maze entrance is too large. The reader is cautioned to evaluate the specific situation for the validity of the equation.

For accelerator facilities having a structural design similar to the one shown in Fig. 8, the neutron dose equivalent may be obtained using an alternative method developed by Wu and McGinley [29]. They found that the neutron dose decreases along the maze with a tenth value length proportional to the square root of the cross-sectional area of the maze:

$$T_N = 2.06 \times \sqrt{S_1} \qquad (28)$$

where

T_N is the tenth value length, in m;
S_1 is the cross-sectional area of the maze, in m.

Wu and McGinley [29] also found that the neutron dose equivalent at a point along the maze is given by the equation:

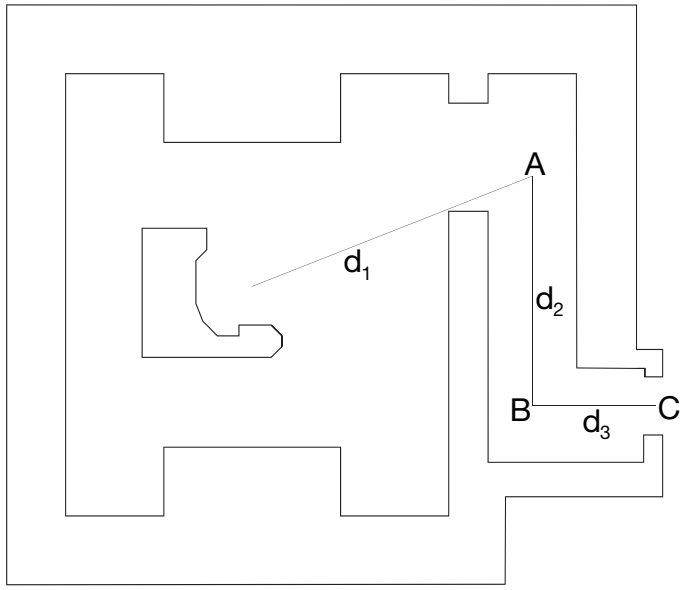

FIG. 9. Room with two bends in the maze showing distances used to determine the capture gamma dose.

$$D_n = 2.4 \times 10^{-15} \times \varphi_A \times \sqrt{A_r / S_1} \times \left[1.64 \times 10^{-\left(\frac{d_2}{1.9}\right)} + 10^{-\left(\frac{d_2}{T_N}\right)} \right] \tag{29}$$

where

D_n is the neutron dose equivalent at the maze entrance, in Sv per X ray·Gy at isocentre;

φ_A is the neutron fluence given by Eq. (23).

Equations (26), (27) and (29) all give reliable dose equivalent estimates. Equation (27) usually produces more conservative estimates for shielding purposes. For treatment room designs of exceptional size, or mazes of exceptional width or length, Eq. (29) will produce more accurate results. The reader is advised to evaluate the merits of both equations before choosing the value to obtain the estimated weekly dose due to neutrons.

The weekly dose due to neutrons is given by the following equation:

$$D_E = W \times D_N \tag{30}$$

where

D_E is the weekly dose equivalent due to neutrons, in Sv·week^{-1};
W is the weekly workload (Gy·m^2).

The total weekly dose D_W at the external maze entrance is the sum of all three components: D_d from Eq. (18), D_c from Eq. (25) and D_E from Eq. (30):

$$D_W = D_d + D_c + D_E \tag{31}$$

5.7.3. Maze door design

The door design for shielding against the scatter and leakage photons reaching the maze door is described in Section 5.7. For high energy accelerators, the scatter and leakage dose is relatively low compared with the other two components (capture gamma and neutron). The average energy of capture gamma radiation is 3.6 MeV [14], and could be up to about 10 MeV [26] for very short mazes. The thickness of lead is determined using a TVL of 61 mm [26]. For rooms with a maze length greater than 5 m, the energy of the gamma rays is much lower, requiring a TVL of about 6 mm lead [31]. The average neutron energy at the maze entrance is about 100 keV for all accelerators. The TVL in polyethylene is 45 mm [26]. Borated polyethylene (5% wt) is only a little more effective in fast neutron shielding, but is much more effective for thermal neutrons compared with polyethylene without boron. The TVL is 38 mm for 2 MeV neutrons, and 12 mm for thermal neutrons as reported in some publications. For purposes of maze door shielding, it is recommended that 45 mm be used in calculating the borated polyethylene (BPE) thickness requirement.

Many accelerator rooms with adequate maze length will require 6–12 mm lead, and 20–40 mm BPE for shielding to below the design limit. The usual arrangement is to sandwich the BPE between two layers of lead. The lead on the radiation side of the BPE is to reduce the energy of the neutrons by non-elastic scattering, and hence making the BPE more effective in neutron shielding. The lead on the outside of the BPE will serve to attenuate the capture gamma radiation from the BPE of 0.473 MeV in energy.

Accelerator rooms with short maze length will require much thicker lead and BPE. This is because the capture gamma produced by neutron interaction with concrete has an average energy of 7.2 MeV, with highest energy up to 10 MeV [32]. The TVL for this energy range is 61 mm lead. Furthermore, neutrons at the entrance of short mazes are of higher energies and less thermalized, requiring as much as three times the thickness of BPE for

shielding. For more information on short maze and direct shielded door constructions, the reader is referred to other publications [13, 26].

An accelerator room with a long maze similar to that shown in Fig. 1 will require a relatively light door as shown in Section 6.3.3.4, Example 12, and Sections 9.3.7 and 9.3.8, Examples 7 and 8. Neutron shielding accounts for most of the weight of the door. To design a treatment room that requires less door shielding, one can consider increasing the length of the maze, reducing the area of the inner maze opening, and adding a bend to the maze. Other ways to reduce the door shielding requirements include applying BPE in maze walls to reduce neutron dose [33], and adding an inner maze door that can be closed when high energy radiation is used [29].

5.8. DATA

TABLE 2. SUMMARY OF RECOMMENDED/LEGAL EFFECTIVE DOSE LIMITS AND DESIGN EFFECTIVE DOSE LIMITS

Dose limit	IAEA [1]	USA	United Kingdom
Occupational exposure dose limit	20 mSv per year averaged over 5 consecutive years and 50 mSv in any single year	Implied annual limit of 10 mSv, cumulative dose of age × 10 mSv, and 50 mSv in any single year [9]	20 mSv in a year or 100 mSv in 5 consecutive years and 50 mSv in any single year [7]
Design limit for occupational exposure		Fraction of 10 mSv annually [9]	6 mSv in a year [7] IDR is 7.5 $\mu Sv \cdot h^{-1}$ [6]
Public dose limit	1 mSv in a year	Infrequently, 5 mSv annually, and continually, 1 mSv annually [9]	1 mSv in a year [7]
Design limit for public area		1 mSv annually [10] 20 μSv in any hour [8]	0.3 mSv in a year [7] IDR is <7.5 $\mu Sv \cdot h^{-1}$ [6] TADR is <0.5 $\mu Sv \cdot h^{-1}$[6] TADR2000 <0.15 $\mu Sv \cdot h^{-1}$ [6]

TABLE 3. DIFFERENT SUGGESTED OCCUPANCY FACTORS (*T*)
(*whenever possible, the local situation should be assessed before determining the occupancy factor to be used*)

Type of area	NCRP 49 [2]	BIR/IPEM 2000 [12]
Offices, reception areas, laboratories, shops, children's play areas, nurse's stations, staff rooms Control room	1	1
Wards, patient rooms	1	0.2
Patient examination and treatment rooms	—	0.5
Corridors	1/4	0.2
Toilets, bathrooms, outside areas with seating	1/16	0.1
Stairways, unattended waiting rooms, store rooms (not film)	1/16	0.05

TABLE 4. TENTH VALUE LAYER (TVL) FOR ^{60}Co AND X RAY ENERGIES
(*approximate values based on large attenuation*)

	Co-60[a]	4 MV[b]	6 MV[b]	10 MV[b]	15 MV[b]	18 MV[b]	20 MV[b]	24 MV[b]
TVL for concrete (density 2350 kg · m^{-3}) (in mm)								
Primary beam gamma/ X rays	218	290	343	389	432	445	457	470
Leakage gamma and X rays (90°)	218	254	279	305	330	330	343	356
TVL for steel (density 7800 kg · m^{-3}) (in mm)								
Primary beam gamma/ X rays	71	91	98	105	108	111	111	107
Secondary beam gamma/ X rays	69	79	80	85	87	87	88	89
TVL for lead (density 11360 kg · m^{-3}) (in mm)								
Primary beam gamma/ X rays	41	53	55	56	57	56	55	52
Secondary beam gamma/ X rays	40	47	45	46	47	47	49	51

[a] Cobalt-60 data from Ref. [2].
[b] Adapted from Varian Associates. The TVL of leakage X rays is based on calculations by Nelson and LaRiviere [22].

TABLE 5. SCATTER FRACTIONS OF DOSE *a*, AT 1 m, FOR A 400 cm^2 INCIDENT BEAM

Angle (degree)	Co-60[a]	6 MV[b]		10 MV[b]		18 MV[b]		24 MV[b]	
		Max *a*	*a* at 1.5 cm	Max *a*	*a* at 2.5 cm	Max *a*	*a* at 2.5 cm	Max *a*	*a* at 2.5 cm
10	1.1×10^{-2}	1.68×10^{-2}	1.04×10^{-2}	1.69×10^{-2}	1.66×10^{-2}	2.43×10^{-2}	1.42×10^{-2}	2.74×10^{-2}	1.78×10^{-2}
20	8.0×10^{-2}	1.15×10^{-2}	6.73×10^{-3}	1.03×10^{-2}	5.79×10^{-3}	1.17×10^{-2}	5.39×10^{-3}	1.27×10^{-2}	6.32×10^{-3}
30	6.0×10^{-3}	5.36×10^{-3}	2.77×10^{-3}	6.73×10^{-3}	3.18×10^{-3}	7.13×10^{-3}	2.53×10^{-3}	7.21×10^{-3}	2.74×10^{-3}
45	3.7×10^{-3}	2.97×10^{-3}	1.39×10^{-3}	3.25×10^{-3}	1.35×10^{-3}	3.05×10^{-3}	8.64×10^{-4}	3.06×10^{-3}	8.30×10^{-4}
60	2.2×10^{-3}	1.74×10^{-3}	8.24×10^{-4}	1.84×10^{-3}	7.46×10^{-4}	1.42×10^{-3}	4.24×10^{-4}	1.37×10^{-3}	3.86×10^{-4}
90	9.1×10^{-4}	7.27×10^{-4}	4.26×10^{-4}	7.14×10^{-4}	3.81×10^{-4}	3.75×10^{-4}	1.89×10^{-4}	3.53×10^{-4}	1.74×10^{-4}
135	5.4×10^{-4}	4.88×10^{-4}	3.00×10^{-4}	3.70×10^{-4}	3.02×10^{-4}	2.59×10^{-4}	1.24×10^{-4}	2.33×10^{-4}	1.20×10^{-4}
150	1.5×10^{-4}	3.28×10^{-4}	2.87×10^{-4}	3.16×10^{-4}	2.74×10^{-4}	2.26×10^{-4}	1.20×10^{-4}	2.12×10^{-4}	1.13×10^{-4}

[a] Values are measured data in Ref. [2].

[b] Computed data from Monte Carlo simulations [20]. The measured values quoted in Ref. [2] fall between the computed surface values and at a depth, demonstrating the difficulty of measuring the scatter primary ratio.

TABLE 6. DIFFERENTIAL DOSE ALBEDO (WALL REFLECTION COEFFICIENT) 45° INCIDENT ANGLE, ORDINARY CONCRETE [34]

	Angle of reflection (from normal)			
	75	45	15	0
24 MV	3.37E-03	3.91E-03	3.91E-03	3.74E-03
20 MV	3.75E-03	4.20E-03	4.14E-03	3.95E-03
18 MV	4.01E-03	4.41E-03	4.32E-03	4.11E-03
15 MV	4.48E-03	4.78E-03	4.56E-03	4.34E-03
10 MV	5.75E-03	5.75E-03	5.38E-03	5.10E-03
6 MV	7.69E-03	7.35E-03	6.71E-03	6.35E-03
4 MV	9.36E-03	9.01E-03	8.19E-03	7.77E-03
Co-60	1.26E-02	1.19E-02	1.07E-02	1.02E-02
0.5 MeV	1.70E-02	2.15E-02	2.10E-02	2.03E-02
0.25 MeV	1.82E-02	3.05E-02	3.50E-02	3.39E-02

TABLE 7. DIFFERENTIAL DOSE ALBEDO (WALL REFLECTION COEFFICIENT) NORMAL INCIDENCE, ORDINARY CONCRETE [34]

	Angle of reflection (from normal)				
	75	60	45	30	0
24 MV	1.47E-03	2.30E-03	2.82E-03	3.15E-03	3.20E-03
20 MV	1.57E-03	2.43E-03	2.98E-03	3.31E-03	3.34E-03
18 MV	1.62E-03	2.51E-03	3.07E-03	3.42E-03	3.46E-03
15 MV	1.75E-03	2.69E-03	3.29E-03	3.65E-03	3.66E-03
10 MV	2.06E-03	3.15E-03	3.83E-03	4.24E-03	4.25E-03
6 MV	2.60E-03	3.92E-03	4.76E-03	5.28E-03	5.35E-03
4 MV	3.16E-03	4.77E-03	5.81E-03	6.46E-03	6.62E-03
Co-60	4.06E-03	5.94E-03	7.00E-03	7.65E-03	7.79E-03
0.5 MeV	7.54E-03	1.26E-02	1.58E-02	1.78E-02	1.82E-02

TABLE 8. SUGGESTED TRANSMISSION FACTORS (PERCENTAGE DEPTH DOSES FOR A 10 cm × 10 cm FIELD, 100 cm SSD AT A DEPTH OF 30 cm)[21]

Energy	Co-60	6 MV	10 MV	15 MV	18 MV	25 MV
Transmission, f	0.15	0.23	0.28	0.33	0.34	0.38

TABLE 9. APPARENT NEUTRON SOURCE STRENGTH, Q_N, IN 10^{12} NEUTRONS PER X RAY · Gy AT ISOCENTRE [14, 29]

Manufacturer	Model	Stated MV	NAP[a] MV	Q_N
Varian	1800	10	Unknown	0.06
GE	Saturne 41	12	11.2	0.24
GE	Saturne 41	15	12.5	0.47
Varian	2100 EX	15	13	0.50[b]
Philips	SL-20	17	17	0.69
Varian	1800	15	13	0.76
Siemens	KD	20	16.5	0.92
Varian	1800	18	16.8	1.22
GE	Saturne 43	18	14	1.50
Philips	SL-25	22	20.4	2.37
GE	Saturne 43	25	18.5	2.40

[a] NAP is the nominal accelerating potential defined in the TG21 protocol [35].
[b] Ref. [29].

TABLE 10. NEUTRON DOSE EQUIVALENT H_1 AT 1 m FROM THE TARGET (IN mSv PER X RAY · Gy AT ISOCENTRE)

Accelerator manufacturer	Model	Stated MV	NAP MV	H_1
Varian	1800	10	Unknown	0.08
GE Saturne	41	12	11.2	0.18
Siemens	MD	15	Unknown	0.34
GE Saturne	41	15	12.5	0.64
Philips/Elekta	SL-20	20	17	0.87
GE Saturne	43	18	14	1.09
Varian	1800	15	Unknown	1.57–2.58
Varian	1800	18	16.8	2.03–3.18
Siemens	KD	20	16.5	2.19–2.47
GE Saturne	43	25	18.5	2.74
Philips/Elekta	SL-25	25	22	3.98

Note: Prepared from the H_0 values from (Table 2) [14] by multiplying the H_0 values with 1.41^2. H_0 is the neutron dose equivalent at 1.41 m from target per unit dose of X ray at the isocentre.

TABLE 11. FIRST TVL[a] (IN mm OF CONCRETE) FOR PATIENT SCATTER RADIATION AT VARIOUS SCATTERED ANGLES[b]

Scatter angle	Co-60	4 MV	6 MV	10 MV	15 MV	18 MV	20 MV	24 MV
15	223	320	367	410	436	449	457	477
30	213	248	261	275	285	288	290	293
45	197	223	229	233	237	238	239	240
60	189	201	205	209	211	211	212	212
90	151	169	171	173	174	174	174	175
135	128	143	144	144	145	145	145	145

[a] First TVL values are greater than approximate TVL values based on large attenuation. Values are valid for shielding design purposes and are conservative in nature.

[b] TVL values for a scattered angle of 15° are primary beam TVL values by Nelson and LaRiviere. [22] TVL values for scattered angles of 30–135° were derived from Figs 10 and 15 in Ref. [2], based on the assumption that the TVLs for the scatter radiation are closely related to the energies of the monochromatic photon scattered due to Compton interaction.

6. WORKED EXAMPLES OF EXTERNAL BEAM FACILITIES

6.1. ^{60}Co BEAM FACILITY

This example is based on a case published in Ref. [36]. Figure 10 shows the elevation and plan views of a ^{60}Co radiation therapy vault. Note that the use of a maze allows for a 6.5 mm lead-lined door instead of a much heavier direct

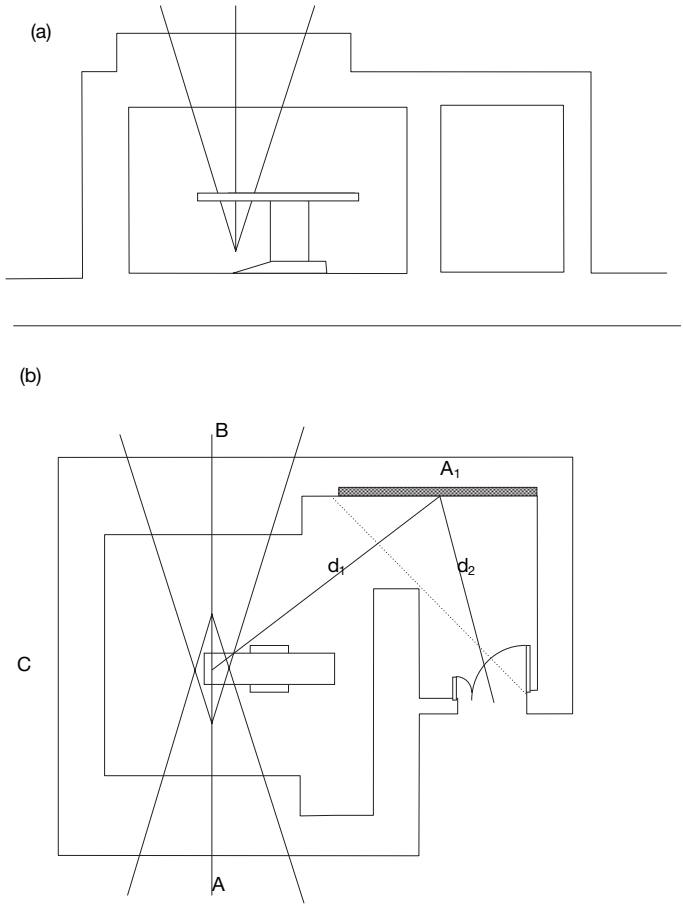

FIG. 10. Schematic layout of a ^{60}Co room showing (a) elevation and (b) plan.

shielded door. The figure also shows that the room requires primary thick barriers on the walls and ceiling wherever the ^{60}Co beam may aim since there is no beam-stopper attached to this unit. If there were space below the floor, then the floor would also need to be a very thick primary barrier. However, because of the weight of the treatment unit and its shielding it is always best to put such a facility on unexcavated ground.

6.1.1. Design dose limits

In the United Kingdom, a design dose limit of 6 mSv/a is used for controlled areas [6, 7]. If no special procedures are to be performed, then the dose will be distributed evenly throughout the year and the weekly dose limit will be $(6 \div 50 =)$ 0.12 mSv·week^{-1}. For public areas a design limit of 0.3 mSv/a is used, or $(0.3 \div 50 =)$ 6 μSv·week^{-1} [6, 7]. This example illustrates barrier calculations based on this set of limits. Depending on local regulations, other limits may be applied and different barrier requirements will be obtained.

6.1.2. Source specification

If the source specification is 0.8 Gy/min at 1 m, and the isocentric distance of the treatment unit (SAD) is 80 cm, then the dose rate at the isocentre is $(0.8 \times (100/80)^2 \times 60 =)$75 Gy·h^{-1}. The dose rate at 1 m is $(0.8 \times 60 =)$ 48 Gy·h^{-1}.

6.1.3. Workload

For a ^{60}Co treatment facility, 40 patients/d (8 h) is a reasonable assumption. If the dose delivered per patient at the isocentre is 3 Gy and the facility is used five days per week, then the workload is $(40 \times 3 \times 5 =)$ 600 Gy·week^{-1} at the isocentre (SAD = 80 cm) or $(600 \times 0.8^2 =)$ 384 Gy·week^{-1} at 1 m.

The total dose delivered at the isocentre per day is $(40 \times 3 =)$120 Gy. So the total beam-on time per day is $(120 \div 75)$ = 1.6 h. The TADR for this example is determined from Eq. (1):

$$\mathrm{TADR} = \mathrm{IDR} \times \frac{1.6 \times U}{8}$$

6.1.4. Primary barrier

The required attenuation B is determined from Eq. (5), where

P	the design limit for a controlled area is 0.12 mSv·week^{-1};
SAD	is 0.8 m;
d	the distance from the isocentre to the point of interest (A and B in Fig. 10) is 3.0 m;
W	is 384 × 10^3 mGy·week^{-1};
U	the use factor is 0.25;
T	the occupancy is 1.

$$B = \frac{0.12 \times (3.0 + 0.8)^2}{384 \times 10^3 \times 0.25 \times 1} = 1.81 \times 10^{-5}$$

From Eq. (6), the number of TVLs of concrete density 2350 kg·m^{-3} can be determined:

$$n\text{TVLs} = \log_{10}\left(\frac{1}{1.81 \times 10^{-5}}\right) = 4.74$$

The TVL for ^{60}Co in concrete (density 2350 kg·m^{-3}) is 218 mm (Table 4). Therefore, the required thickness for the primary barriers is (4.74 × 218 =) 1033 mm.

For this barrier thickness the IDR beyond the barrier is determined. The dose rate DR_0 is obtained from the specification of the source at 1 m. If the source specification is 0.8 Gy/min at 1 m (DR_0 = 48 Gy·h^{-1} = 48 ×10^6 μGy·h^{-1}), the IDR outside this primary barrier will be:

$$\text{IDR} = \frac{48 \times 10^6 \times 1.81 \times 10^{-5}}{(3 + 0.8)^2} = 60\ \mu\text{Sv·h}^{-1}$$

The TADR (R_8) may be determined from this IDR value. The total beam-on time per day has previously been estimated to be 1.6 h per 8 h day. Assuming a use factor of 0.25, the TADR beyond this barrier will be:

$$\text{TADR}(R_8) = 60 \times \frac{1.6 \times 0.25}{8} = 3\ \mu\text{Sv·h}^{-1}$$

The TADR2000 [6] may also be determined by averaging the design dose limit over 2000 h (6 mSv ÷ 2000 =) 3 μSv·h^{-1}. The use factor has already been accounted for in this value, but the occupancy has been assumed to be unity. If the area beyond this barrier is an office with a high occupancy, then it would need to be a controlled area. However, if the area only has a low occupancy of 0.05 with no public access the TADR2000 would be (6 mSv ÷ 2000 × 0.05 =) 0.15 μSv·h^{-1}. At this level of occupancy the area should be designated a supervised area under the guidance notes in the United Kingdom [6].

If the area beyond the primary barrier is intended to be a public area, then a design limit of 0.3 mSv·a^{-1}, or an IDR of 7.5 μSv·h^{-1} may be used [6]. The barrier thickness required to limit the IDR is therefore determined.

The same values are used, except that P the design limit is 7.5 μSv·h^{-1} and DR_0 the dose rate at 1 m is used in place of (WUT).

From Eq. (7) the required attenuation B_{IDR} is given by:

$$B_{IDR} = \frac{7.5(3.0+0.8)^2}{1\times 48\times 10^6} = 2.26\times 10^{-6}$$

$$n\text{TVLs} = \log_{10}\left(\frac{1}{2.26\times 10^{-6}}\right) = 5.65$$

The wall thickness required to reduce the IDR to 7.5 μSv·h^{-1} is therefore (5.65 × 218 =) 1232 mm concrete. Based on IDR considerations, the thickness of 1232 mm would be required for the primary barriers if they are shielding public areas.

An alternative method is to use a design dose limit of 0.3 mSv·a^{-1} (Table 2). Using Eq. (5) and applying the input data of:

P = (0.3 × 10^3 μSv·a^{-1} / 50 =) 6 μSv·week^{-1};
d = 3 m;
SAD = 0.8 m;
W = 384 × 10^6 μGy·week^{-1};
U = 0.25;
T = 1

$$B = \frac{6\times(3+0.8)^2}{384\times 10^6\times 0.25\times 1} = 9.03\times 10^{-7}$$

$$n\text{TVLs} = \log_{10}\left(\frac{1}{9.03\times10^{-7}}\right) = 6.04$$

Therefore, a $(6.04 \times 218 =)$1317 mm thick concrete primary barrier is required to shield a public area with an occupancy of 1. For a public area with occupancy factor of 0.5, a similar calculation gives the barrier thickness of 1252 mm. For a public area with an occupancy factor of 0.2, the barrier requirement is 1165 mm and, based on IDR considerations, a barrier thickness of 1232 mm should be used. A risk assessment should be performed to assess the likely occupancy of the shielded area in order to define the necessary shielding.

The primary barrier should be sufficiently wide that it will also shield small angle scattered radiation (see Section 2.1) before reducing to the secondary barrier thickness as shown in Fig. 10(b).

In summary, the concrete primary wall barriers should be 1033 mm thick if they are shielding a controlled area and 1165 mm thick if they are shielding a public area with an occupancy factor less than or equal to 0.2, according to guidance from the United Kingdom [6].

6.1.5. Secondary barrier

6.1.5.1. Leakage radiation

For leakage radiation from the treatment head, the manufacturer's specification should be used. There may be two values of leakage radiation quoted by the manufacturer, one when the source is in the safe position and one when the source is exposed for treatment; the larger value should be used in the shielding calculations. This value is usually less than the 0.1% (1/1000) of the primary radiation that is allowed. To determine the required barrier thickness, Eq. (8) is used.

In this example:

- d_s the distance from the isocentre to just outside the secondary barrier (point C) is 2.6 m;
- P the design limit for a public area is 6 μSv·week^{-1};
- T the occupancy is 1.

$$B = \frac{1000\times6\times(2.6)^2}{384\times10^6\times1} = 1.06\times10^{-4}$$

$$n\text{TVLs} = \log_{10}\left(\frac{1}{1.06\times10^{-4}}\right) = 4.0$$

i.e. a wall thickness of (4 × 218 =) 872 mm concrete is required.

The IDR is determined by re-arranging Eq. (8):

$$\text{IDR} = \frac{\text{DR}_0 \times B}{1000 \times d_s{}^2} = \frac{48\times10^6 \times 1.06\times10^{-4}}{1000\times(2.6)^2} = 0.8 \ \ \mu\text{Sv}\cdot\text{h}^{-1}$$

6.1.5.2. Scatter radiation

The barrier thickness necessary to shield against radiation scattered by the patient is determined from Eq. (9):

P is 6 μSv·week^{-1};
d_{sca} the isocentric distance is 0.8 m;
d_{sec} has the same value as d_s in the previous calculation, 2.6 m;
a the scatter fraction for 90° scatter is 0.0009 (Table 5) per 400 cm^2 of area irradiated;
F is the maximum field area incident on the patient (20 cm × 20 cm =) 400 cm^2:

$$B = \frac{6\times0.8^2\times2.6^2}{0.0009\times384\times10^6\times1\times(400/400)} = 7.5\times10^{-5}$$

$$n\text{TVLs} = \log_{10}\left(\frac{1}{7.5\times10^{-5}}\right) = 4.12$$

This is similar to the number of TVLs required to shield against leakage radiation. For 90° scatter the energy of the scattered radiation will be degraded and the protection designed for the leakage radiation should provide adequate protection against radiation scattered from the patient. (The TVL for 90° scattered radiation is 151 mm concrete (Table 11) compared with 218 mm concrete for broad beam ^{60}Co radiation (Table 4).)

6.1.6. Dose at entrance door

The worst case will be when the treatment unit is aimed at wall B. For this case the dose at the entrance door will comprise dose scattered by the patient,

primary beam scattered by wall B, leakage radiation scattered down the maze and leakage radiation transmitted through the maze wall.

The dose scattered by the patient D_p (Eq. (13)) to wall B for all gantry angles is determined from the following values:

W is 384 Gy·week^{-1};
a for 90° scatter is 0.0009 (Table 5);
F is 400 cm^2;
α the scatter coefficient at the wall for 0.5 MeV is 0.021 for 45° incidence and 15° reflection (value rounded from Table 6);
A_1 the area of wall is (3.0 m (W) × 2.5 m (H) =) 7.5 m^2;
d_{sca} is 0.8 m;
d_1 is 5.0 m;
d_2 is 3.0 m.

$$D_p = \frac{384 \times 1 \times 0.0009\left(400/400\right)\left(0.021 \times 7.5\right)}{\left(0.8 \times 5.0 \times 3.0\right)^2} = 3.78 \times 10^{-4} \ \text{Gy·week}^{-1}$$

Similarly, the IDR will be given by:

$$\text{IDR}_p = \frac{48 \times 10^6 \times 0.0009 \times 0.021 \times 7.5}{\left(0.8 \times 5.0 \times 3.0\right)^2} = 47 \ \mu\text{Sv} \cdot \text{h}^{-1}$$

The dose scattered by wall *B* to the entrance D_w is determined from Eq. (14):

U_H is assumed to be 0.25;
d_H the distance to wall B is 1.6 m;
α_H the reflection coefficient for normal incidence and 75° reflection for ^{60}Co is 4.06 × 10^{-3} (Table 7);
α_r the reflection coefficient for normal incidence, 75° reflection for 0.5 MeV is 7.54 × 10^{-3};
A_H is the area of the maximum field size projected on wall B at distance d_H (0.04 × (1.6/0.8)^2) = 0.16 m^2;
A_r is the cross-sectional area of the inner maze opening (1.5 W × 2.5 H);
d_r is 4.3 m;
d_z is 2.5 m.

$$D_w = \frac{384 \times 0.25}{1.6^2} \times \frac{4.06 \times 10^{-3} \times (0.16) \times 7.54 \times 10^{-3} \times (1.5 \times 2.5)}{(4.3)^2 \times (2.5)^2}$$

$$= 5.96 \times 10^{-6} \text{ Gy·week}^{-1}$$

The IDR will be:

$$\text{IDR}_w = \frac{48 \times 10^6}{1.6^2} \times \frac{4.06 \times 10^{-3} \times (0.16) \times 7.54 \times 10^{-3} \times (1.5 \times 2.5)}{(4.3)^2 \times (2.5)^2}$$

$$= 2.98 \text{ μSv·h}^{-1}$$

The leakage scattered down the maze D_L is determined from Eq. (16):

L_0 is 0.001 (0.1% of the primary beam);
α_1 is 1.07×10^{-2} for 45° incidence and 15° reflection for ^{60}Co (Table 6);
A_1 is 7.5 m^2 (2.5 m H × 3.0 m W);
d_i is 5.0 m;
d_m is 3.0 m.

The dose at the maze entrance from head leakage scattered down the maze D_L for all gantry rotations (Eq. (16)) is:

$$D_L = \frac{0.001 \times 384 \times 0.0107 \times 7.5}{(5.0 \times 3.0)^2} = 1.37 \times 10^{-4} \text{ Gy·week}^{-1}$$

and the IDR is:

$$\text{IDR}_L = \frac{0.001 \times 48 \times 10^6 \times 0.0107 \times 7.5}{(5.0 \times 3.0)^2} = 17 \text{ μSv·h}^{-1}$$

The dose at the maze entrance arising from leakage transmitted through the maze wall D_T is given by Eq. (17):

B is the transmission factor for the barrier (1.06×10^{-4});
d_t is 5.0 m.

$$D_T = \frac{0.001 \times 384 \times 1.06 \times 10^{-4}}{5.0^2} = 1.63 \times 10^{-6} \text{ Gy·week}^{1}$$

$$\text{IDR}_T = \frac{0.001 \times 48 \times 10^6 \times 1.06 \times 10^{-4}}{5.0^2} = 0.2 \text{ μSv} \cdot \text{h}^{-1}$$

The total dose at the door D_d for the worst case when the beam is directed at wall B is obtained by using a modified Eq. (11) for one gantry orientation only:

$$D_d = \frac{3.78 \times 10^{-4}}{4} + (1.0) \times 5.96 \times 10^{-6} + \frac{1.37 \times 10^{-4}}{4} + \frac{1.63 \times 10^{-6}}{4}$$
$$= 1.35 \times 10^{-4} \text{ Gy·week}^{-1} = 135 \text{ μSv·week}^{-1}$$

The first, third and fourth terms are each divided by 4 since it is assumed that the gantry will only be in this orientation for 0.25 of the total use. The second term, which arises from the primary beam scattered by the wall, will usually be attenuated by the patient before it strikes the wall, but a transmission factor of 1.0 has been used. Since this is the dose for the worst case the total dose per week will be less than four times this amount i.e. less than $(4 \times 135 =)$ 540 μSv·week^{-1}.

According to Eq. (18), the total dose at the maze entrance is $(2.64 \times 135 =)$ 356 μSv·week^{-1}.

The instantaneous dose rate at the door IDR_d for the worst case will be:

$$\text{IDR}_d = 47 + 2.98 + 17 + 0.2 = 67.2 \text{ μSv} \cdot \text{h}^{-1}$$

If the area immediately outside the doors is a controlled area, then the dose limit is 120 μSv·week^{-1} (6 mSv/a). To reduce the dose to an acceptable level, one TVL would be adequate. The radiation scattered by the patient, the primary beam scattered by wall B and the leakage radiation scattered down the maze have all suffered at least one scatter to arrive at the maze entrance, so the TVL for 90° scattered radiation may be used to determine the necessary door thickness. The TVL for 90° scattered radiation is 6.5 mm lead (Table 23), so doors with this thickness of lead would reduce the weekly dose from 356 μSv·week^{-1} to around 35 μSv·week^{-1}, which is well within the design dose limit. The worst case IDR_d would be reduced from 67.2 μSv·week^{-1} to 7 μSv·h^{-1} with a 6.5 mm lead door in place. This would give a TADR of $(7 \times 1.6 \div 8 =)$ 1.4 μSv·h^{-1}, which would be very acceptable.

6.2. 6 MV LINEAR ACCELERATOR FACILITY

Figure 11 shows a proposal for a 6 MV linear accelerator facility. The design dose limits to be used are those for public areas — 0.3 mSv per year per installation [6, 7]. The IDR should be limited to 7.5 μSv·h^{-1} [6, 7]. The expected workload is 50 patients per day (8 h), 5 days per week and a dose of 3 Gy delivered at the isocentre per patient.

6.2.1. Primary barrier

6.2.1.1. Example 1

To determine the required barrier thickness based on an annual dose limit, Eq. (5) is used where:

P the design limit for a public area is 0.3 mSv per annum (0.3 ÷ 50 = 6 μSv·week^{-1});
d the distance from the isocentre to the point of interest on the far side of the barrier is 5 m;
SAD is 1 m;

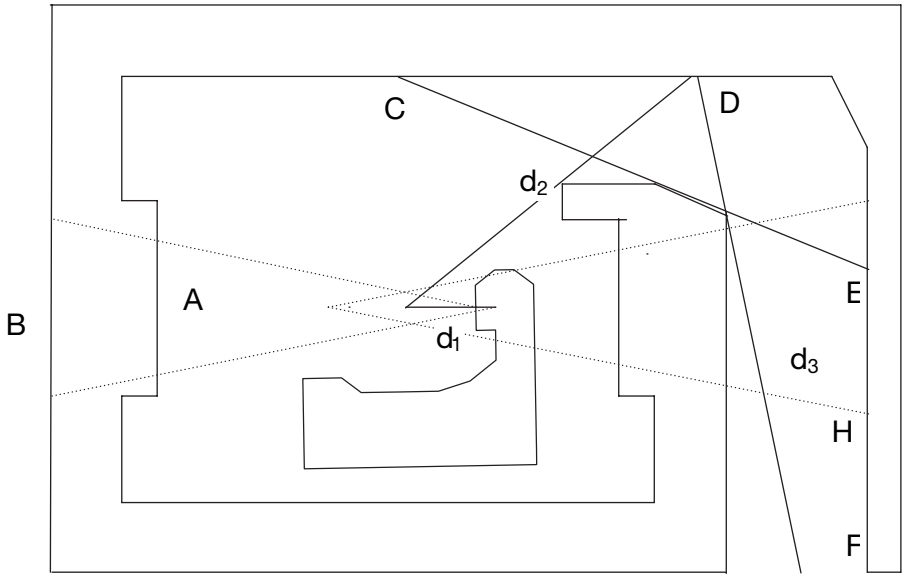

FIG. 11. Schematic layout of a 6 MV facility.

W the workload for a 5 day week will be nominally 10^3 Gy ($50 \times 3 \times 5$);
U the use factor is 0.25;
T the occupancy factor is 0.1.

Then:

$$B = \frac{6(5+1)^2}{10^3 \times 10^6 \times 0.25 \times 0.1} = 8.6 \times 10^{-6}$$

The required number of TVLs to produce this attenuation is determined from Eq. (6):

$$\text{No. of TVLs} = \log_{10}\left(\frac{1}{8.6 \times 10^{-6}}\right) = 5.1$$

From Table 4 the TVL for 6 MV X rays in concrete is 343 mm and the required barrier thickness is ($5.1 \times 343 =$) 1750 mm.

6.2.1.2. Example 2

In Fig. 11, the required attenuation by the primary barriers B will be determined from Eq. (7) using the IDR dose limit:

P_{IDR} a design dose limit of 7.5 μSv·h^{-1} is required,
d the distance from the isocentre to the point of interest on the far side of the barrier is 5 m as in Example 1;
SSD is 1 m;
DR_0 the dose rate is 2.5 Gy·min^{-1} (= 150 Gy·h^{-1}).

$$B = \frac{7.5 \times (5+1)^2}{2.5 \times 10^6 \times 60} = 1.8 \times 10^{-6}$$

The number of TVLs required to produce this attenuation is determined from Eq. (6):

$$\text{No. of TVLs} = \log_{10}\left(\frac{1}{1.8 \times 10^{-6}}\right) = 5.7$$

The TVL for 6 MV X rays in concrete (density 2350 kg·m^{-3}) is 343 mm (Table 4); therefore, the required barrier thickness is (343 × 5.7 =) 1955 mm.

This is more than the barrier thickness of 1750 mm required in Example 1. It would be prudent to use the greater thickness since the use factor and occupancy can only be best estimates and may change in the future.

The values used for TVLs in concrete are based on a concrete density of 2350 kg·m^{-3}. If the concrete used locally has a different density, then the wall thickness must be adjusted accordingly. So if the required thickness was determined as 1955 mm of 2350 kg·m^{-3} density concrete but the local concrete density is only 2000 kg·m^{-3}, then the actual wall thickness will be (1955 × 2350 ÷ 2000 =) 2300 mm local density concrete.

6.2.1.3. Example 3

If in Example 2 the dose rate DR_0 had been 5 Gy·min^{-1}, the attenuation B required to reduce the dose rate to 7.5 μSv·h^{-1} would be:

$$B = \frac{7.5 \times (5+1)^2}{5 \times 10^6 \times 60} = 9 \times 10^7$$

The number of TVLs necessary to achieve this reduction would then be:

$$\text{No. of TVLs} = \log_{10}\left(\frac{1}{9 \times 10^7}\right) = 6$$

and the required barrier thickness (343 × 6 =) 2100 mm.

The extent of the primary barrier will be determined by the divergence of the primary beam (as defined by the primary cone) to the outside of the wall, with an additional extension of 300 mm on each side to allow for internal scatter (also called the plume effect — Section 2.1). For a primary cone of 500 mm diameter at the isocentre, the divergence to the outside of a wall at 5 m from the isocentre will be (500 × (1 + 5) =) 3000 mm. An additional 300 mm on each side will make the total required extent of the barrier 3600 mm.

6.2.2. Secondary barrier

6.2.2.1. Leakage radiation

The shielding required for protection against leakage radiation is determined from Eq. (8). The leakage radiation is assumed to be 0.1% (1/1000) of the primary beam, where

- P the public dose limit is 6 μSv·week^{-1};
- d_s the distance from the isocentre to the point of interest beyond the secondary barriers is 5.0 m;
- W the workload is 10^3 Gy·week^{-1};
- T the occupancy factor is 1 for one secondary barrier (control area) and 0.1 for the other barrier.

The required attenuation B_L is given by:

$$B_L = \frac{1000 \times 6 \times 5^2}{10^3 \times 10^6 \times 1} = 1.5 \times 10^{-4} \text{ (or } 1.5 \times 10^{-3} \text{ for occupancy of 0.1)}$$

$$\text{No. of TVLs} = \log_{10}\left(\frac{1}{1.5 \times 10^{-4}}\right) = 3.8 \text{ (or 2.8 TVLs for occupancy 0.1)}$$

From Table 4, the TVL in concrete for 6 MV leakage radiation is 279 mm. Therefore, one secondary barrier should be (3.8×279 =) 1060 mm and the other (2.8×279 =) 780 mm, where both values have been rounded to the nearest 10 mm.

6.2.2.2. Scattered radiation

The barrier transmission required to shield against radiation scattered by the patient is determined from Eq. (9), where

- P the public dose limit is 6 μSv·week^{-1};
- d_{sca} is 1.0 m;
- d_{sec} is 5.0 m;
- a the scatter fraction for 90° scatter from 6 MV X rays is 0.0006 per 400cm^2 of area irradiated (Table 5);
- W the workload is 10^3 Gy·week^{-1};

T the occupancy factor is 1 for one secondary barrier (control area), and 0.1 for the other barrier;

F is 400 cm^2 (the maximum field size is 40 cm × 40 cm but the use of a field size of 20 cm × 20 cm is more realistic).

$$B_p = \frac{6 \times 1^2 \times 5^2}{0.0006 \times 10^3 \times 10^6 \times 1 \times (400/400)}$$
$$= 2.5 \times 10^{-4} \text{ (or } 2.5 \times 10^{-3} \text{ for T = 0.1)}$$

$$\text{No. of TVLs} = \log_{10}\left(\frac{1}{2.5 \times 10^{-4}}\right) = 3.6 \text{ (or 2.6 TVLs for T = 0.1)}$$

These TVL values are the same as those determined to shield against leakage radiation. Therefore, an additional HVL should be added to the wall thickness (see Section 5.2.2). For a TVL of 279 mm, one HVL will be 84 mm, so the secondary barrier thicknesses will be (1060 + 84 =) 1150 mm and (780 + 84 =) 870 mm with occupancies of 1 and 0.1, respectively.

6.2.3. Dose rate at maze entrance

In this example, the IDR has been determined by substituting the values W and U with the dose rate at the isocentre DR_0. The following example determines the dose rate at the maze entrance when the beam is directed at the maze wall which will be the worst case.

6.2.3.1. Dose rate arising from patient DR_p

The dose rate produced by radiation scattered by patient DR_p is determined from Eq. (13), where:

DR_0 the dose rate is 2.5 Gy·min^{-1} ($2.5 \times 60 \times 10^6$ μGy·h^{-1}) at the isocentre;

a the scatter primary ratio is 0.0006 for 6 MV X rays at 90º (Table 5);

F the field size, is 20 cm × 20 cm;

α the reflection coefficient for 0.5 MeV X rays, is 0.022 (value rounded from Table 6 for a 45° reflection;

A_1 the area of wall contributing scatter to the maze, is 3.3 m L (CD) and 3.5 m H;

A_2 the cross-sectional area of the maze, is 3.0 m H × 2.0 m W (the ceiling height is reduced in the maze to reduce the scattered radiation at the maze entrance);
d_{sca} the distance from the source to patient, is 1 m;
d_1 the mean distance to the wall (CD), is 4 m;
d_2 the distance to the maze entrance, is 7.2 m

$$DR_p = \frac{2.5 \times 60 \times (0.0006 \times 1) \times (0.022 \times 3.3 \times 3.5) \times (0.022 \times 2.0 \times 3.0)}{(1 \times 4 \times 7.2)^2}$$
$$= 3.6 \ \mu Sv \cdot h^{-1}$$

6.2.3.2. Dose rate arising from the primary beam DR_w

The transmission of the primary beam into the maze through the maze wall must be accounted for using Eq. (15), where:

DR_0 the IDR is $(2.5 \times 60 \times 10^6)$ μGy·h^{-1};
B_{pr} the transmission of the primary beam through the maze barrier is 1.8×10^{-6};
α_P the reflection coefficient for the 75° scatter from the attenuated primary beam striking the outer maze wall is 0.0003 (Table 7);
A_P the projection of the maximum field size on the far side of the maze wall is 4.0 m wide and the height is limited by the height of the room 3.0 m;
d_P the distance from the source to the outer maze wall is 8.0 m;
d'' the distance from the centre of area A_p to the maze entrance is 4.5 m.

$$DR_{wT} = \frac{2.5 \times 60 \times 1.8 \times 10^{-6} (0.0003 \times 4.0 \times 3.0)}{(8 \times 4.5)^2} = 0.75 \times 10^{-3} \mu Sv \cdot h^{-1}$$

6.2.3.3. Dose rate of head leakage scattered to the maze entrance DR_L

The contribution of scattered head leakage radiation is determined from Eq. (16), where:

DR_0 the dose rate at the isocentre is $(2.5 \times 60 \times 10^6)$ μGy·h^{-1};
L_0 leakage at 1.0 m is 10^{-3} (0.1%);
α_1 the reflection coefficient at the concrete wall for 6 MV X rays is 0.007;

A_1 the cross-sectional area of the maze, is 2.0 m W × 3.0 m H to the ceiling;

d_I the distance from the source to the maze centreline is 7.75 m (worst case);

d_m centreline distance along the maze is 8.75 m.

In this example the dose rate arising from leakage scattered to the maze entrance will be:

$$\mathrm{DR}_L = \frac{2.5 \times 60 \times 10^{-3} \times (0.007 \times 2.0 \times 3.0)}{(7.75 \times 8.75)^2} = 1.4\ \mu\mathrm{Sv} \cdot \mathrm{h}^{-1}$$

6.2.3.4. Dose rate from head leakage transmission to the maze entrance DR_T

This is determined from Eq. (17), where:

DR_0 is (2.5 × 60) Gy·h^{-1};

L_0 the leakage is 10^{-3} as before;

B the transmission through the secondary barrier to the maze entrance is 1.5×10^{-4};

d_t the shortest distance from the source to the maze entrance is 6.0 m

$$\mathrm{DR}_L = \frac{2.5 \times 60 \times 10^{-3} \times (1.5 \times 10^{-4})}{(6.0)^2} = 0.6\ \mu\mathrm{Sv} \cdot \mathrm{h}^{-1}$$

The total dose rate at the maze entrance DR_d will be the sum of these components:

$$\mathrm{DR}_d = 3.6 + (0.75 \times 10^{-3}) + 1.4 + 0.6 = 5.6\ \mu\mathrm{Sv} \cdot \mathrm{h}^{-1}$$

This is well below the limit of 7.5 μSv·h^{-1}. The largest contribution arises from the radiation scattered from the patient.

6.3. 18 MV LINEAR ACCELERATOR FACILITY

Figure 12 shows a proposal for an 18 MV linear accelerator facility located in the USA. The design dose limits to be used are 1 mSv per year per

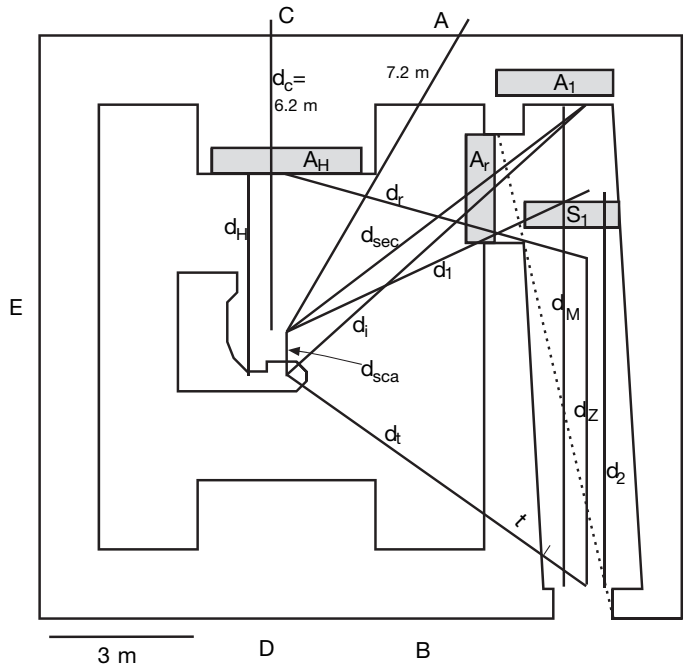

FIG. 12. Schematic layout of an 18 MV facility.

installation for public areas, and 5 mSv per year for the treatment control area [9]. The dose in any hour limit (R_h) is 20 μSv. The expected workload is 40 patients per eight hour day, five days per week and a dose of 3 Gy delivered at the isocentre per patient. The accelerator has a maximum dose output rate of 12 Gy·min^{-1}, and the normal rate used is 5 Gy·min^{-1}.

6.3.1. Primary barrier

6.3.1.1. Public area at location C

Example 1: Primary barrier

To determine the required barrier thickness at location C, an unattended parking lot, Eq. (5) is used:

P the design limit for a public area is 20 μSv·week^{-1} (1 ÷ 50 = 20 μSv·week^{-1});
d_C the distance from the isocentre, is 6.2 m;

W the workload for a five day week is 600 Gy (40 × 3 × 5);
U the use factor is 0.25;
T the occupancy factor is 0.0625 (1/16) from Table 3

$$B = \frac{20 \times 10^{-6} \times (6.2+1)^2}{600 \times 0.25 \times 0.0625} = 1.11 \times 10^{-5}$$

The required number of TVLs to produce this attenuation is determined from Eq. (6):

$$n = \log_{10}\left(\frac{1}{2.76 \times 10^{-5}}\right) = 3.96$$

The TVL for 18 MV X rays in concrete is 445 mm (Table 4), and therefore the required barrier thickness is (3.96 × 445 =) 1762 mm.

Example 2: TADR considerations

To determine if the dose in-any-hour limit is met, the maximum dose output rate at isocentre 12 Gy·min^{-1} is used. At this dose output rate, the expected dose rate at location C, with attenuation $B = 1.11 \times 10^{-4}$, is:

$$\text{IDR} = \frac{12 \times 60 \times 1.11 \times 10^{-4}}{7.2^2} = 1.54 \times 10^{-3}\ \text{Gy·h}^{-1}$$

It is determined that in an hour, no more than 12 patients can be irradiated, which corresponds to a workload of 36 Gy. Comparing an hourly workload figure of 600 Gy if the weekly work is to be done in one hour, with the maximum hourly workload of 36 Gy, the lower value of 36 is taken as the value for W_h.

From Equation (4), the dose in any hour is:

$$R_h = 1.54 \times 10^{-3} \times \frac{36 \times 0.25}{12 \times 60} = 1.93 \times 10^{-5}\ \text{Sv}$$

which meets the 20 μSv in any hour requirement.

Example 3: Leakage considerations

To determine the barrier thickness required to shield against leakage radiation for location C, Eqs (6) and (8) are used. Because treatment units are generally shielded to better than 0.1% (the 1/1000 factor), the primary barrier is adequate for shielding the additional radiation from leakage, as illustrated in the following example. The input data values are:

$P = 20 \times 10^{-6}$ Sv·week^{-1};
$d_s = 6.2$ m;
$W = 600$ Gy·week^{-1};
$T = 0.0625$ (1/16)

$$B_L = \frac{1000 \times 20 \times 10^{-6} \times 6.2^2}{600 \times 0.0625} = 2.05 \times 10^{-2}$$

and

$$n = \log_{10}\left(\frac{1}{2.05 \times 10^{-2}}\right) = 1.69$$

The number of TVLs to shield against leakage radiation is much lower than the number required for primary beam shielding. Therefore, the leakage shielding requirement is more than adequately met by the primary barrier thickness.

Example 4: Patient scatter considerations

To determine the thickness required for patient scatter shielding at location C, Eq. (9) is used. The worst case is when the beam is pointing directly at C because the scatter fraction a is the largest, and the energy of the small angle scatter radiation is also the highest. If the primary barrier is sufficiently wide that it will also shield small angle scattered radiation, no additional thickness is needed to shield the scatter radiation. The following example illustrates this point. The input data values are:

$P = 20 \times 10^{-6}$ Sv·week^{-1};
$d_{sca} = 1$ m;
$d_{sec} = 6.2$ m;
$a = 1.42 \times 10^{-2}$ (Table 5, 18 MV scatter through 10° at 2.5 cm depth);
$W = 600$ Gy·week^{-1};

T = 0.0625 (1/16);
F = 40×40 cm^2 (the maximum field size is used for conservative reasons)

$$B_p = \frac{20 \times 10^{-6} \times 1 \times 6.2^2}{1.42 \times 10^{-2} \times 600 \times 0.25 \times 0.0625 \times (40 \times 40 / 400)} = 3.61 \times 10^{-4}$$

The required TVLs to produce this attenuation is determined from Eq. (6):

$$n = \log_{10}\left(\frac{1}{3.61 \times 10^{-4}}\right) = 3.44$$

Compared with the number of TVLs required to attenuate the primary beam ($n = 3.96 + 2 \times 0.301 = 4.56$) calculated above, the thickness requirement to attenuate the worst case of patient scatter is more than one TVL lower. Therefore, the wall thickness determined for the primary barrier will be more than adequate to shield against scattered radiation.

For other gantry angles, the scatter fraction will be much reduced and the energy of the scatter radiation is much lower. Therefore, the barrier thickness required to attenuate the primary beam will be sufficient to attenuate all scattered radiation.

6.3.1.2. Treatment control area

Example 5: Primary barrier at location D

For the treatment control area, the design dose limit P is 5 mSv/a, or 0.1 mSv·week^{-1}. Other input data values for Eq. (5) are:

d = 6.2 m, the distance from D to the isocentre;
W = 600 Gy·week^{-1};
U = 0.25;
T = 1

$$B = \frac{0.1 \times 10^{-3} \times (6.2 + 1)^2}{600 \times 0.25 \times 1} = 3.46 \times 10^{-5}$$

$$n = \log_{10}\left(\frac{1}{3.46\times10^{-5}}\right) = 4.46$$

The required barrier thickness is (4.46 × 445 mm =) 1985 mm.

The primary barrier can be shown, (as in examples 3 and 4), to be adequate for shielding against leakage radiation and patient scatter.

6.3.2. Secondary barrier

6.3.2.1. Public area at location A

Example 6: Leakage and patient scatter considerations

Only leakage and patient scatter are considered since there is no primary radiation directed at location A. For conservative reasons, the minimum scatter angle of 30° is used to look up the scatter fraction a from Table 5. The input data values used in Eqs (6), (8) and (9) are:

P = 20×10^{-6} Sv·week^{-1};
d_s = 7.2 m;
d_{sca} = 1 m;
d_{sec} = 7.2 m;
a = 2.53×10^{-3} (for 18 MV at 2.5 cm depth);
W = 600 Gy·week^{-1};
F = 40 × 40 cm^2;
T = 0.0625.

For leakage radiation using Eq. (8),

$$B_L = \frac{1000\times20\times10^{-6}\times7.2^2}{600\times0.0625} = 2.76\times10^{-2}$$

n (leakage) = 1.56

The TVL for 18 MV leakage radiation is 330 mm concrete (Table 4); therefore, the required leakage barrier thickness is (1.56 × 330 =) 515 mm concrete.

For determining shielding against patient scatter, Eq. (9) is used:

$$B_p = \frac{20\times10^{-6}\times1\times7.2^2}{2.53\times10^{-3}\times600\times0.0625\times(40\times40/400)} = \times\,10^{-3}$$

and

n (patient scatter) = 2.56

From Table 11, the TVL for 30° patient scatter is 288 mm concrete. Therefore, the patient scatter barrier thickness is (2.56 × 288 =) 737 mm

The difference between the scatter and leakage barrier thickness requirements (737 mm–515 mm) is less than one TVL. Therefore, one HVL should be added to the higher value (see Section 5.2.2). For a TVL of 330 mm, one HVL is 99 mm. Therefore, the barrier thickness required for location A is (737 + 99 =) 836 mm. This thickness equates to 2.90 TVLs for 30º scatter (Table 11) and an attenuation B_p of 1.25×10^{-3}. The same thickness equates to 2.53 TVLs for leakage and an attenuation B_L of 2.93×10^{-3}.

Example 7: TADR R_h considerations

To determine if the dose in any hour limit is met, the maximum dose output rate at isocentre 12 Gy·min^{-1} should be used. At this dose output rate, the expected dose rate at location A is the sum of the IDR contributed by patient scatter and leakage. Using the scatter fraction $a = 2.53 \times 10^{-3}$ from Table 5, the patient scatter dose rate is:

$$\mathrm{IDR}_p = \frac{12 \times 60 \times 2.53 \times 10^{-3} \times (40 \times 40 / 400) \times 1.25 \times 10^{-3}}{7.2^2}$$
$$= 1.76 \times 10^{-4}\ \mathrm{Gy \cdot h^{-1}}$$

and the leakage dose rate is:

$$\mathrm{IDR}_L = \frac{12 \times 60 \times 2.93 \times 10^{-3}}{1000 \times 7.2^2} = 4.07 \times 10^{-5}\ \mathrm{Gy \cdot h^{-1}}$$

The total IDR at location A is:

$$\mathrm{IDR} = \mathrm{IDR_p} + \mathrm{IDR_L} = 1.76 \times 10^{-4} + 4.07 \times 10^{-5} = 2.2 \times 10^{-4}\ \mathrm{Gy \cdot h^{-1}}$$

Using 36 Gy·h^{-1} as the value for W_h as described in example 2, and from Eq. (4), the dose in any hour is:

$$R_h = 2.2 \times 10^{-4} \times \frac{36 \times 1}{12 \times 60} = 1.1 \times 10^{-5}\ \text{Sv·h}^{-1}$$

which is below the limit of 20 μSv in any hour.

6.3.2.2. Secondary barrier at location B

Example 8

There is no primary radiation directed at location B. Only leakage and patient scatter are to be considered. For conservative reasons, the minimum scatter angle of 30° is used to look up the scatter function *a* from Table 5. The input data values used in Eqs (6), (8) and (9) are:

P = 0.1×10^{-3} Sv·week^{-1};
d_s = 7.2 m;
d_{sca} = 1 m;
d_{sec} = 7.2 m;
a = 2.53×10^{-3};
W = 600 Gy·week^{-1};
F = 40×40 cm^2;
T = 1.

For leakage radiation (Eq. (8)):

$$B_L = \frac{1000 \times 0.1 \times 10^{-3} \times 7.2^2}{600 \times 1} = 8.64 \times 10^{-3}$$

n (leakage) = 2.06

The barrier thickness required to shield from leakage radiation will be:

leakage barrier = 2.06 × 330 = 681 mm concrete

For patient scatter (Eq. (9)):

$$B_p = \frac{0.1 \times 10^{-3} \times 1^2 \times 7.2^2}{2.53 \times 10^{-3} \times 600 \times 1 \times (40 \times 40 / 400)} = 8.54 \times 10^{-4}$$

and

n (patient scatter) = 3.07

From Table 11, the TVL for 30° patient scatter is 288 mm concrete Therefore, the barrier thickness required to shield against radiation scattered by the patient is (3.07 × 288 =) 884 mm

The difference between the required scatter and leakage barrier thicknesses (884 mm – 681 mm) is less than one TVL. Therefore, an additional HVL thickness for leakage is added to the greater thickness (see Section 5.2.2). The total barrier thickness for location B is therefore (884 + 99 =) 983 mm.

6.3.3. Maze door area

6.3.3.1. Example 9: Leakage and scatter

For a high energy accelerator, the contribution of leakage and scatter radiation reaching the maze door is relatively low compared with the capture gamma and neutron dose components shown in examples 10 and 11. Since the room layout is similar to that shown in Fig. 4, Eq. (18) may be used to simplify the calculation for the dose at the door D_d

$$D_d = 2.64\left(D_{pH} + f \times D_{wH} + D_{LH} + D_{TH}\right)$$

where each component is calculated as follows.

Patient scatter component D_{pH}

Equation (13) is used to determine the dose at the door, scattered by the patient with the beam pointing at wall H, or location C, as shown in Fig. 12. The input data values are:

W = 600 Gy·week^{-1};
U_0 = 0.25;
F = 40 × 40 cm^2;
d_{sca} = 1 m;
d_1 = 7.3 m, the distance from isocentre to wall A_1;
d_M = 9.9 m, the distance from wall A_1 to the door;
A_1 is 2.8 m × 4.2 m = 11.8 m^2, the area of the wall,
a = 8.64 × 10^{-4} the scatter function at 45° scatter angle (Table 5);

α_1 = 2.03×10^{-2}, the concrete wall reflection coefficient for incident angle 45° and reflection angle 0° for 0.5 MeV monoenergetic photons (Table 6).

The concrete wall reflection coefficient α_1 is a function of the incident beam energy and the incident angle. After scattering by the patient, the energy can be as low as 0.5 MeV due to Compton interactions. Table 6 demonstrates that the reflection coefficient increases as the energy decreases so using the 0.5 MeV coefficient will not underestimate the dose to the maze door.

Using input data values shown above, Eq. (13) is evaluated to obtain D_{pH}:

$$D_{pH} = \frac{600 \times 0.25 \times 8.64 \times 10^{-4} \times (40 \times 40 / 400) \times 2.03 \times 10^{-2} \times 11.8}{(1 \times 7.3 \times 9.9)^2}$$

$$= 2.38 \times 10^{-5} \text{ Gy·week}^{-1}$$

Wall scatter component D_{wH}

The input data values used in Eq. (14) are:

W = 600 Gy·week^{-1};
U_H = 0.25.

The distances as shown in Fig. 12 are:

d_H = 4.2 m;
d_r = 5.9 m;
d_z = 6.8 m.

The wall reflection coefficients are:

α_H = 1.62×10^{-3} (Table 7, normal incidence, 75° angle of reflection, 18 MV);
α_r = 7.54×10^{-3} (Table 7, normal incidence, 75° angle of reflection, 0.5 MeV);
A_H = 2.82 m^2, the maximum field size 40 × 40 cm^2 projected onto wall H (= 168 × 168 cm^2);
A_r is 10.2 m^2 the cross-sectional area of the inner maze entrance.

Equation (14) gives the value of D_{wH}:

$$D_{wH} = \frac{600 \times 0.25 \times 1.62 \times 10^{-3} \times 2.82 \times 7.54 \times 10^{-3} \times 10.2}{(4.2 \times 5.9 \times 6.8)^2}$$
$$= 1.86 \times 10^{-6} \text{ Gy·week}^{-1}$$

Head leakage wall scatter component D_{LH}

Input data values used in Eq. (16) are as follows:

L_0 = 1×10^{-3};
W = 600 Gy·week^{-1};
U_H = 0.25;
α_1 = 4.11×10^{-3} (Table 6, 45° incidence, 0° reflection angle, 18 MV);
A_1 = 11.8 m^2;
d_i = 7.9 m;
d_m = 9.9 m.

The dose at the maze door from head leakage scattered by the wall A_1 is:

$$D_{LH} = \frac{1 \times 10^{-3} \times 600 \times 0.25 \times 4.11 \times 10^{-3} \times 11.8}{(7.9 \times 9.9)^2}$$
$$= 1.19 \times 10^{-6} \text{ Gy·week}^{-1}$$

Head leakage through the maze wall D_{TH}

The input data values used in Eq. (17) are:

L_0 = 1×10^{-3};
W = 600 Gy·week^{-1};
U_H = 0.25;
d_t = 7.1 m.

The oblique thickness of the maze wall t is 1200 mm concrete. Since the TVL in concrete for leakage radiation is 330 mm (Table 4), the transmission B is:

$$B = 10^{-1200/330} = 2.31 \times 10^{-4}$$

The dose D_{TH} from Eq. (17) is:

$$D_{TH} = \frac{1 \times 10^{-3} \times 600 \times 0.25 \times 2.31 \times 10^{-4}}{(7.1)^2} = 6.87 \times 10^{-7} \text{ Gy·week}^{-1}$$

Total dose due to scatter and leakage D_d

The total dose at the maze door due to scatter and leakage is, using Eq. (18), and $f = 0.34$ (from Table 8):

$$D_d = 2.64 \times (2.38 \times 10^{-5} + 0.34 \times 1.86 \times 10^{-6} + 1.19 \times 10^{-6} + 6.87 \times 10^{-7})$$
$$= 6.95 \times 10^{-5} \text{ Gy·week}^{-1}$$

6.3.3.2. Example 10: Capture gamma dose at the maze door

Assume again for this example that the workload is 600 Gy·week^{-1}. The length of the maze from the inner maze point to the door is (d_2 =) 8.5 m. To determine the capture gamma dose D_φ, Eq. (24) is used.

The total neutron fluence φ_A at the inner maze point is first determined using Eq. (23). The accelerator is a Varian 18 MV machine, and from Table 9 $Q_N = 1.22 \times 10^{12}$ neutrons per isocentre Gy. The distance from the isocentre to the inner maze point is (d_1 =) 6.4 m. The treatment room layout and dimensions are shown in Figs 13 and 14.

The room surface area S for use in Eq. (23) is the sum of the areas of ceiling and floor, front and back walls, and left and right walls. The average room height is 3.65 m, the average width is 7.8 m, and the average length is 7.8 m (see Section 5.6). The surface area of the room is therefore:

$$S = 2 \times (7.8 \times 3.65 + 7.8 \times 3.65 + 7.8 \times 7.8) = 236 \text{ m}^2$$

The total neutron fluence per isocentre X ray Gy at the inner maze point A from Eq. (23) is:

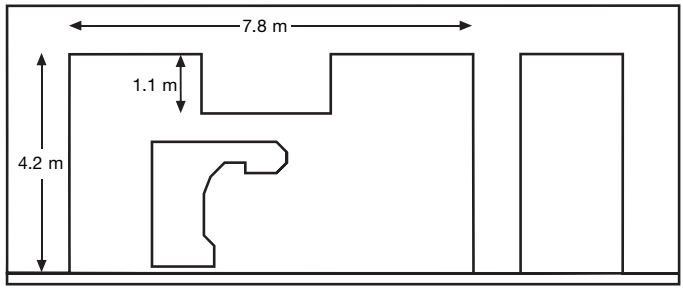

FIG. 13. Sectional diagram of the treatment room.

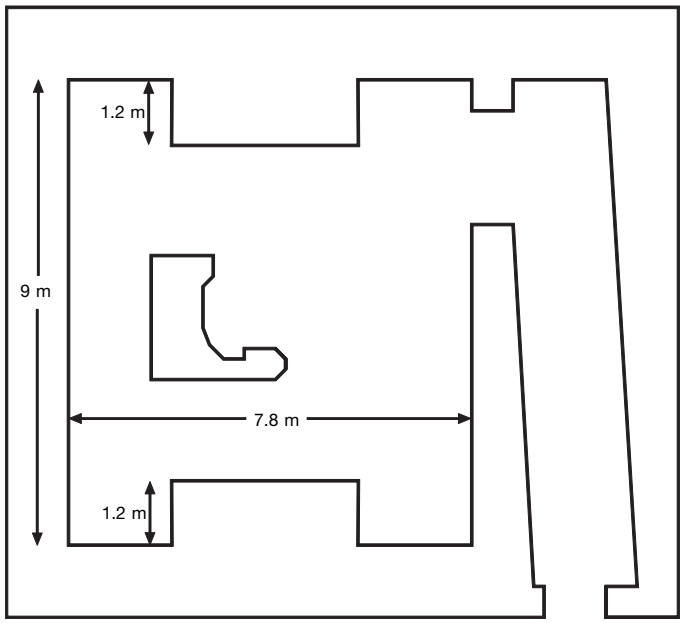

FIG. 14. Treatment room dimensions.

$$\varphi_A = \frac{1.22\times10^{12}}{4\pi\times6.4^2} + \frac{5.4\times1.22\times10^{12}}{2\pi\times236} + \frac{1.26\times1.22\times10^{12}}{2\pi\times236}$$
$$= 7.85\times10^{9}\ \text{neutrons}\cdot\text{m}^{-2}$$

The capture gamma dose at the maze door is, from Eq. (24):

$$D_{\varphi} = 5.7\times10^{-16}\times7.85\times10^{9}\times10^{-(8.5/6.2)} = 1.9\times10^{-7}\ \text{Gy/isocentre Gy}$$

The weekly dose at the maze door D_c is, from Eq. (25):

$$D_c = 600\times1.9\times10^{-7} = 1.14\times10^{-4}\ \text{Sv}\cdot\text{week}^{-1}$$

6.3.3.3. Example 11: Neutron dose at the maze door

To determine the neutron dose at the maze entrance for the treatment room described in Example 10, the area of the inner maze opening A_r, and the cross-sectional area of the maze S_1, as shown in Fig. 12, are needed. The values for this room are:

$A_r = 10.2\ \text{m}^2$ and $S_1 = 8.76\ \text{m}^2$

The neutron dose at the maze entrance is then determined using Eq. (26), and input data values listed in Example 10, and the highest value of H_1 for an 18 MeV X ray treatment unit from Table 10:

$$D_n = 3.18 \times 10^{-3} \times (10.2/8.76)(1/6.4)^2 \times 10^{-8.5/5}$$
$$= 1.80 \times 10^{-6}\ \text{Sv per X ray·Gy at isocentre}$$

To estimate the neutron dose using the alternative method by Wu and McGinley [29], the tenth value maze length T_N is first determined using Eq. (28):

$$T_N = 2.06 \times \sqrt{8.76} = 6.1\ \text{m}$$

The neutron dose at the maze entrance is then determined using Eq. (29), input data values listed in Example 10, and the value of φ_A obtained in Example 10:

$$D_n = 2.4 \times 10^{-15} \times 7.85 \times 10^9 \times \sqrt{10.2/8.76} \times \left[1.64 \times 10^{-\left(\frac{8.5}{1.9}\right)} + 10^{-\left(\frac{8.5}{6.1}\right)} \right]$$
$$= 0.83 \times 10^{-6}\ \text{Sv per X ray·Gy at isocentre}$$

For the room design as shown, this alternative method is expected to give a more accurate estimate than the Kersey method.

6.3.3.4. Example 12: Shielding barrier for the maze door

The maze entrance is located in a controlled area and the design limit is 0.1 mSv·week^{-1} according to the US NCRP standard [9] (half of 10 mSv·a^{-1}, divided by 50 weeks to obtain 0.1 mSv·week^{-1}).

The weekly neutron dose at the maze entrance is, using Eq. (30):

$$D_E = 600 \times 0.83 \times 10^{-6} = 5.0 \times 10^{-4}\ \text{Sv·week}^{-1}$$

To reduce the neutron dose of 5.0×10^{-4} Sv·week^{-1} to 0.1 mSv·week^{-1}, the number of TVLs required is

$$n = \log_{10}\left(\frac{0.5}{0.1}\right) = 0.7$$

Using a TVL of 45 mm for BPE (Section 5.7.3), the required thickness is (0.7 × 45 =) 32 mm for neutron shielding.

The weekly dose due to scatter and leakage (D_d from Example 9) and capture gamma (D_c from Example 10) is:

$$D_d + D_c = 6.95 \times 10^{-5} + 1.14 \times 10^{-4} = 0.18 \times 10^{-3}\ \text{Sv·week}^{-1}$$

To reduce the weekly dose from 0.18 mSv·week^{-1} to 0.1 mSv·week^{-1}, the number of TVLs required is:

$$n = \log_{10}\left(\frac{0.18}{0.1}\right) = 0.26$$

Using a TVL of 6 mm for lead (Section 5.7.3), the thickness required is (0.26 × 6 =) 1.5 mm.

The total shielding required for the maze door is 1.5 mm lead and 32 mm BPE. The BPE would then be sandwiched between two 0.75 mm thicknesses of lead.

7. WORKED EXAMPLES OF A SIMULATOR AND AN ORTHOVOLTAGE UNIT

7.1. SIMULATOR

A conventional simulator has an isocentric mounting, with radiographic and fluoroscopic capabilities. A simulator room is typically enclosed by gypsum wallboards or concrete walls. Additional shielding, if required, is usually provided by replacing or adding to the regular wall boards with lead-lined ones of specified lead equivalent thickness. The lead-lined wallboards need only extend up to a height of about 2.1 m, unless the ceiling does not adequately reduce the dose level above the simulator. The simulator should be positioned in the room so that the primary beam cannot directly strike any protective screens, windows or doors. The control console area should be shielded adequately from the primary, scatter and leakage radiation. This is usually achieved by the use of lead-lined gypsum board partition, with a leaded-glass window to allow full view of the patient and the simulator. The control console

area should be designed so that no primary or single scatter radiation reaches the operator directly. Although the control booth is for radiation workers only, the design dose limit is set to equal the limit for an uncontrolled or public area. A typical simulator room is shown in Fig. 15.

Shielding calculation methods described in Sections 5.1–5.3 are also applicable for simulator rooms. Because the patient attenuates the primary beam by a factor of up to 1000, the primary radiation scattered by the wall is usually negligible and may be ignored. The patient scatter may be evaluated using Eq. (9) and the scatter fraction '*a*' tabulated in Table 12 [38], or using the following equation and the scatter factor '*S*' [37] tabulated in Table 13 [37].

$$B_p = \frac{P d_{\mathrm{sca}}{}^2 d_{\mathrm{sec}}{}^2}{S W_{\mathrm{DAP}} T} \tag{32}$$

The parameters B_p, P, d_{sca}, d_{sec} and T are the same as those used in Eq. (9). The scatter factor S is the scatter air kerma at 1 m from the scatterer per dose-area product (DAP) at the location of the scatterer. The scatter factor is related to the scatter fraction by the following expression:

$$S = \frac{a}{400}$$

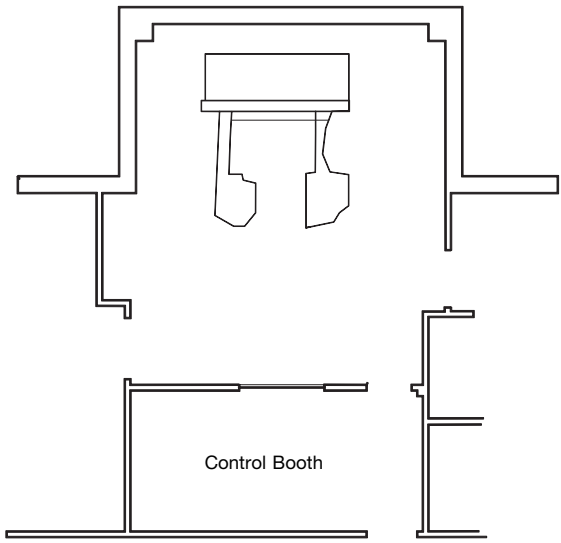

FIG. 15. A typical room for a simulator with fluoroscopy capability.

To evaluate the patient scatter using Eq. (9), data from Table 12 gives the scatter fraction of radiation at the point of interest based on the work of Simpkin and Dixon [38]. Scatter fractions recommended here are more conservative for shielding purposes than the values presented in NCRP 49 [2] as the measurements were made in such a way to minimize self-absorption by the scatterer. If Eq. (32) is used to evaluate patient scatter, then Table 13 gives the required scatter factor S, derived from measurements with a Rando phantom [37].

In Eqs (5), (8) and (9), the workload W is the air kerma in Gy·week^{-1}, based on the expected number of cases of patient simulation in a week. In Eq. (32) the weekly averaged dose–area product W_{DAP} may be measured by dose–area product (DAP) meters, and is in units of Gy·cm^2 (or Sv·cm^2 if P is expressed in Sv). The workload depends on the technique factors used in each case, or the readings from a DAP meter from an existing simulator could be used. If this information is not available, a weekly workload of 1 Gy (or 1000 mSv) at 1 m may be used with Eq. (9), or weekly DAP W_{DAP} of 400 Gy·cm^2 with Eq. (32). This workload is based on performing 25 simulation procedures weekly. Alternatively, the weekly workload may be approximated by measuring the air kerma at 1 m for a 20 cm × 20 cm field at 100 kVp and 40 mAs. The measured value is then scaled by 2.5 radiographic exposures per patient, using 100 kVp and 40 mAs per exposure, and 5 mA-min. of fluoroscopy exposure. The workload corresponding to this mA-min. usage is taken as 1 Gy-week^{-1}. However, if the expected weekly number of simulation procedures is significantly different from 25, or the usage pattern of radiographic and fluoroscopic exposure is significantly different from what is stated above, then the workload should be adjusted accordingly.

The use factor for each wall, ceiling and floor may be estimated based on actual usage. If the information is not available, a use factor of 0.25 may be used for the two walls and ceiling which form the primary barriers, and 1.0 for the floor. The use factor for leakage shielding is always unity.

To shield against radiation scattered by the patient for a secondary barrier, the allowed transmission B_p may also be determined from Eq. (9), as described above for the primary barrier. The scatter fraction or scatter factor for the worst case scenario should be used and the barrier design based on meeting the dose limit requirement for the worst case. Table 12 gives values of scatter fraction for angles up to 140°, and Table 13 gives values of scatter factor up to 150°. It is recommended that the maximum value is used and the barrier thickness determined for primary beam attenuation even though the scatter photon energy is reduced.

The required attenuation factors B for the barriers are calculated, and the lead, steel, or concrete thickness required may be obtained using Tables 15–18

(Refs [39–41]). The tables give the thickness of lead, concrete and steel for 100 kVp X rays. The maximum operational potential of the simulator may be higher, but the same tables should be used. Tables 15–17 are generated using mathematical models published by Archer et al. [39], and Simpkin [40]. Table 18 gives TVL data [41]. Note that the secondary X ray is composed of leakage and scatter and is more penetrating due to the hardening of the X ray filtered through the source head shielding.

7.1.1. Other shielding details

The image intensifier system or amorphous silicon flat panel usually intercepts the primary beam of a simulator. These systems may be considered part of the primary barrier if they are appropriately interlocked, such that the primary radiation is collimated to always fall within the boundaries of the imaging device and therefore always be attenuated. The image device may be assumed to fully attenuate the primary beam and shielding will only be required against the scatter and leakage. However, if there is no built-in image reception system, or the image reception system is retractable to allow part of the unattenuated beam to reach the wall, the primary barrier should be the full thickness. The width of the primary barrier should be larger than the diagonal dimension of the maximum field size.

The floor and ceiling construction design should be evaluated to ensure adequate shielding if radiation dose levels above and/or below the simulator are of concern.

The door into the simulator room is usually made of wood. If additional shielding is required, the wood door is lined with lead and the door frame should be lead-lined in such a way that the lead in the door and the lead in the frame will overlap.

The viewing window between the control room and the simulator should be lead glass with the same lead equivalent thickness as the barrier it replaces. The glass frame may need internal lead lining to avoid any gap between the glass and the lead-lined wallboard. Lead glass viewing windows are expensive and a closed circuit TV system between the control room and simulator room may be less costly.

Ventilation ducts, conduits, plumbing, etc., should penetrate the barriers at a height above 2.1 m from the floor, or otherwise should be located in a secondary barrier. If duct works or service boxes penetrate any barrier such that the transmitted radiation level will be increased, a radiation baffle may be needed to give the proper shielding effect. The actual design of the baffle should be carefully made based on the radiation beam orientation and field

size, the size and location of the opening, and the persons, instruments, or materials to be protected.

7.1.2. Dark room and film storage area

If required, the dark room and film storage area should be conveniently located near the simulator room. To avoid costly shielding, the dark room should not be adjacent to a primary barrier. The shielding for secondary radiation should extend higher than 2.1 m depending on the shelving designed for film storage.

The film pass-box between the darkroom and the simulator room should be interlocked so that the doors on the simulator side and on the dark room side cannot be opened simultaneously. The lead equivalent of the pass-box walls should provide adequate shielding to minimize fogging of the film in the cassette stored in the pass-box.

7.1.3. Example calculations

Consider shielding the primary and secondary barriers of a room shown in Fig. 16 used for conventional radiotherapy simulation using a high-frequency X ray generator with energies up to 125 kVp. The source–axis–distance of the simulator is 1 m. The weekly patient load is 50. Location 1 is in a parking lot, 3 m from the isocentre, with an occupancy factor T= 1/16. Location 2 is in a corridor, 3 m from the isocentre, and is designated a non-controlled (public) area, where the regulated shielding limit is 0.02 mSv/week [10] and the occupancy factor T is ¼. Location 3 is the control console area, 3.2 m from the isocentre, where the dose design limit is 0.1 mSv/week and the occupancy factor T = 1.

7.1.3.1. Example 1: Location 1, parking lot

Primary barrier shielding

The required attenuation B is determined from Eq. (5), where:

- P the design dose limit for a non-controlled area is 0.02 mSv/week. (1 mSv ÷ 50 = 0.02 mSv);
- d is 3 m;
- W is 2000 mSv/week (since the workload is 1000 mSv for 25 patients per week);

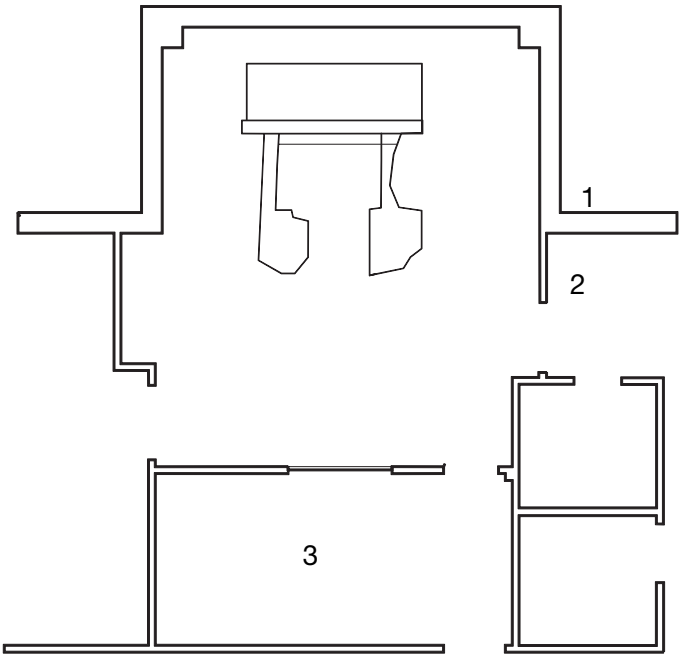

FIG. 16. Schematic layout of a simulator room.

U is ¼;
T is1/16

$$B = \frac{0.02 \times (3+1)^2}{2000 \times (1/4) \times (1/16)} = 1.02 \times 10^{2}$$

$$n = \log_{10}\left(\frac{1}{1.02 \times 10^{-2}}\right) = 2 \text{ TVL}$$

From Table 15, a barrier with 0.9 mm lead is needed for shielding the primary beam. The barrier can be shown to be adequate for leakage and scatter radiation as evaluated below.

Leakage radiation

The required attenuation B_L is determined from Eq. (8). It is assumed that the shielding in the X ray tube reduces the leakage radiation to 1/1000 of the useful beam, where:

P is 0.02 mSv/week;
d_s is 3 m;
W is 2000 mSv/week;
T *is* 1/16

$$B_L = \frac{1000 \times 0.02 \times 3^2}{2000 \times (1/16)} = 1.44 \quad \text{(0 TVLs)}$$

Since B is several orders of magnitude lower than B_L, the primary barrier thickness calculation is adequate for leakage protection.

Scatter radiation

The required attenuation B_p is determined from Eq. (9), where:

P is 0.02 mSv/week;
d_{sca} is 1 m;
d_{sec} is 3 m;
F is 400 cm^2;
a is the scatter fraction at 90° = 0.0021 for 125 kVp (from Table 12)

$$B_p = \frac{0.02 \times 1^2 \times 3^2}{0.0021 \times 2000 \times (1/16) \times (400/400)} = 0.68 \quad \text{(0 TVLs)}$$

Since there is a more than one TVL difference from the primary beam protection thickness of 2 TVLs obtained above, it is not necessary to add more shielding thickness to the primary barrier.

IDR and TADR considerations

Instantaneous dose rates are not usually applicable to diagnostic X ray facilities. While a megavoltage treatment field may take a fraction of a minute or more to deliver, a diagnostic X ray exposure will only take a fraction of a second. In clinical practice it is extremely unlikely that more than one exposure per minute would be made. It is not therefore practical to measure the IDR (averaged over one minute) for a diagnostic X ray exposure.

Additionally, for a diagnostic X ray facility the patient will attenuate the X ray beam by between 10^{-3} and 0.1, depending on the site and this should be taken into account when designing the shielding. (In contrast, for a

megavoltage facility the patient will only attenuate the X ray beam by 50% so the shielding is based on the unattenuated beam.) The total shielding required for Location 1 is 0.9 mm lead (2 TVLs).

7.1.3.2. Example 2: Location 2, corridor

Primary barrier shielding

The required attenuation B is determined from Eq. (5), where:

P is 0.02 mSv/week;
d is 3 m;
W is 2000 mSv/week;
U is 0.25;
T is 0.25

$$B = \frac{0.02 \times (3+1)^2}{2000 \times 0.25 \times 0.25} = 2.56 \times 10^{-3}$$

$$n = \log_{10}\left(\frac{1}{2.56 \times 10^{-3}}\right) = 2.6 \text{ TVL}$$

From Table 7.4, 1.4 mm lead is needed for shielding the primary barrier. The shielding for secondary radiation is considered below.

Leakage radiation

The required attenuation B_L is determined from Eq. (8), where:

P is 0.02 mSv/week;
d_s is 3 m;
W is 2000 mSv/week;
T is 0.25

$$B_L = \frac{1000 \times 0.002 \times 3^2}{2000 \times (0.25)} = 0.36$$

$$n = \log_{10}\left(\frac{1}{0.36}\right) - 0.44 \text{ TVL}$$

The primary barrier alone is adequate for both primary and leakage protection.

Scatter radiation

The required attenuation B_p is determined from Eq. (9), where:

P is 0.02 mSv/week;
d_{sca} is 1 m;
d_{sec} is 3 m;
a is 0.0034, the scatter fraction for the worst scenario at 0° (from Table 12);
T is 0.25,
F is 400 cm^2

$$B_p = \frac{0.02 \times 1^2 \times 3^2}{0.0034 \times 2000 \times (0.25) \times (400/400)} = 0.11$$

$$n = \log_{10}\left(\frac{1}{0.11}\right) = 1 \text{ TVL}$$

Since the requirement is more than one TVL less than the primary beam protection requirement of 2.6 TVLs obtained above, no additional shielding is needed. The total shielding required for Location 2 is 1.4 mm lead.

7.1.3.3. Example 3: Location 3, control console area

Secondary barrier shielding

Since it is not possible to direct the primary beam at Location 3, no primary barrier is needed, only a secondary barrier.

Leakage radiation

The required attenuation B_L is determined from Eq. (8), where:

P is 0.1 mSv/week;
d_s is 3.2 m;
W is 2000 mSv/week;
T is 1

$$B_L = \frac{1000 \times 0.1 \times 3.2^2}{2000 \times 1} = 0.51$$

$$n = \log_{10}\left(\frac{1}{0.51}\right) = 0.3 \text{ TVL}$$

From Table 15, 0.1 mm lead is needed for leakage protection as read from the secondary barrier data.

Scatter radiation

The required attenuation B_p is determined from Eq. (9), where:

P is 0.1 mSv/week;
d_{sca} is 1 m;
d_{sec} is 3.2 m;
a is 0.0021 from Table 12, for 125 kVp X rays at scatter angle 90°;
T is 1;
F is 400 cm^2

$$B_p = \frac{0.1 \times 1^2 \times 3.2^2}{0.0021 \times 2000 \times 1 \times (400/400)} = 0.24$$

$$n = \log_{10}\left(\frac{1}{0.24}\right) = 0.6 \text{ TVL}$$

From the secondary beam column of Table 15, the required thickness is 0.2 mm lead. Since it is only 0.3 TVLs different from the leakage protection requirement obtained above, it is necessary to add one HVL thickness to the thicker barrier. A thickness of 0.3 mm lead will be more than adequate.

7.1.3.4. Example 4: Location 3, control console area (with machine oriented such that the area is within primary radiation)

It is recommended that when planning a room, the simulator should be oriented so the primary beam will not be able to point towards the control console area. As an example, to show the shielding calculation for the case when the simulator has to be oriented in the room such that the primary beam may strike the barrier protecting the control console area, the following input data will be used to obtain the primary barrier thickness:

d is 3.2 m;
W is 2000 mSv/week;
U is ¼;
T is 1

$$B = \frac{0.1\times\ (3.2\ +1)^2}{2000\ \times\ (1/4)\ \times\ 1} = 3.53\times10^{\ 3}$$

$$n = \log_{10}\left(\frac{1}{7.06\times10^{-3}}\right) = 2.45 \text{ TVL}$$

From the primary beam column of Table 15, the required thickness is 1.3 mm lead. Since this is more than one TVL larger than the scatter and leakage barrier, the latter may be ignored.

7.2. SUPERFICIAL AND ORTHOVOLTAGE UNITS

A superficial treatment unit may operate between 50 and 150 kV and an orthovoltage X ray unit may operate in the range of 50 kV up to 300 kV. Both types of equipment require structural shielding. The protection requirement should be based on the highest energy at which the treatment unit may be used. In this energy range the photoelectric coefficient is large in materials with high atomic number (Z). Hence a thin layer of lead will be equivalent to a thick layer of concrete. The barriers would normally be constructed of concrete, which would be the cheapest option. However brick walls lined with lead would be another option if space were at a premium.

Superficial and orthovoltage units do not have isocentric mountings and the treatment machines can potentially irradiate all the shielding walls, floor and roof. The treatment unit should be positioned such that the main X ray beam will not be directed at the room door or viewing window during normal use of the unit. In some cases it may be necessary to restrict the use of the treatment unit for certain orientations with either mechanical or electrical stops. These limitations should be written into the requirements governing the use of the treatment unit.

For viewing the patient there are two options: a lead glass window in the barrier between the treatment room and the control desk, or closed circuit TV. Superficial and orthovoltage rooms do not normally have mazes but would have a lead lined door instead. The doors should have good overlaps and the door frames should also include lead protection with overlaps to the doors and the adjacent walls.

The dose rates produced by orthovoltage units are considerably less than those produced by megavoltage treatment units and the workload is therefore less. For X rays generated at 500 kV and below the exposure from leakage radiation will be of the same order as that from scattered radiation, namely 0.1% of the intensity of the primary beam at the scatterer. The scattered radiation is assumed to require the same attenuation as if it were primary

radiation. Tabulated values of TVL in the energy range 50–300 kV are given in Table 15 for lead, steel and concrete [41]. For these types of installations the use factor is taken to be 1 for the floor and 0.25 for the walls. The use factor for the ceiling will depend firstly on whether the unit can be physically aimed at the ceiling. In the past a use factor of 0.06 has been suggested for the ceiling [42], but a more conservative factor of 0.25 may be preferred. Each installation should be assessed independently.

7.2.1. Example calculations

An example of a layout for an orthovoltage room is shown in Fig. 17. The orthovoltage unit is mounted on a floor stand. Two of the room walls are external and one wall is a primary barrier for an adjacent megavoltage unit. The fourth wall has a control desk on the other side and also has a viewing window and entry door.

The orthovoltage unit operates at 250 kV. The dose rate at the treatment distance of 50 cm is 0.6 Gy·min^{-1}. The workload is 30 patients/d for 5 days/week, with an average dose of 4 Gy/patient at 50 cm. The value of W is $(30 \times 5 \times 4 \times (50/100)^2 =)$ 150 Gy·week^{-1} at 1 m.

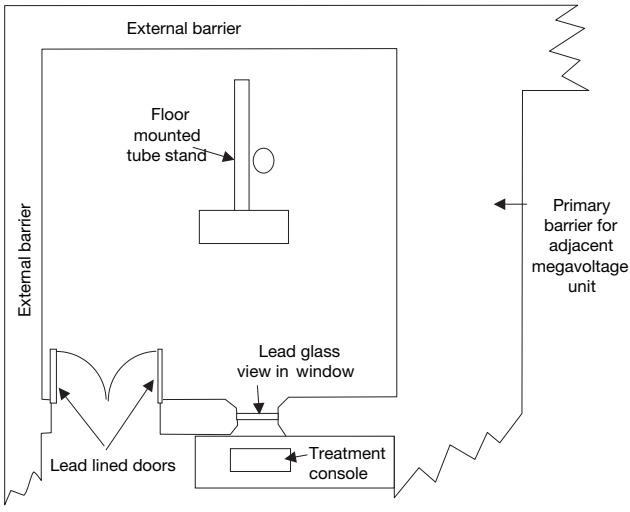

FIG. 17. Example layout of an orthovoltage room.

7.2.1.1. Example 1: Primary barrier calculation (control console on opposite side)

The necessary transmission for the barrier is determined from Eq. (5), where:

P is the design dose, is 0.12 mSv·week^{-1} (6 mSv/50 = 0.12 mSv);
d is the distance from the treatment position to the point of interest (treatment console), is 3 m;
SSD is 0.5 m;
W is the workload for a 5 day week is 150 Gy·week^{-1};
U is the use factor, is 0.25;
T is the occupancy factor is 1 for the treatment control area

$$B = \frac{0.12 \times 10^{-3} (3 + 0.5)^2}{150 \times 0.25 \times 1} = 3.92 \times 10^{-5}$$

The number of TVLs is given by Eq. (6):

$$\text{No. of TVLs} = \log_{10}\left(\frac{1}{3.92 \times 10^{-5}}\right) = 4.4$$

From Table 18, the TVL is 2.8 mm lead or 98 mm concrete. The primary barrier would need to be (2.8 mm × 4.4 =) 12.3 mm lead equivalent glass for the viewing window and (98 mm × 4.4 =) 430 mm concrete for the wall (concrete density 2350 kg·m^{-3}).

For the external walls the parameters will be the same except that the occupancy factor would be taken as 0.1. This may seem to be an unnecessarily high occupancy factor for an outside area, but the building may be extended in the future. With this value of occupancy the external walls would need to be 3.4 TVLs (98 mm × 3.4 =) 340 mm concrete. The thickness of the remaining wall is determined by the megavoltage treatment unit, which will exceed any requirement for the orthovoltage unit.

7.2.1.2. Example 2: IDR in the control area

The IDR at the control console is determined from the attenuated dose rate:

$$\text{IDR} = 0.6 \times \left(\frac{50}{100}\right)^2 \times 60 \times \left(\frac{1}{3.5}\right)^2 \times 3.92 \times 10^{-5} = 28.8\ \mu\text{Sv} \cdot \text{h}^{-1}$$

The TADR is determined from the daily beam-on time, which is the dose per patient divided by the dose rate multiplied by the number of patients:

$$\text{Daily beam-on time} = \frac{4}{0.6} \times 30 = 200 \text{ min or } 3.3 \text{ h}$$

Assuming a use factor of 0.25 and an 8 h day, the use of Eq. (1) gives:

$$\text{TADR} = 28.8 \times \frac{3.3 \times 0.25}{8} = 3.0 \ \mu\text{Sv} \cdot \text{h}^{-1}$$

These dose rates indicate that the area should be supervised as defined by the BSS [1] since the IDR is greater than 7.5 $\mu Sv \cdot h^{-1}$ and the TADR is greater than 2.5 $\mu Sv \cdot h^{-1}$ [6]. This means that the occupational exposure conditions must be kept under review though specific protective measures and safety provisions are not needed. In practice it is most likely that the primary beam will be attenuated by the patient and the actual dose rates will be much lower than calculated. However, procedures should prohibit the unattenuated beam being directed towards the control area during QC tests and radiation output measurements.

7.2.1.3. Example 3: Secondary barrier

If the movement of the unit is restricted so that it cannot be aimed at the entry door, then the entry door may be treated as a secondary barrier. This restriction must also be written into the operating procedures. Provided the area immediately outside the entry door is not used as a seating area, then it may be considered as a corridor with an occupancy factor of 0.2.

Leakage radiation

For therapy tube housings the leakage is limited to 10 mSv (1 R/h) at 1 m from the source. The dose rate is 0.6 $Gy \cdot min^{-1}$ at 50 cm equivalent to 9 $Gy \cdot h^{-1}$ at 1 m. Therefore, leakage is of the order of 1/1000 (0.1%).

The shielding necessary for a secondary barrier against leakage is determined from Eq. (8);

P is 0.12 $mSv \cdot week^{-1}$ (since the area beyond the secondary barrier is a controlled area);

d_s the distance from the treatment position to the point of interest is 3.5 m;
W the workload is 150 Gy·week^{-1};
T the occupancy factor, is 0.2

$$B_L = \frac{1000 \times 0.12 \times 10^{-3} \times 3.5^2}{150 \times 0.2} = 4.9 \times 10^{-2}$$

$$\text{No. of TVLs} = \log_{10}\left(\frac{1}{4.9 \times 10^{-2}}\right) = 1.3$$

Scattered radiation

The shielding required to protect against scattered radiation is determined from Eq. (9), where

P is 0.12 mSv·week^{-1};
d_{sca} is 0.5 m;
d_{sec} is 3.5 m;
a the scatter fraction for 90° scatter is 0.0019 (Table 14);
W the workload, is 150 Gy·week^{-1};
T the occupancy factor, is 0.2;
F the maximum field size, is 15 × 15 cm = 225 cm^2

$$B_p = \frac{0.12 \times 10^{-3} \times 0.5^2 \times 3.5^2}{0.0019 \times 150 \times 0.2 (225/400)} = 1.15 \times 10^{-2}$$

$$\text{No. of TVLs} = \log_{10}\left(\frac{1}{1.15 \times 10^{-2}}\right) = 1.9$$

The barrier requires 1.3 TVLs against leakage radiation and 1.9 TVLs against scattered radiation. These two values are within one TVL of each other, so the required barrier attenuation is 1.9 TVLs plus 1 HVL. The door, therefore, requires a lining of ((2.8 mm × 1.9) + 0. 84 mm =) 6.16 mm lead.

TABLE 12. SCATTER PRIMARY RATIO *a*, AT 1 m FROM A HUMAN SIZE PHANTOM, FOR A RADIATION FIELD SIZE OF 400 cm^2 AT THE PHANTOM SURFACE FOR A TARGET TO PHANTOM DISTANCE OF 1 m [38]

Scatter angle (from central ray)	Peak X ray energy				
	50 kVp	70 kVp	100 kVp	125 kVp	150 kVp
0	0.0029	0.0030	0.0032	0.0034	0.0035
10	0.0025	0.0026	0.0028	0.0030	0.0031
20	0.0022	0.0023	0.0025	0.0026	0.0028
30	0.0019	0.0020	0.0022	0.0024	0.0025
40	0.0017	0.0018	0.0020	0.0022	0.0023
50	0.0016	0.0017	0.0019	0.0020	0.0022
60	0.0015	0.0016	0.0018	0.0020	0.0021
70	0.0015	0.0016	0.0018	0.0020	0.0021
80	0.0015	0.0016	0.0018	0.0020	0.0021
90	0.0016	0.0017	0.0019	0.0021	0.0022
100	0.0017	0.0018	0.0020	0.0022	0.0023
110	0.0018	0.0020	0.0022	0.0023	0.0025
120	0.0020	0.0022	0.0023	0.0025	0.0027
130	0.0022	0.0024	0.0026	0.0027	0.0029
140	0.0025	0.0026	0.0028	0.0030	0.0031

TABLE 13. RATIO OF SCATTER KERMA TO DOSE–AREA PRODUCT (SCATTER FACTOR) S (μGy) (Gy · cm^2)$^{-1}$ AS A FUNCTION OF SCATTERING ANGLE (α) AND KILOVOLTAGE [37]

Scattering angle	Kilovoltage				
	50	70	85	100	125
30°	1.77	2.11	2.41	2.71	3.18
60°	1.82	2.14	2.40	2.70	3.16
90°	2.99	3.43	3.79	4.08	4.56
120°	5.53	6.32	6.82	7.27	7.89
150°	7.85	8.96	9.67	10.31	11.11

TABLE 14. SCATTER PRIMARY RATIO a, MEASURED AT 1 m FROM A HUMAN SIZE PHANTOM FOR A RADIATION FIELD SIZE OF 400 cm^2 AT THE PHANTOM SURFACE FOR A TARGET TO PHANTOM DISTANCE OF 1 m [43]

Energy	Scattering angle from central ray (degrees)					
	30	45	60	90	120	135
50 kV	0.0005	0.0002	0.00025	0.00035	0.0008	0.0010
100 kV	0.0015	0.0012	0.0012	0.0013	0.0020	0.0022
150 kV	0.0020	0.0016	0.0016	0.0016	0.0024	0.0026
200 kV	0.0024	0.0020	0.0019	0.0019	0.0027	0.0028
250 kV	0.0055	0.0021	0.0019	0.0019	0.0027	0.0028
300 kV	0.0026	0.0022	0.0020	0.0019	0.0026	0.0028

TABLE 15. LEAD THICKNESS AND THE CORRESPONDING ATTENUATION FACTOR *B* FOR SIMULATOR ROOM PRIMARY AND SECONDARY SHIELDING CALCULATIONS, 100 kVp X RAY [39, 40]

Thickness (mm)	Required attenuation, *B*		Thickness (mm)	Required attenuation, *B*	
	Primary	Secondary		Primary	Secondary
0	1.00E+00	1.00E+00			
0.1	3.01E–01	3.20E–01	2.6	1.13E–04	1.72E–04
0.2	1.47E–01	1.67E–01	2.7	8.79E–05	1.34E–04
0.3	8.53E–02	1.02E–01	2.8	6.84E–05	1.04E–04
0.4	5.44E–02	6.78E–02	2.9	5.32E–05	8.11E–05
0.5	3.66E–02	4.72E–02	3.0	4.14E–05	6.31E–05
0.6	2.55E–02	3.39E–02	3.1	3.22E–05	4.91E–05
0.7	1.83E–02	2.48E–02	3.2	2.51E–05	3.82E–05
0.8	1.33E–02	1.84E–02	3.3	1.95E–05	2.97E–05
0.9	9.85E–03	1.38E–02	3.4	1.52E–05	2.31E–05
1.0	7.36E–03	1.05E–02	3.5	1.18E–05	1.80E–05
1.1	5.54E–03	7.99E–03	3.6	9.21E–06	1.40E–05
1.2	4.20E–03	6.12E–03	3.7	7.17E–06	1.09E–05
1.3	3.20E–03	4.70E–03	3.8	5.59E–06	8.49E–06
1.4	2.45E–03	3.62E–03	3.9	4.35E–06	6.60E–06
1.5	1.88E–03	2.79E–03	4.0	3.39E–06	5.14E–06
1.6	1.45E–03	2.16E–03	4.1	2.64E–06	4.00E–06
1.7	1.11E–03	1.67E–03	4.2	2.05E–06	3.11E–06
1.8	8.61E–04	1.30E–03	4.3	1.60E–06	2.42E–06
1.9	6.66E–04	1.01E–03	4.4	1.25E–06	1.89E–06
2.0	5.16E–04	7.81E–04	4.5	9.70E–07	1.47E–06
2.1	4.00E–04	6.07E–04	4.6	7.56E–07	1.14E–06
2.2	3.10E–04	4.71E–04	4.7	5.88E–07	8.89E–07
2.3	2.41E–04	3.66E–04	4.8	4.58E–07	6.92E–07
2.4	1.87E–04	2.85E–04	4.9	3.57E–07	5.38E–07
2.5	1.45E–04	2.22E–04	5.0	2.78E–07	4.19E–07

TABLE 16. CONCRETE THICKNESS AND THE CORRESPONDING ATTENUATION FACTOR *B* FOR SIMULATOR ROOM PRIMARY AND SECONDARY SHIELDING CALCULATIONS, 100 kVp X RAY [39, 40]

Thickness (mm)	Required attenuation, *B*		Thickness (mm)	Required attenuation, *B*	
	Primary	Secondary		Primary	Secondary
0	1.00E+00	1.00E+00			
5	5.63E–01	5.70E–01	130	4.89E–04	7.15E–04
10	3.42E–01	3.54E–01	135	3.96E–04	5.81E–04
15	2.20E–01	2.33E–01	140	3.20E–04	4.73E–04
20	1.47E–01	1.60E–01	145	2.60E–04	3.85E–04
25	1.02E–01	1.13E–01	150	2.11E–04	3.14E–04
30	7.18E–02	8.19E–02	155	1.72E–04	2.56E–04
35	5.18E–02	6.04E–02	160	1.40E–04	2.09E–04
40	3.80E–02	4.53E–02	165	1.14E–04	1.71E–04
45	2.83E–02	3.43E–02	170	9.26E–05	1.40E–04
50	2.13E–02	2.63E–02	175	7.55E–05	1.14E–04
55	1.62E–02	2.03E–02	180	6.16E–05	9.33E–05
60	1.24E–02	1.58E–02	185	5.03E–05	7.64E–05
65	9.59E–03	1.24E–02	190	4.11E–05	6.25E–05
70	7.45E–03	9.79E–03	195	3.36E–05	5.12E–05
75	5.82E–03	7.75E–03	200	2.75E–05	4.19E–05
80	4.58E–03	6.16E–03	205	2.25E–05	3.43E–05
85	3.61E–03	4.92E–03	210	1.84E–05	2.81E–05
90	2.86E–03	3.93E–03	215	1.51E–05	2.30E–05
95	2.27E–03	3.16E–03	220	1.23E–05	1.89E–05
100	1.81E–03	2.54E–03	225	1.01E–05	1.55E–05
105	1.45E–03	2.05E–03	230	8.27E–06	1.27E–05
110	1.16E–03	1.65E–03	235	6.78E–06	1.04E–05
115	9.33E–04	1.34E–03	240	5.56E–06	8.52E–06
120	7.51E–04	1.08E–03	245	4.56E–06	6.99E–06
125	6.05E–04	8.80E–04	250	3.74E–06	5.73E–06

TABLE 17. STEEL PLATE THICKNESS AND THE CORRESPONDING ATTENUATION FACTOR *B* FOR SIMULATOR ROOM PRIMARY AND SECONDARY SHIELDING CALCULATIONS, 100 kVp X RAY [39, 40]

Thickness (mm)	Required attenuation, *B*		Thickness (mm)	Required attenuation, *B*	
	Primary	Secondary		Primary	Secondary
0	1.00E+00	1.00E+00			
1	2.01E–01	2.23E–01	26	9.06E–06	1.45E–05
2	8.57E–02	1.04E–01	27	6.44E–06	1.03E–05
3	4.55E–02	5.89E–02	28	4.57E–06	7.32E–06
4	2.68E–02	3.65E–02	29	3.25E–06	5.20E–06
5	1.68E–02	2.37E–02	30	2.31E–06	3.69E–06
6	1.09E–02	1.58E–02	31	1.64E–06	2.62E–06
7	7.26E–03	1.08E–02	32	1.17E–06	1.86E–06
8	4.91E–03	7.42E–03	33	8.29E–07	1.32E–06
9	3.37E–03	5.16E–03	34	5.89E–07	9.38E–07
10	2.33E–03	3.61E–03	35	4.19E–07	6.66E–07
11	1.62E–03	2.54E–03	36	2.97E–07	4.73E–07
12	1.14E–03	1.79E–03	37	2.11E–07	3.36E–07
13	7.97E–04	1.26E–03	38	1.50E–07	2.38E–07
14	5.61E–04	8.93E–04	39	1.07E–07	1.69E–07
15	3.96E–04	6.32E–04	40	7.59E–08	1.20E–07
16	2.80E–04	4.48E–04	41	5.39E–08	8.54E–08
17	1.98E–04	3.18E–04	42	3.83E–08	6.06E–08
18	1.40E–04	2.25E–04	43	2.72E–08	4.30E–08
19	9.96E–05	1.60E–04	44	1.94E–08	3.06E–08
20	7.06E–05	1.13E–04	45	1.38E–08	2.17E–08
21	5.01E–05	8.05E–05	46	9.78E–09	1.54E–08
22	3.56E–05	5.72E–05	47	6.95E–09	1.09E–08
23	2.53E–05	4.06E–05	48	4.94E–09	7.77E–09
24	1.80E–05	2.88E–05	49	3.51E–09	5.52E–09
25	1.28E–05	2.05E–05	50	2.49E–09	3.92E–09

TABLE 18. TENTH VALUE LAYER DATA FOR EFFECTIVE GENERATING VOLTAGES (BROAD BEAM) IN THE RANGE OF SUPERFICIAL AND ORTHOVOLTAGE ENERGIES [41]

Effective generating voltage	Attenuating material (mm)		
	Lead	Steel	Concrete
50 kV	0.2	1.6	17
100 kV	0.9	8.1	61
200 kV	1.7	17.8	93
250 kV	2.8	20.1	98
300 kV	4.6	22.2	106

8. WORKED EXAMPLE OF A BRACHYTHERAPY FACILITY

8.1. DESIGN CONCEPTS

The following information has been drawn from Refs [3, 41]. Brachytherapy is radiation treatment with sealed radioactive sources that may be placed within body cavities, within the tissues or very close to the surface to be treated. The duration of the treatment may range from a few minutes for HDR brachytherapy up to several days for LDR interstitial therapy. Many different nuclides are available for clinical use. They may be of low energy requiring minimal shielding or high energy requiring the use of specially designed rooms. LDR brachytherapy is performed either by manually loading sources into applicators that have been positioned in the patient or by remote after-loading. The remote after-loader stores the sources in a shielded position and, when required, will drive them into the applicators. It will also retract the sources during the treatment whenever a person needs to attend to the patient and also at the end of the prescribed treatment time. Rooms used for LDR brachytherapy may not need special shielding. The layout of the room should allow patients to be nursed safely and also to be used for non-brachytherapy patients.

HDR brachytherapy is only performed with remote after-loading units, and requires special facilities. The remainder of this section will deal with specially designed rooms.

When designing a room for brachytherapy, the following points should be considered:

— Which treatment techniques will the room be used for?
— What is the likely number of patients per day/week/year?
— How much radioactivity will be used per treatment/procedure?
— Which nuclides will be used and what is their energy?
— Where will sources be stored prior to use and after their removal?
— How will the security performance objectives for brachytherapy be achieved? (See Chapter 3 and, specifically, Section 3.11 for further information.)

Specially designed rooms should have sufficient shielding to limit the radiation dose received by other patients, nursing staff and members of the public in the surrounding area to allowable levels.

The room should be accessible from the operating theatre and X ray and CT facilities. Also, its location relative to the surrounding area, including facilities above and below the intended location, should be considered.

In brachytherapy, the protection must be sufficient to reduce the primary and scattered radiation to the design limit in all directions since the sources are unshielded in all directions. The dose rate within the room will be more than 7.5 $\mu Sv \cdot h^{-1}$ and the room will be designated a controlled area [6]. The dose rate outside the brachytherapy room should be reduced to 2.5 $\mu Sv \cdot h^{-1}$. With this design dose limit a patient in an adjoining room for a 24 hour treatment would receive 60 μSv. The annual dose constraint of 0.3 mSv [7] would be reached after five treatment days and this should be considered when designing the facility and its location. The patient receiving brachytherapy will attenuate the radiation. The extent of the attenuation will depend on the energy of the nuclide in use, the size of the patient and the location of the source(s) within the patient.

Since brachytherapy sources are not collimated, the shielding requirements will be based on the transmission of the primary beam through the barriers. If possible the room should be designed so that there is no direct line from the door to the patient's bed. If there is sufficient space for a maze, a protected room door may be unnecessary, but otherwise a lead-lined door will normally be needed.

A definitive area around the patient where the dose rate exceeds 7.5 $\mu Sv \cdot h^{-1}$ must be designated as a controlled area — this area will normally be

defined by the treatment room walls and radiation warning signs can be posted outside the room [6]. A β–γ monitor which measures the dose rate in the patient area should be clearly visible at the entrance to the controlled area.

It is recommended that there be remote viewing of the patient from the nurse's station by closed circuit TV, together with a two way intercom to reduce the amount of time nursing staff need to spend in the radiation environment. It should be possible to view access to the room from the nurse's station.

8.2. LDR AND MDR TREATMENT ROOMS

For remote after-loading systems (either LDR or MDR) the treatment room door will be interlocked to the after-loading unit so that the radiation exposure of nursing staff is minimized. Mobile lead shields may be used to reduce radiation dose rates when ideal requirements are not possible. The weight and the need to maintain manoeuvrability of the shield limit the thickness and size of mobile lead shields. Lead shields typically have a thickness of 25 mm and a shielded area of 700–1000 mm by 500–600 mm. They are usually designed to protect the abdomen of a worker who stands behind them.

Some after-loading machines allow the treatment of more than one patient at a time so a suite of rooms will be required. Space will be needed for the after-loading machine itself and the source transfer tubes. Ideally, the after-loading unit will be stored outside the treatment room in a separate closed area. This allows for servicing of the unit when a patient not receiving brachytherapy occupies the treatment room.

8.3. HDR TREATMENT ROOMS

HDR remote after-loading units need special facilities. All the walls, the floor and the ceiling will be primary barriers and must be of adequate thickness to protect the staff, who remain outside the room during the patient treatment. It is advisable to limit the position of the source within the room otherwise all the shielding requirements will need to be determined based on the source being in any position within the room. This may make the barriers unnecessarily thick. HDR sources are usually ^{192}Ir or ^{60}Co. For both sources, the high activity and HDRs require that the room have concrete barriers 400–800 mm thick. They will also need a heavy lead door unless a maze has been included in the design. HDR units are often installed in former radiotherapy treatment rooms that already have sufficiently thick walls, ceilings, floors and mazes or shielded doors.

In HDR brachytherapy the patients are often treated directly after the appliances have been positioned. Ideally, there will also be an X ray facility within the room so that the correct placement of the applicators can be confirmed immediately prior to the treatment being delivered. A waiting area for a patient on a trolley may be required where the patient may be nursed while the treatment planning calculations are completed.

An HDR facility should have an interlocked room door so that the source is returned to the safe position whenever the door is opened, and there should be a radiation warning sign at the room entrance indicating the 'on-off' status of the source.

Examples of treatment types and barrier thicknesses are given in Table 19.

8.4. CALCULATION METHODS

To determine the required attenuation of the primary barriers, Eq. (5) is used. For brachytherapy the workload W is based on the dose delivered per treatment and the number of treatments:

$$W = \mathrm{RAKR} \times A \times t \times n \tag{33}$$

where

$RAKR$ is the reference air kerma rate for a source of unit activity;
A is the total activity (activity per source × number of sources);
t is the average duration of treatment in hours;
n is the number of treatments per week.

Using the AAPM Report 21 specifications [44], the workload may be represented by:

$$W = S_k \times t \times n \tag{34}$$

where

S_k is the air kerma strength of the source in units of U or $\mu Gy \cdot m^2 \cdot h^{-1}$.

Similarly, the dose rate D_0 will be given by:

$$D_0 = \mathrm{RAKR} \times A \tag{35}$$

or, using the AAPM Report 21 specifications [44]:

$$D_0 = S_k \tag{36}$$

For brachytherapy the sources are not collimated so the use factor U will always be unity.

A modified version of Eq. (5) for brachytherapy shielding may be written as:

$$B = \frac{Pd^2}{\text{RAKR} \times A \times t \times n \times T} \tag{37}$$

or

$$B = \frac{Pd^2}{S_k \times t \times n \times T} \tag{38}$$

where

P is the design limit;
d is the distance, in m, from the exposed source position to the point of interest outside the barrier;
T is the occupancy of the area outside the barrier.

Unlike megavoltage bunkers, brachytherapy rooms are not used so regularly. Their use is often limited by the number of operating room sessions available for placing the source applicators in the patient. Consequently, basing the shielding design on an annual dose limit may result in high IDRs outside the barriers. This may necessitate these areas being designated as controlled areas during the course of the treatment if the IDR exceeds 7.5 $\mu Sv \cdot h^{-1}$ [6, 7]. It is therefore recommended that the IDR be assessed (based on the maximum number of sources normally used) and also the maximum dose rate (based on the maximum number of sources available) before finalizing the shielding design.

8.5. EXAMPLE CALCULATIONS

The HDR room in Fig. 18 is to be used for gynaecological treatments. The HDR unit contains 20 ^{60}Co sources each of 18.5 GBq (500 mCi). The reference air kerma rate (RAKR) for ^{60}Co is 0.308 μGy·MBq^{-1}·m^2·h^{-1} (Table 20). Using the AAPM Report 21 specifications [44], the air kerma strength of each source is 5.70 kU, or 5.70 mGy·m^2·h^{-1}. The intended workload is 30 treatments per week. In general, 13 sources are used for a medium intra-uterine tube with ovoids and 15 sources for a long intra-uterine tube with ovoids. The shielding design will be based on the use of 15 sources per patient with a total activity of 277.5 GBq (7.5 Ci). The average treatment duration is 6 min (0.1 h) to deliver an absorbed dose of 7.5 Gy to the prescription point. The weekly workload is obtained from Eq. (33):

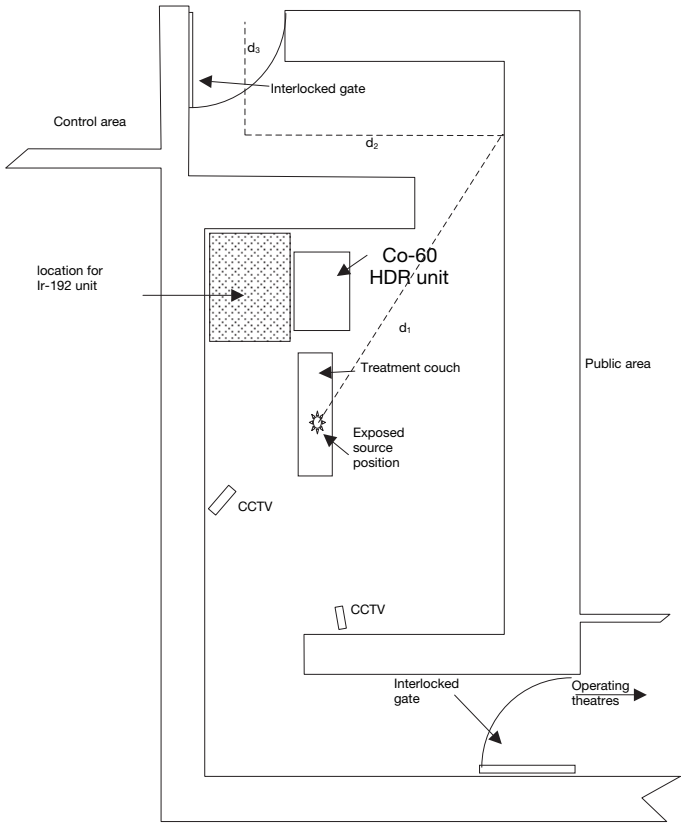

FIG. 18. Plan of an HDR ^{60}Co treatment room.

$$W = 0.308 \times 277.5 \times 10^3 \times 0.1 \times 30 = 2.56 \times 10^5 \ \mu\text{Gy} \cdot \text{m}^2$$

The design limit is 6 μSv/week for a public area ($T = 0.1$) at 3.5 m from the treatment position of the sources.

The required transmission through the barrier is determined from Eq. (5):

$$B = \frac{6(3.5)^2}{2.56 \times 10^5 \times 0.1} = 2.87 \times 10^{-3}$$

Therefore, the number of TVLs required for the barrier shielding is:

$$\log_{10}\left(\frac{1}{2.87 \times 10^{-3}}\right) = 2.54$$

The TVL of ^{60}Co is 218 mm in concrete (Table 22 [2]), so the barrier would need to be (218 × 2.54 =) 554 mm thick to meet the annual dose constraint of 0.3 mSv/a.

However, the IDR for the worst case with all 20 sources exposed must also be considered:

$$D_0 = 0.308 \times 18.5 \times 10^3 \times 20 = 113{,}960 \ \ \mu\text{Gy} \cdot \text{h}^{-1} \cdot \text{m}^2$$

To reduce the dose rate to the design limit for an unsupervised public area, the IDR must be less than 7.5 μSv·h^{-1} [6] at 3.5 m from the source:

$$B = \frac{7.5(3.5)^2}{113{,}960} = 8.1 \times 10^{-4}$$

$$\text{No. of TVLs} \ = \log_{10}\left(\frac{1}{8.1 \times 10^{-4}}\right) = 3.1$$

So the barrier would need to be (218 × 3.1 =) 676 mm thick concrete for the worst case scenario.

For a worst case, assume 5 patients per 8 hour day with the maximum number of sources, and a treatment period of 0.1 h (6 min) per patient. Also assume that the patient attenuates the radiation by 0.81 for a 10 cm depth in tissue (Table 21 [45]). The TADR will be (7.5 × 0.1 × 0.81 × 5/8 =) 0.38 μSv·h^{-1}.

This still falls below the upper guidance limit of a TADR of less than 0.5 μSv·h^{-1} for a non-supervised area [6] so the area would not need to be designated as a supervised or controlled area provided the barrier thickness was 676 mm concrete.

The dose rates at the maze entrances to the treatment room must also be determined. The method is similar to that for a megavoltage treatment room maze except that there is no separate leakage radiation to consider. The dose at the maze entrance will arise from primary radiation transmitted through the patient and the maze wall and from primary radiation scattered by the wall down the maze entrance. The required attenuation through the maze wall as a primary barrier is determined from Eq. (5). The design limit P is 7.5 μSv·h^{-1} and d the distance from the exposed sources to the maze entrance is 5 m. The shielding is determined for 15 sources as before:

$$B = \frac{7.5\left(5^2\right)}{0.308 \times 18.5 \times 10^3 \times 15} = 2.2 \times 10^{-3}$$

which gives 2.7 TVLs. The maze wall needs to be (218 mm × 2.7 =) 589 mm thickness of concrete.

Since the patient attenuates the radiation by 0.81 (Table 21), the actual dose rate will be (7.5 × 0.81 =) 6.08 μSv·h^{-1}.

The scatter down the maze is determined from Eq. (14). In the example below, the dose rate at the outer maze entrance is determined. The distance from the exposed sources to the inner maze entrance is 4.5 m (d_1), the length of the inner leg of the maze axis is 3.75 m (d_2), and the outer leg is 1 m (d_3), as shown in Fig. 18. The ceiling is 2.2 m high throughout. The inner maze entrance is 1.25 m wide, and the main maze is 1.5 m wide. The reflection coefficients for ^{60}Co for concrete (Tables 6 and 7) are 1.02×10^{-2} for 45° incidence and 0° reflection (first scatter), and 4.06×10^{-3} at normal incidence and 75° reflection (second scatter):

$$\mathrm{DR}_w = \frac{0.308 \times 18.5 \times 10^3 \times 15 \times 0.81}{4.5^2}$$

$$\times \frac{1.02 \times 10^{-2} \times \left(1.5 \times 2.2\right) \times 4.06 \times 10^{-3} \times \left(1.5 \times 2.2\right)}{3.75^2 \times 1^2} = 0.11 \text{ μSv·h}^{-1}$$

Therefore, the total dose rate at the maze entrance will be (6.08 + 0.12 =) 6.2 μSv·h^{-1}, which is satisfactory.

The room may be used in the future with an HDR unit containing a single 370 GBq ^{192}Ir source (e.g. Microselectron by Nucletron). The intended workload is again 30 treatments per week with a prescribed dose of 7.5 Gy at 1 cm, with an average treatment time of 10 min (0.167 h). The RAKR for ^{192}Ir is 0.111 $\mu Gy \cdot h^{-1} \cdot MBq^{-1} \cdot m^2$ (Table 20).

The weekly workload is determined from Eq. (33):

$$W = 0.111 \times 370 \times 10^3 \times 0.167 \times 30 = 2.06 \times 10^5 \ \ \mu Gy \cdot m^2$$

For the same public area in Fig. 18, with an occupancy T of 0.1 and a design limit of 6 μSv/week, the attenuation required for the barrier is given by Eq. (37):

$$B = \frac{6(3.5)^2}{2.06 \times 10^5 \times 0.1} = 3.6 \times 10^{-3} \text{ (2.45 TVLs)}$$

The number of TVLs is similar to the requirement for ^{60}Co; however, for ^{192}Ir the TVL in concrete is only 152 mm compared with 218 mm for ^{60}Co. Any shielding designed for an HDR ^{60}Co unit should be more than adequate for an ^{192}Ir unit. However it would be important to restrict the position of the ^{192}Ir mobile unit within the room to the area indicated in Fig. 18, and the patient position for treatment should also be as shown.

8.6. DATA

TABLE 19. EXAMPLES OF TREATMENT TYPES AND TYPICAL CONCRETE BARRIER THICKNESSES AT 3 m FROM A RADIATION SOURCE [3]

Treatment type	Nuclide	Activity (GBq)	Concrete thickness (mm) to reduce dose rate to	
			7.5 $\mu Sv \cdot h^{-1}$	2.5 $\mu Sv \cdot h^{-1}$
MDR afterloading	Caesium-137	22.2	280	360
HDR afterloading	Cobalt-60	185	680	770
LDR afterloading	Iridium-192	37	310	360
HDR afterloading	Iridium-192	370	440	510

TABLE 20. PHYSICAL DATA OF SOME NUCLIDES USED FOR BRACHYTHERAPY

Nuclide	Mean photon energy (MeV)	Half-life	RAKR ($\mu Gy \cdot MBq^{-1} \cdot m^2 \cdot h^{-1}$)
Co-60	1.25	5.27 a	0.308
I-125	0.028	60.1 d	0.034
Cs-137	0.662	30.0 a	0.077
Ir- 192	0.37	74.0 d	0.111
Au-198	0.42	64.7 h	0.056
Ra-226	0.78	1600 a	0.195

TABLE 21. COMPUTED VALUES OF BRACHYTHERAPY TISSUE AIR RATIO ($F_2(D, \theta)$ FOR PATH LENGTH OF 10 cm IN WATER [45]

Nuclide	Co-60	Cs-137	Ir-192	Au-198	Ra-226
Tissue air ratio	0.81	0.86	0.93	0.90	0.86

TABLE 22. APPROXIMATE VALUES OF HALF AND TENTH VALUE LAYERS BASED ON LARGE ATTENUATION FOR RADIONUCLIDES USED IN BRACHYTHERAPY [2] (APPENDIX D, FIGS 11–13[a])

Nuclide	Lead		Steel		Concrete	
	HVL (mm)	TVL (mm)	HVL (mm)	TVL (mm)	HVL (mm)	TVL (mm)
Co-60	12 ($HVL_1 = 15$)	41	21 ($HVL_1 = 35$)	71 ($TVL_1 = 87$)	62	218 ($TVL_1 = 245$)
I-125 [46]	0.03	0.1	—	—	—	—
Cs-137	6.5	22	16 ($HVL_1 = 30$)	53 ($TVL_1 = 69$)	48	175
Ir-192	6	16	13 ($HVL_1 = 19$)	43 ($TVL_1 = 49$)	43	152
Au-198	3.3	11[b]	—	—	41	142
Ra-226	16.6	45	22 ($HVL_1 = 35$)	76 ($TVL_1 = 86$)	69	240

[a] First HVL and first TVL values are given where they differ greatly from the approximate values based on large attenuation. In these cases, the first TVL and first HVL should be used in calculations where less than 2 TVLs or less than 7 HVLs of shielding material are needed.

[b] Holds for the first two TVLs and increases to 16 mm thereafter.

TABLE 23. HALF VALUE LAYERS AND TENTH VALUE LAYERS FOR 90° SCATTERING FROM GAMMA RAYS [47]

Nuclide		HVL	TVL_1	TVL_2	TVL_3
Cobalt-60	Lead	1.3	6.5	11.1	—
	Concrete	44	142	141	122
Caesium-137	Lead	0.6	3.2	5.5	7.0
	Concrete	37	84	122	123

9. WORKED EXAMPLES FOR SPECIAL PROCEDURES

9.1. SPECIAL RADIOTHERAPY PROCEDURES

The calculation methods described in Section 5 are most appropriate for the evaluation of treatment room barriers for conventional radiotherapy treatment procedures. With some minor modifications they are also applicable for special radiotherapy procedures such as total body irradiation (TBI) and intensity modulated radiation therapy (IMRT), and for quality assurance (QA) and other beam-on activities.

9.1.1. Total body irradiation

The workload (Gy·week^{-1} at 1 m) for TBI is usually significantly higher than conventional radiotherapy treatments for the same unit patient dose because extended treatment distances are used. The workload for leakage radiation is also higher for the same reason, and is different from the workload for patient scatter and wall scatter. The primary barrier thickness usually needs to be increased appropriately depending on the workload and use factor. If the procedure is limited to one gantry angle and one primary barrier, the cost of adding shielding thickness may be kept to a minimum.

The TBI workload W_{TBI} is the dose at 1 m, and therefore is the product of the weekly total patient dose PD_{TBI} , and the square of the treatment distance d_{TBI}, as shown in the equation:

$$W_{TBI} = PD_{TBI} \times d_{TBI}^{2} \tag{39}$$

where d_{TBI} is the TBI treatment distance in m.

Since the patient is usually positioned close to one of the primary barriers for the TBI procedure, instead of at the isocentre, the effect of patient scatter at the room entrance should be considered. This is especially true if there is a maze instead of a direct shielded door. In some room arrangements the source of scattered radiation (the TBI patient) will be much closer to the room entrance than the isocentre, and the consequent dose rate at the entrance will be higher.

9.1.2. Intensity modulated radiation therapy

IMRT procedures use small pencil beams produced by multi-leaf collimators or mechanical shutters. Due to the small field sizes of a large number of beamlets used, the accelerator monitor units (MU) required are much higher than would have been required for conventional radiotherapy for the same patient dose. The ratio of the MU for IMRT and the MU for conventional treatment delivering the same prescribed dose is called the IMRT factor, C_I. The IMRT factor C_I may be obtained using the following method. Take a sample of IMRT cases and calculate the average total MU required to deliver a unit prescribed dose. The quantity M_{IMRT} is first calculated using the equation:

$$M_{\mathrm{IMRT}} = \frac{\mathrm{Average\ \ total\ \ MU}}{\mathrm{Dose(Gy)}} \tag{40}$$

Then calculate or measure the MU required to deliver the same unit dose to a phantom at $d_{\max}$ depth at 100 cm SSD, using field size 10 cm × 10 cm, to obtain the quantity M_{conv}. The IMRT factor C_I is simply equal to M_{IMRT} divided by M_{conv}:

$$C_I = \frac{M_{\mathrm{IMRT}}}{M_{\mathrm{conv}}} \tag{41}$$

The factor C_I can have values from 2 to 10 or more. The increase in MU does not significantly increase the workload for the primary barrier, the patient scatter, or the wall scatter components of the secondary barrier. This is because the patient dose is similar for IMRT compared with conventional radiotherapy. However, the leakage workload is significantly higher by a factor equal to the IMRT factor C_I.

9.1.3. Quality assurance

If QA measurements are routinely performed during normal working hours, and the workload is not negligible compared with the conventional treatment workload, the impact on barrier shielding requirements should be evaluated. QA measurements include daily, monthly and annual tests, commissioning measurements, IMRT dose verifications, research, and other activities conducted with radiation on. If IMRT dose verification constitutes a significant

part of the QA measurements, a QA factor (C_{QA}) similar to the IMRT factor may be required to account for the increase in MU.

9.2. SHIELDING CALCULATIONS

9.2.1. Primary barrier calculations

The primary barrier and wall scatter of the primary beam to the secondary barrier may be evaluated using Eqs (5) and (10) in Section 5. To account for the difference in usage described above, the products of workload and use factor in the two equations are replaced by the sum of the products of the workload and use factor for each technique (conventional treatments, TBI, IMRT, QA and other non-conventional treatment procedures and activities):

$$\mathrm{WU}]_{\mathrm{pri}} = \mathrm{WU}]_{\mathrm{wall\ scat}} = W_{\mathrm{conv}}U_{\mathrm{conv}} + W_{\mathrm{TBI}}U_{\mathrm{TBI}} + W_{\mathrm{IMRT}}U_{\mathrm{IMRT}} + W_{\mathrm{QA}}U_{\mathrm{QA}} + ... \quad (42)$$

where

$\mathrm{WU}]_{\mathrm{pri}}$ and $\mathrm{WU}]_{\mathrm{wall\ scat}}$ are the workload–use products for the primary barrier and wall scatter;

W_x is the workload in Gy/week at 1 m for procedure type x;

U_x is the use factor or fraction of time that the beam is likely to be incident on the barrier for procedure type x.

9.2.2. Patient scatter calculations

The shielding required against the patient scatter component for the secondary barrier is evaluated with Eq. (9). The workload will be given by the sum of the workloads for all techniques performed at the isocentre. The use factor is taken as unity for patient scatter considerations:

$$W]_{\mathrm{pat\ scat_{iso}}} = W_{\mathrm{conv}} + W_{\mathrm{IMRT}} + W_{\mathrm{QA}} + ... \quad (43)$$

For TBI performed at extended SSD, the patient scatter arises from a different location than the isocentre. Consequently, the values d_{sca} and d_{sec} will be different. The shielding required for the TBI component of patient scatter therefore needs to be determined separately with Eq. (9).

If the TVLs required to shield the two components of patient scatter (isocentric and TBI) differ by less than 1 TVL, then use the larger and add a further HVL of shielding. Otherwise use the larger value.

9.2.3. Leakage shielding considerations

For leakage considerations, Eq. (8) may be used. The workload W_L is given by the following:

$$W_L = W_{\text{conv}} + W_{\text{TBI}} + C_{\text{I}} \times W_{\text{IMRT}} + C_{\text{QA}} \times W_{\text{QA}} + ... \quad (44)$$

where W_{TBI} is determined from Eq. (39).

9.2.4. Maze entrance calculations

The method for evaluating the maze entrance dose is described in Section 5.4. Equations (13)–(15) are used for obtaining the doses at the maze entrance due to patient scatter, wall scatter after attenuation by the patient and wall scatter after attenuation by the patient and the maze wall, respectively. For special procedures the dose scattered by the patient must be determined separately for isocentric and non-isocentric (TBI) techniques. In Eq. (13), W will take the value of $W]_{\text{pat scat}_{\text{iso}}}$ (Eq. (43)) for isocentric techniques and for TBI the W value will be PD_{TBI} (Eq. (39)). The dose arising from patient scatter at the maze entrance will be given by:

$$D_p = D_{p_{\text{iso}}} + D_{p_{\text{TBI}}} \quad (45)$$

where $D_{p\,\text{iso}}$ and $D_{p\,\text{TBI}}$ are the doses scattered by the patient for isocentric and TBI techniques, respectively.

In Eqs (14) and (15), WU_{H} and WU_{m} will take the value of $\text{WU}]_{\text{pri}}$ in Eq. (42).

The doses at the maze entrance due to head leakage scattered by the end wall of the maze, and the head leakage transmitted through the maze wall may be obtained using Eqs (16) and (17), respectively, using the workload W_L given by Eq. (44).

The assumption for the special case described by Eq. (18) might be invalid because the use factor is dependent on the special procedures described here. The reader is advised to evaluate the maze entrance doses using Eqs (11) and (12) directly.

For treatment machines below 10 MV, the maze entrance dose arises predominantly from scatter and leakage photons with negligibly low neutron

and capture gamma contribution. For higher energy machines, the capture gamma dose at the maze entrance is determined from Eqs (23)–(25). The neutron dose equivalent at the maze entrance is determined from Eqs (26), (27) or (29), and Eq. (30), as described in Section 5.7. For special procedures like TBI, IMRT and QA, the workload W in Eqs (25) and (30) is replaced by the workload represented by Eq. (44). However, the neutron dose equivalent obtained using these equations are for radiation beams pointing downward. If the TBI set-up employs the horizontal beam orientation, and the gantry head is closest to the inner maze entrance, the actual neutron dose equivalent is higher. For conservative reasons it is recommended that the D_E value obtained using Eq. (30) be multiplied by a factor of 1.5 to give the neutron dose estimate for the horizontal beam configuration for TBI contribution.

At the present time, most IMRT procedures are performed using energies below 10 MV. At these energies, the capture gamma and neutron dose equivalents in the room and the maze entrance are usually small. The increase in dose at the maze entrance is entirely due to the increase in leakage because of the C_I fold rise in monitor units. However, if energies of 10 MV and higher are used, the dose at the maze entrance will increase rapidly with energy.

9.2.5. Time averaged dose rates

Section 2.4 describes the concept of TADR. Equations (2)–(4) are used for the evaluation of barrier designs and for the determination of barrier thicknesses.

For special procedures like TBI, IMRT and QA, the workload will take the value of W_d, W, or W_h (daily, weekly or hourly) for the procedure in question. To evaluate the TADR beyond the primary barrier, and for the wall scatter of the primary beam to the secondary barrier, the product of workload and use factor will be that of $\mathrm{WU}]_{\mathrm{pri}}$ in Eq. (42), where the workload is per day, week or hour, as appropriate. Likewise, when evaluating the TADR due to scatter from the patient the workload will be $\mathrm{W}]_{\mathrm{pat\ scat}_{\mathrm{iso}}}$ (Eq. (43)) or $\mathrm{W}_{\mathrm{TBI}}$ (Eq. (39)) for the appropriate time period. For leakage radiation the workload will be given by W_L (Eq. (44)) again for the appropriate time period.

9.3. EXAMPLE CALCULATIONS

Examples 1–4 demonstrate how to use the TADR (R_W) to evaluate a barrier. The weekly TADR (R_W) defined in Section 2.4 is useful in the evaluation of barrier design adequacy. Because the TADR (R_W) is the time averaged barrier attenuated dose per week, it follows that the product of

TADR (R_W) and occupancy (T) is simply the barrier attenuated dose per week with the occupancy taken into consideration. For any area of interest to meet the required weekly dose limit below a certain value P, it is necessary that the product $R_W T$ is less than P.

9.3.1. Example 1

A primary barrier shields the public area ($T = 1/16$) to IDR of 0.80 mSv·h^{-1}. The linac operates at a maximum dose output rate of 5.5 Gy·min^{-1}, $U = 0.25$, and $W = 600$ Gy/week. Is the shielding adequate?

The 40 h week TADR is, using Eq. (3):

$$R_W = 0.8 \times \frac{600 \times 0.25}{60 \times 5.5} = 0.36 \ \text{mSv} \cdot \text{week}^{-1}$$

When the occupancy of the area is taken into account, the barrier fails to meet the design limit of 0.02 mSv·week^{-1} limit for a public area [10]:

$$R_W \times (1/16) = 0.023 \ \text{mSv} \cdot \text{week}^{-1}$$

which is larger than 0.02 mSv·week^{-1}.

The barrier fails to meet the recommendation of the NCRP for a public area [10].

The TADR (R_8) is obtained using Eq. (2):

$$R_8 = 0.8 \times 10^3 \times \frac{600 \times 0.25}{40 \times 60 \times 5.5} = 9.1 \ \mu\text{Sv} \cdot \text{h}^{-1}$$

Since the IDR is more than 7.5 μSv·h^{-1} and the TADR is greater than 0.5 μSv·h^{-1}, the area beyond the barrier does not meet the requirement for a public area in the United Kingdom [6, 7] and the shielding would need to be increased.

9.3.2. Example 2

A primary barrier shields the dedicated TBI treatment beam to an IDR of 0.8 mSv·h^{-1} in a controlled area. The linac's TBI workload is 300 Gy·m^2 per week, the dose output rate is 12 Gy·min^{-1}. Is the barrier adequate?

Because the room is a dedicated TBI room, $U = 1$ for the barrier in question. The TADR is, per Eq. (3):

$$R_W = 0.8 \times \frac{300 \times 1}{60 \times 12} = 0.33 \ \text{mSv} \cdot \text{week}^{-1}$$

The barrier meets NCRP recommendations [9] only if T is less than about 0.25 because:

$$R_W \times (0.25) = 0.083 \ \text{mSv} \cdot \text{week}^{-1}$$

which is below the 0.1 mSv·week^{-1} controlled area limit requirement stated above. Use of the area as a corridor will meet NCRP recommendations [9]. However, since the IDR is more than 7.5 μSv·h^{-1}, the area cannot be used as a public area in the United Kingdom [6].

9.3.3. Example 3

A primary barrier reduces the linac beam operating at the maximum dose output rate of 12 Gy·min^{-1} down to an IDR of 0.1 mSv·h^{-1} in a public area. The linac gives TBI treatments only, W = 1000 Gy·week^{-1}. Is the barrier adequate?

The TADR (R_w) is, from Eq. (3):

$$R_W = 0.1 \times \frac{1000 \times 1}{60 \times 12} = 0.14 \ \text{mSv} \cdot \text{week}^{-1}$$

To reduce $R_W \times T$ below 0.02 mSv·week^{-1}, T has to be less than 1/7. Toilets, stairways and unattended waiting rooms are acceptable for public use of this area.

9.3.4. Example 4

If W for TBI is 100 Gy·week^{-1} in Example 3 and the rest of the workload is for conventional radiotherapy with dose output rate limited to 6 Gy·min^{-1}, is the barrier adequate for a public area?

Note that the IDR becomes 0.05 mSv·h^{-1} if the dose output rate is halved to 6 Gy·min^{-1}. Applying Eq. (3) to obtain the TADR (R_W):

$$R_W = \left(0.1 \times \frac{100 \times 1}{60 \times 12} + 0.05 \times \frac{900 \times 0.25}{60 \times 6}\right)$$
$$= 0.0139 + 0.0313 = 0.045 \ \text{mSv} \cdot \text{week}^{-1}$$

For $R_W \times T$ to be less than 0.02 mSv·week^{-1}, T has to be less than 0.4. The barrier is adequate if T is less than 0.4 according to NCRP guidance. [10]

However, since the IDR is 100 μSv·h^{-1}, which is more than the limit of 7.5 μSv·h^{-1}, the area should not be used as a public area in the United Kingdom [6], unless 1.13 TVL additional shielding is installed. (log (100/7.5)=1.13).

9.3.5. Example 5: Public area shielding for IMRT

In Fig. 12 in Section 6.3, the public area E is shielded by a secondary barrier to an IDR of 0.04 mSv·h^{-1} at a dose output rate of 5 Gy·min^{-1} according to the survey result. The occupancy factor at E is 1/4 and W = 600 Gy·week^{-1}. How much additional shielding is needed to allow 50% IMRT usage?

The IMRT factor is 4 (see Section 9.1.2). U = 1 for leakage barrier considerations. Applying Eqs (44) and (3):

$$W_L = 300 + (4 \times 300) = 1500 \ \text{Gy} \cdot \text{week}^{-1}$$

$$R_W = 0.04 \times \frac{(1500 \times 1)}{5 \times 60} = 0.2 \ \text{mSv} \cdot \text{week}^{-1}$$

$R_W \times (1/16) = 0.0125$ mSv·week^{-1}

$$\text{TVL required} = \log_{10}\left(\frac{0.05}{0.02}\right) = 0.4$$

The barrier needs 0.4 TVLs of additional thickness to reduce the dose from 0.05 mSv to below 0.02 mSv·week^{-1}. Since leakage is dominant, this approximate method gives a conservative estimate of the additional barrier requirement.

In the United Kingdom, an additional thickness of 0.7 TVLs is needed to reduce the IDR from 0.04 mSv·h^{-1} to below 7.5 μSv·h^{-1} [6, 7].

9.3.6. Example 6: Shielding barrier for IMRT

The recently developed IMRT procedure usually uses 6 MV low energy photons for a number of reasons. However, this example uses 18 MV in the facility depicted in Fig. 12 in Section 6.3, to show the worst case scenario, when the neutron considerations cannot be ignored. The workload of 600 Gy·week^{-1} specified in Section 6.3, Example 1, is modified to allow half of the patients to be treated with IMRT and the remainder with conventional treatments. The IMRT factor is assumed to be 4. This means the weekly workload for conventional treatment is 300 Gy ($20 \times 3 \times 5$), and the weekly workload for IMRT is ($4 \times 20 \times 3 \times 5 =$) 1200 Gy.

The patient dose received per fraction for IMRT is about the same as for conventional treatments. Therefore, the workload for the primary barrier will still be 600 Gy·week^{-1} (as in Section 6.3, Examples 1–3) and the primary barrier thickness at C, and the secondary barrier thickness due to patient scatter at A will stay the same.

The barrier thickness required to shield against leakage radiation is determined from Eq. (8). The requirement will differ from Example 3, Section 6.3, since the workload is greater. In this example, the workload will be ($1200 + 300 =$) 1500 Gy·week^{-1}. Substituting this value of W in Eq. (8) gives:

$$B_L = \frac{1000 \times 20 \times 10^{-6} \times 6.2^2}{1500 \times 0.0625} = 8.2 \times 10^{-3}$$

and

$$n = \log_{10}\left(\frac{1}{8.2 \times 10^{-3}}\right) = 2.09$$

This compares with 1.69 TVLs for a workload of 600 Gy·week^{-1}. However, compared with the 3.96 TVLs required to shield the primary beam (Example 1 of Section 6.3), the difference is more than 1 TVL and no additional shielding for leakage is required at location C.

For the barrier at location A (Fig. 12), the attenuation required for leakage radiation is determined from Eq. (8):

$$B_L = \frac{1000 \times 20 \times 10^{-6} \times 7.2^2}{1500 \times 0.0625} = 1.11 \times 10^{-2}$$

and

$$n = \log_{10}\left(\frac{1}{1.11 \times 10^{-2}}\right) = 1.96$$

The TVL for 18 MV leakage radiation is 330 mm concrete (Table 4), therefore the leakage barrier thickness will be (1.96×330=) 647 mm concrete. (This compares with 1.56 TVLs or 515 mm concrete in Example 6, Section 6.3.)

For protection against radiation scattered by the patient at location A of Fig. 12, the workload remains at 600 Gy·week^{-1}, and the barrier thickness required remains as 2.56 TVLs (737 mm concrete) (Example 6, Section 6.3). Since the difference is less than 1 TVL, 1 HVL additional thickness is needed to give adequate shielding to both leakage and patient scattered radiation. The barrier thickness for location A is (737 + 99 =) 836 mm concrete, the same as for the conventional use shown in Example 6 of Section 6.3. This is because the increase in IMRT workload has not increased the leakage barrier requirement beyond the patient scatter barrier requirement. If the IMRT workload increases or the IMRT factor increases, the barrier thickness required will increase.

The TADR (R_h) consideration shown in Example 7 of Section 6.3 remains the same, since none of the applied input data is affected by the IMRT workload. The primary barrier requirement shown in Example 5 of Section 6.3 will not change because the workload for the primary beam remains unchanged.

For the leakage barrier at location B in Fig. 12, the workload to be used is 1500 Gy·week^{-1},

$$B_L = \frac{1000 \times 0.1 \times 10^{-3} \times 7.2^2}{1500} = 3.46 \times 10^{-3}$$

and

$$n = \log_{10}\left(\frac{1}{3.46 \times 10^{-3}}\right) = 2.46$$

The required barrier thickness is (2.46×330 =) 812 mm concrete.

For the patient scatter barrier at location B in Fig. 12, the barrier thickness is the same as determined in Example 8 of Section 6.3, and is 3.07 TVLs (884 mm concrete). As the difference between leakage and scatter requirements is less than one TVL, an additional HVL must be added to the barrier thickness. The total barrier thickness requirement for location B will be (884 + 100 =) 984 mm concrete, which will be adequate to shield against the leakage and patient scattered radiation.

In summary, the use of IMRT does not change the final shielding requirements for the main vault for this specific example, although the shielding requirements at the maze entrance will change as shown in the following example. In some installations where the IMRT factor is much higher than 4, or the fractional use of IMRT is higher, the leakage barrier requirements will exceed that of the patient scatter barrier. The reader is advised to evaluate the impact of adding IMRT procedures according to the specific situation.

9.3.7. Example 7: Dose equivalent at the maze entrance for IMRT

9.3.7.1. Total dose due to scatter and leakage D_d

Following the calculations described in Example 9 in Section 6.3, the patient scatter component D_{pH} (2.38×10^{-5} Gy·week^{-1}) and the wall scatter component D_{wH} (1.86×10^{-6} Gy·week^{-1}) will remain the same because the IMRT will not increase the patient dose per fraction.

However, the head leakage wall scatter component D_{LH} will increase because W will increase from 600 to 1500 Gy·week^{-1}. From Eq. (16):

$$D_{\mathrm{LH}} = \frac{1\times10^{-3}\times1500\times0.25\times4.11\times10^{-3}\times11.8}{(7.9\times9.9)^2} = 2.97\times10^{-6}\ \text{Gy·week}^{-1}$$

Similarly, the head leakage through maze wall D_{TH} will also increase (Eq. (17)):

$$D_{\mathrm{TH}} = \frac{1\times10^{-3}\times1500\times0.25\times2.31\times10^{-4}}{(7.1)^2} = 1.72\times10^{-6}\ \text{Gy·week}^{-1}$$

The total dose due to scatter and leakage D_d is, using Eq. (18):

$$D_d = 2.64 \times (2.38 \times 10^{-5} + 0.34 \times 1.86 \times 10^{-6} + 2.97 \times 10^{-6} + 1.72 \times 10^{-6})$$
$$= 7.69 \times 10^{-5}\ \text{Gy·week}^{-1}$$

9.3.7.2. Capture gamma dose at the maze door, D_c

The total neutron fluence is dependent on the energy and design of the accelerator, the room and maze structure, and is independent of the workload. Therefore, the weekly capture gamma dose at the maze door, D_c, may be obtained from Eq. (26), as shown in Example 10 of Section 6.3. (In Example 10, D_φ was determined to be 1.9×10^{-7} Gy per isocentre Gy):

$$D_c = 1500 \times 1.9 \times 10^{-7} = 2.85 \times 10^{-4} \text{ Sv·week}^{-1}$$

The total X ray and gamma dose is given by:

$$D_d + D_c = 7.69 \times 10^{-5} + 2.85 \times 10^{-4} = 3.63 \times 10^{-4} \text{ Sv·week}^{-1}$$

9.3.7.3. Neutron dose at the maze door, D_E

The weekly neutron dose at the maze entrance is determined from Eq. (30), as shown in Example 12 of Section 6.3, the product of the workload and D_n:

$$D_E = 1500 \times 0.83 \times 10^{-6} = 1.25 \times 10^{-3} \text{ Sv·week}^{-1}$$

9.3.8. Example 8: Shielding requirements for the maze door for IMRT

To reduce the X ray and capture gamma dose ($D_d + D_c$) from 3.63×10^{-4} Sv·week^{-1} to 0.1 mSv·week^{-1}, the number of TVLs required is:

$$n = \log_{10}\left(\frac{0.363}{0.1}\right) = 0.56$$

Using a TVL value of 6 mm of lead (Section 5.7.3, Ref. [31]), the required thickness is 3.4 mm.

To reduce the neutron dose equivalent from 1.25×10^{-3} Sv·week^{-1} to 0.1 mSv·week^{-1}, the number of TVLs required is:

$$n = \log_{10}\left(\frac{1.25}{0.1}\right) = 1.1$$

For a TVL of 45 mm of BPE (see Section 5.7.3, Ref. [26]), the required thickness of BPE is ($1.1 \times 45 =$) 50 mm.

In summary, the total shielding required for the maze door is two layers of lead with a total thickness of 3.4 mm, with the 50 mm thickness of BPE sandwiched between the lead layers.

10. RADIATION SURVEY

Once the construction of a treatment bunker or modification of an existing bunker is complete the treatment unit can be installed. When the treatment unit has been made operational, a preliminary radiation survey is performed when the radiation beam is exposed for the first time. If the treatment unit is a linear accelerator, this survey should be performed with the maximum photon energy available on the unit at the maximum dose rate. This ensures that any hazards are identified at an early stage before the installation engineer and personnel occupying the surrounding area are put at risk. Provided no hazards are identified, the installation engineer may then commission the treatment unit. Once the acceptance testing has been completed a full radiation survey should be performed.

10.1. SURVEY EQUIPMENT

A Geiger–Müller (GM) counter or scintillation counter may be used for gamma ray facilities. Neither of these instruments is suited to measuring absolute dose rates on linear accelerator facilities. The comparatively large dead time on the GM counters makes them unsuitable for measuring the pulsed fields produced by linear accelerators. Scintillation counters can easily saturate when used to measure pulsed radiation produced by linear accelerators. Both types of detector will consequently underestimate the dose rate of pulsed radiation. However, they have a fast response time, which makes them suitable for scanning the barriers of isotope units and linear accelerator facilities to detect voids and cracks.

For linear accelerator installations, an ionization chamber survey meter is required for absolute photon measurements. Ideally this instrument will have an integrating mode as well as a rate mode. An integrating mode will enable measurements to be made without the operator being present to read the meter while the radiation is on. Ion chamber instruments have a slow response time and it is therefore difficult to use them to search for defects in the radiation barriers. The instrument should also be protected from interference from radio frequencies that are generated by linear accelerators. If the linear accelerator operates at 10 MV or above, then a portable neutron survey meter will also be required.

10.2. SURVEY MEASUREMENTS

10.2.1. External beam facilities

For the initial measurements, the degree of shielding afforded by the barriers should be assessed. The outside of each barrier should be scanned with a GM or scintillation counter to identify any defects in the shielding. If the treatment facility is a linear accelerator it should be operated at the highest available energy at the maximum dose rate for these measurements. If any defects in the shielding are identified then further measurements should be made at these positions using the appropriate type of detector.

The primary radiation barriers should be assessed with the radiation beam directed at each barrier in turn. The maximum available field size should be set on the treatment unit and the collimators rotated though 45° so that the diagonal of the radiation field (maximum dimension) is along the length of the barrier. It is especially important to survey the region where the primary barrier changes to a secondary barrier to confirm that the length of the primary barrier is adequate. Measurements should also be made at junctions between the ceiling slab and the walls. If the facility is an existing one that has been upgraded for a higher energy machine, then measurements must be made at the junctions of additional shielding or modifications. The plans of the treatment facility should be available when the survey is being performed so that these positions can be identified. These measurements are performed without any phantom material in the radiation beam.

For secondary barriers on external beam units the measurements are made with phantom material in the beam to simulate the patient. The phantom material is placed at the isocentre, but if the facility has been designed for TBI, then further measurements should be made with the phantom material in the required position in the room for this procedure. For each secondary barrier measurements with the gantry at 0°, 90°, 180° and 270° should be made. The junctions between secondary and primary barriers should be measured carefully to ascertain whether or not there is any leakage from small angle scatter at the extremities of the primary barrier.

Measurements (with phantom material in the beam) must also be made at the door or maze entrance to the facility for the four gantry angles and at the egress of ducts. For high energy linear accelerators these sites should also be surveyed for neutrons.

Measurements should also be made outside the facility to determine radiation levels due to skyshine. If there are tall buildings adjacent to the facility, then measurements should also be made on the upper floors of these buildings to assess any hazard.

For each measurement the result and the conditions for the measurement must be documented covering the:

— Operation energy of the treatment unit;
— Dose rate;
— Field size;
— Gantry angle;
— Collimator angle;
— Amount of phantom present (or not);
— Position of the phantom.

Measurements made with maximum field size will be worst case conditions. Further measurements should be made with the average field size used clinically. If the facility is a linear accelerator with more than one X ray energy, these measurements should be repeated for the lower energies.

Once all these measurements have been made the effectiveness of the barriers may be determined. This will take into account the use factor for the barrier, the occupancy of the area outside the barrier, the workload of the machine and the duty cycle of the treatment unit.

10.2.2. Brachytherapy facilities

The general principles of Section 9.2.1 apply. In these treatment facilities, the walls, ceiling and floor are primary barriers and they will all be irradiated continuously whenever the radiation sources are exposed within the room. The effectiveness of the barriers is determined by positioning the source applicators at the approximate patient position within the room. Measurements are then performed while the sources are exposed with no attenuation by phantom material. Measurements should be made for both the maximum number of available sources exposed and also for the average number of sources to be used clinically at one time. The likely duration of the treatment and the number of treatments per week must be taken into account when determining the effectiveness of the radiation barriers together with the occupancy of the surrounding areas.

10.3. SURVEY REPORT

The following information should be included in the report of the radiation survey:

— The type of radiation unit, the location of the unit, the date of the survey and the name of the person who performed the survey and prepared the report.
— The values of workload (W), use factors (U) and occupancy factors (T) used to determine the effectiveness of the shielding.
— The instruments used to perform the measurements: Type, model, serial number and date of calibration.
— The results of the measurements, indicating the machine parameters, position of measurement and dose rate at the isocentre.
— Conclusions: whether or not the shielding is effective.
— A floor plan of the treatment facility with survey points indicated. Section views or an elevation may also be helpful.

If the survey shows that the shielding afforded by the barriers is sub-optimal there are various options available:

— Provide additional shielding.
— Restrict the orientation of the radiation beam to prevent it striking the area with inadequate shielding. This may be a temporary measure until the additional shielding is put in place or permanent. If permanent, then mechanical or electrical interlocks should be put in place to prevent this orientation. This restriction of use should also be written into the operating procedures for the facility.
— Restrict access. This may be achieved by designating the area that exceeds design specification dose rates as a controlled area and posting appropriate notices and erecting physical barriers to restrict access. If the area is not normally occupied it may be reasonable to make it a prohibited area and keep access locked. Another alternative may be to restrict access during certain operating conditions. In this instance persons requiring access to the area would need to obtain a permit to work (permission) from the operators of the treatment unit.

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