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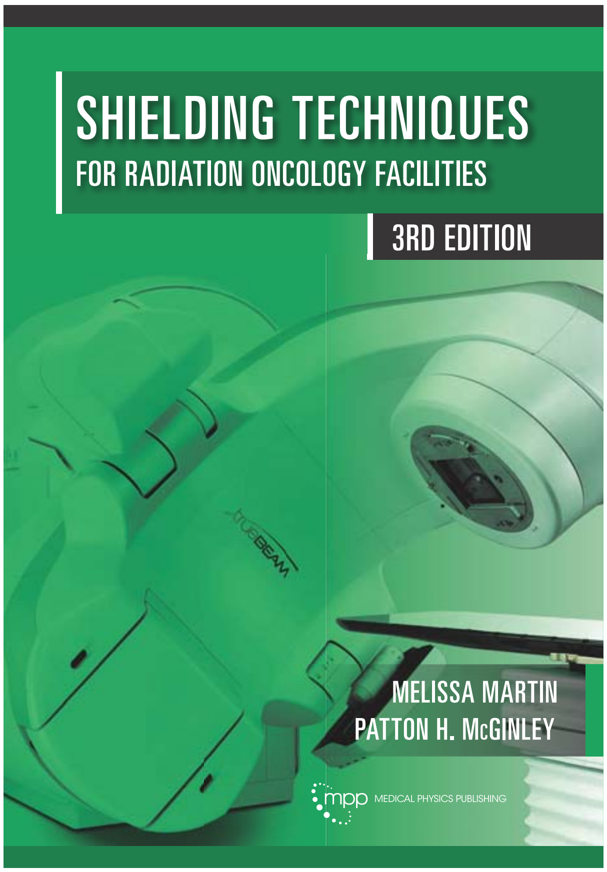

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2

Conventional Shielding Design

Shielding Design Goals and Occupancy

The purpose of radiation shielding is to reduce the effective dose of radiation produced by radiation therapy equipment to a sufficiently low level outside the room. The effective dose level required is determined by the local or national regulatory bodies. The required dose level is typically different for public occupancy (uncontrolled access) vs. occupational occupancy (controlled access).

The dose rate reaching a protected location is directly proportional to the workload (W), a measure of the radiation produced by the machine. For a linear accelerator, workload at isocenter is the absorbed dose-rate at isocenter, determined at the depth of the maximum absorbed dose in water, specified in gray (Gy) per some interval of time (e.g., per hour, week, or year) (NCRP 2005b). The workload at isocenter is then normalized to 1 meter from the x-ray target (if the distance from the x-ray target to isocenter is not 1 meter) to produce the workload (W) used in the shielding calculations.

In addition to workload, the required shielding is also a function of the machine energies (MVs); the distance from the x-ray target, or isocenter, to the point being shielded; the fraction of time that the beam is oriented in that particular direction; and the fraction of time that the space under consideration is considered to be occupied.

The energy rating of a linear accelerator x-ray beam, as stated by the manufacturer, refers to the accelerating voltage and the end point energy of the bremsstrahlung spectrum produced by the linear accelerator. The energy rating of a linear accelerator beam is commonly referred to simply as MV (for megavoltage). Precise definitions of MV are provided by *British Journal of Radiology* (BJR) Supplements No. 11 (BJR 1972) and 17 (BJR 1983). The BJR 11 definition of MV is used as the basis for the parameters included in this book. The term "MeV" is also used throughout this book to refer to monoenergetic photons or particles, not the energy rating of the linear accelerator.

A protected location is a location outside the treatment room that may be occupied. This is customarily considered to be no closer to isocenter than 300 mm beyond a barrier. The shielding design goal (P) is a practical reference limit (or dose constraint) on the dose rate at a protected location. A controlled area is a limited-access area in which the occupational exposure of personnel to radiation or radioactive material is under the supervision of an individual in charge of radiation protection.

NCRP 151 recommended a 5-mSievert (mSv)-per-year shielding design goal for controlled areas and a 1-mSv-per-year shielding design goal for uncontrolled areas. These shielding design goals may also be expressed as the yearly average dose per week (0.1 mSv/week for controlled areas and 0.02 mSv/week for uncontrolled areas) assuming 50 work weeks per year. In this case workload is the annual workload expressed as a per-week average.

Note *NCRP 116* (NCRP 1993) recommended a public dose constraint of 0.25 mSv per year for any individual facility (vs. 1 mSv/year), a discrepancy that delayed publication of *NCRP 151* and the corresponding N*CRP 147* (NCRP 2004b; diagnostic shielding standard). The discrepancy was resolved by *NCRP Statement 10* (NCRP 2004a), which noted the shielding methodology is sufficiently conservative that the actual exposure of the maximally exposed individual would be expected to be at least a factor of four less than the shielding design goal. Adherence to the *NCRP 151* methodology is therefore important independent of any anticipated survey measurements. Specifically, for primary barriers, attenuation provided by a patient or phantom at isocenter must not be included in the shielding calculations or survey measurements. The use factor (U) for primary barrier calculations also should be conservative compared with the fraction of clinical workload directed toward the location with three-dimensional (3D) treatment planning. For secondary barriers, it was common knowledge that the linear accelerators in use when *NCRP*

151 was published had a leakage fraction on the order of a factor of four less than the 0.1%. Using a similarly conservative x-ray leakage fraction is therefore necessary to maintain the intent of *NCRP 151*. Scatter calculations should be based on the maximum field dimensions, with typical dimensions anticipated to be at least a factor of four less in area.

Although *International Commission on Radiological Protection (ICRP) Publication 103* (ICRP 2007) also recommends 1 mSv per year as the individual dose limit for the public, regulatory bodies may impose a lower dose constraint (e.g., 0.3 mSv/year in the United Kingdom). Although there is no biological basis for the requirement, some countries may also impose a limit on instantaneous dose rate to simplify survey measurements.

Occupancy factor (*T*) reflects the fraction of time a protected location may be occupied. The maximum permissible value of shielded dose rate at a location with occupancy *T* is given by *P/T*. The time-averaged dose rate (TADR) for an individual at a protected location is the total shielded dose rate at that location multiplied by the occupancy *T*. The use of TADR allows direct comparison with the shielding design goal. Comparing shielded dose rate with *P/T* or TADR with *P* are equally acceptable ways to express compliance with the shielding design goal.

The occupancy factor guidelines from *NCRP 151* are given in Table 2-1. The appropriate occupancy factor at the entrance will depend on the proximity to nearby high occupancy locations. Assuming T = 1/8 would be appropriate at an isolated entrance loca-

Table 2-1 Suggested occupancy factors [*NCRP 151* Table B.1]

Occupancy Factor	*Location*
1	Full occupancy areas (areas occupied full-time by an individual), e.g., administrative or clerical offices, treatment planning areas, treatment control rooms, nurse stations, receptionist areas, attended waiting rooms, and occupied space in nearby buildings
0.5	Adjacent treatment room and patient examination room adjacent to shielded vault
0.2	Corridors, employee lounges, and staff rest rooms
0.125	Treatment vault doors (if at isolated location)
0.05	Public toilets, unattended vending rooms, storage areas, outdoor areas with seating, unattended waiting rooms, patient holding areas, attics, and janitors' closets
0.025	Outdoor areas with only transient pedestrian or vehicular traffic, unattended parking lots, vehicular drop-off areas (unattended), stairways, and unattended elevators

tion normally occupied only when entering and leaving the treatment room. A corridor immediately beyond an entrance would normally be designated at least T = 1/2 if not T = 1 depending on the proximity of the control area or other high-occupancy location.

The United States Nuclear Regulatory Commission (NRC) requires the shielded dose rate at any unrestricted location to not exceed 0.02 mSv in any hour. This is not an instantaneous dose rate requirement, but it is interpreted by *NCRP 151* to be the shielded dose rate resulting from the maximum number of patient treatments anticipated per hour using the yearly average workload per patient. *NCRP 151* Equation 3.14 effectively places a limit on the maximum value of P/T as shown in Equation (2-1), where N_{max} is the maximum number of patient treatments per hour and N_{wk} is the average number of patient treatments per week. This in turn can then be viewed as a constraint on the minimum occupancy for uncontrolled access locations (P = 0.02 mSv/week) as given in Equation (2-2). Although T = 1/40 is in theory permitted for uncontrolled access locations with only transient occupancy, the NRC 0.02-mSv-per-hour requirement will typically imply a somewhat higher minimum occupancy.

$$P / T_{\max}(mSv / wk) = 0.02\ mSv / hr \times N_{wk} / N_{\max} \quad (2\text{-}1)$$

$$T_{\min} = N_{\max} / N_{wk} \quad (2\text{-}2)$$

Example*: *minimum occupancy

40 patient treatments per day
N_{max} = 6 patient treatments per hour
N_{wk} = 5 × 40 = 200 patient treatments per week
$P/T_{\max}$ = 0.02 × 200 / 6 = 0.667 mSv/week
$T_{\min}$ = 6 / 200 = 0.030

The procedure described above can be adapted for other countries that have a specific requirement for radiation exposure at a location in an hour with the maximum clinical workload per hour (e.g., 0.0075 mSv/hour in the United Kingdom).

Calculation Methods

The shielding design methods described here are based on *NCRP Report No. 151* (NCRP 2005b). Figure 2-1 shows a typical room plan for a high-energy (15 MeV) medical accelerator. Two types of radiation barriers or shields are considered—primary and secondary. The primary barrier is irradiated by the x-ray beam produced by

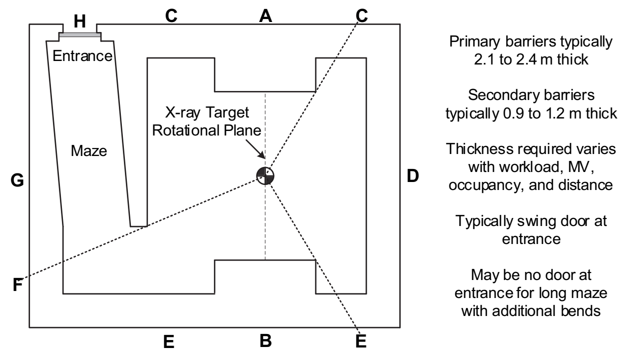

Figure 2-1 Simplified drawing of treatment room with maze. (Letters in the figure are referred to in the text.)

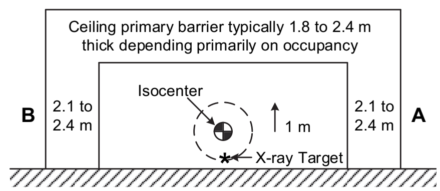

Figure 2-2 Simplified section drawing of treatment room.

the accelerator, and the secondary barrier receives only radiation scattered by the patient and the surfaces of the treatment room and radiation transmitted through the accelerator shielding (head leakage). Primary radiation is limited in direction by the placement of the accelerator in the treatment room, and the maximum beam size is used to determine the portion of the walls, ceiling, and floor that will be designated as primary barriers. Secondary radiation, however, is emitted in all directions and covers all of the treatment room surfaces.

If the linear accelerator operates at multiple energies, separate calculations should be performed at each energy for primary barrier (protecting locations A and B) and secondary barrier calculations (protecting Locations C through G). The total shielded dose rate is the sum of the shielded dose rate values calculated for each energy. The shielding evaluation at the entrance (Location H) must also include not only secondary radiation, but also scattered radiation reaching the entrance through the maze.

As illustrated in Figure 2-2, the ceiling of the treatment room also requires shielding with primary and secondary barriers. Even for a

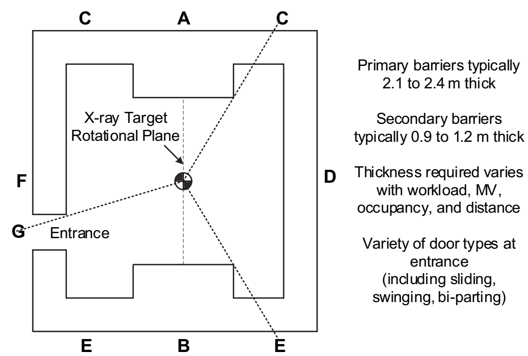

Figure 2-3 Simplified drawing of treatment room with no maze.

single-story facility, it is preferable to provide sufficient shielding for low occupancy on the roof. Restricting access to the roof can reduce, but not eliminate, ceiling shielding because radiation through the ceiling will scatter to surrounding locations. Skyshine calculations must be performed if no primary barrier is included in the ceiling.

As illustrated in Figure 2-3, a treatment room with no maze requires substantially less space. However, the door at the entrance to the treatment room must provide shielding comparable to the adjacent secondary barrier wall, making it far more expensive. Given space constraints faced by medical facilities, treatment rooms with no maze are increasingly common in the United States. Improvements in the design and operation of sliding doors has made the no-maze design more appealing.

Primary Barrier Calculations

The traditional primary barrier approach uses Equation (1-4) to calculate the maximum primary barrier transmission for a given workload and MV. The maximum transmission can then be used to determine the minimum barrier thickness. The more general approach is to develop an expression for the total shielded dose rate beyond the primary barrier, potentially including multiple MVs and both photons and neutrons. The primary barrier composition and thickness(es) are then selected to ensure this total shielded dose rate is suitably less than the required *P*/*T*. This more general approach is described here.

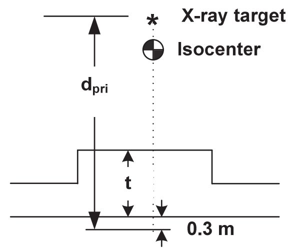

Figure 2-4 Primary barrier geometry.

Primary barrier calculations use the geometry illustrated in Figure 2-4. The unshielded dose rate (H_{UX}) in sievert per week is given by Equation (2-3).

$$H_{UX} = \frac{WU}{d_{pri}^{\;2}} \qquad (2\text{-}3)$$

In Equation (2-3) d_{pri} is the distance from the x-ray target to the point protected in meters; W is the workload or dose in gray per week at 1 m from the x-ray target; and U is the use factor, or fraction of the workload directed toward the primary barrier.

Example: primary barrier unshielded dose rate

Workload at 15 MV: 230 Gy/week

$U = 0.25$

Distance from target to protected location (d_{pri}) = 6.5 m

$H_{UX} = (230)(0.25) / 6.5^2 = 1.36 \times 10^0$ Sv/week = 1.36×10^3 mSv/week

The shielded x-ray dose rate (H_{tr}) (i.e., the calculated transmitted x-ray dose equivalent rate) is given by Equation (2-4).

$$H_{tr} = H_{UX} B \qquad (2\text{-}4)$$

In Equation (2-4), B is the x-ray transmission factor for the barrier. The transmission factor is calculated separately for each layer of material in the barrier, with B then calculated by multiplying the transmission factor for these layers together. The transmission factor for layer i is given by Equation (2-5).

$$B_i = 10\hat{}(-t_{i1} / TVL_1) \times 10\hat{}(-t_{ie} / TVL_e) \qquad (2\text{-}5)$$

where TVL_1 is the first tenth-value layer (TVL) thickness, TVL_e is the thickness for each subsequent TVL, t_i is the thickness of layer i of the barrier, t_{i1} is the amount of t_i (if any) that falls within the first TVL of the barrier, and t_{ie} is $t_i - t_{i1}$. Primary TVLs for customary shielding materials are provided in Table A-1. See also Appendix B, which describes the physical properties of commonly used barrier materials as well as addressing various material-related issues that may arise during design and construction.

***Example*: primary barrier transmission and shielded dose rate**

Barrier: 220 cm normal weight concrete

TVL_1 = 440 mm, TVL_e = 410 mm from Table A-1

B = 10^(–440/440) × 10^[–(2200 – 440)/410] = 5.10×10^{-6}

$H_{tr} = (1.36 \times 10^3$ mSv/week)(5.10×10^{-6}) = 0.0069 mSv/week

The total shielded dose rate is the sum of the shielded dose rate as calculated above for all the linear accelerator MVs. The barrier must be sufficient for the total shielded dose rate to be less than P/T. Alternatively, the shielded dose rate can be multiplied by the occupancy (T) to calculate the TADR for the location, with the TADR then compared directly with the shielding design goal (P) instead of P/T.

If the material thicknesses and densities are consistent with the assumptions, the measured x-ray dose rate is typically very close to the dose rate calculated using Equation (2-4). In practice, slight variation in the construction is to be expected (e.g., concrete density may be slightly lower than anticipated). This may result in the measured x-ray dose rate being slightly higher than the calculated x-ray dose rate. With good construction practice, the measured dose rate should be no larger than the calculated x-ray dose rate multiplied by the recommended x-ray dose rate margin. A factor of two to three margin is typically appropriate for cast-in-place concrete, with lower margin potentially acceptable for manufactured shielding material (because the density is more closely controlled). Where survey results are available for existing construction, it may be unnecessary to include any margin (i.e., a factor of one margin).

With the current United States regulatory requirements, primary barriers are typically the equivalent of 6.5- to 8-foot-thick normal-weight concrete. The thickness varies with location, depending primarily on occupancy and workload. The 6.5-foot thickness would typically be suitable only for an exterior wall with no nearby high occupancy anticipated. The 8-foot thickness is typically compatible with full occupancy uncontrolled access. This thickness also may be used in a standardized design because it could typically be used without modification. A typical primary barrier thickness is 7 to 7.5 feet, which would typically be compatible with a location designated $P = 0.1$, $T = 1$ or $P = 0.2$, $T = 0.2$, which are the most common combinations of shielding design goal and occupancy adjacent to a treatment room.

At energies above 6 MV, photoneutron generation also must be considered if the primary barrier includes metal. This is addressed in Chapter 6.

Secondary Barrier Calculations

Secondary radiation comes from two sources: leakage radiation from the linear accelerator head and scattered radiation from the patient. For energies above 6 MV, both x-ray and neutron leakage must be considered. The unshielded dose rate for secondary barriers is calculated using the geometry in Figure 2-5.

The x-ray leakage unshielded dose rate due to leakage from the linear accelerator head (H_{UL}) in sievert per week is given by Equation (2-6).

$$H_{UL} = \frac{W_L\, f_L}{d_{\text{sec}}^2} \qquad \text{(2-6)}$$

The secondary distance to the protected point (d_{sec}) in Equation (2-6) is customarily measured from isocenter, since this is the average linear accelerator head location. If the amount of shielding varies significantly with gantry orientation, it may be appropriate to measure distance from the linear accelerator head instead, with separate calculations performed as a function of gantry angle. The x-ray leakage

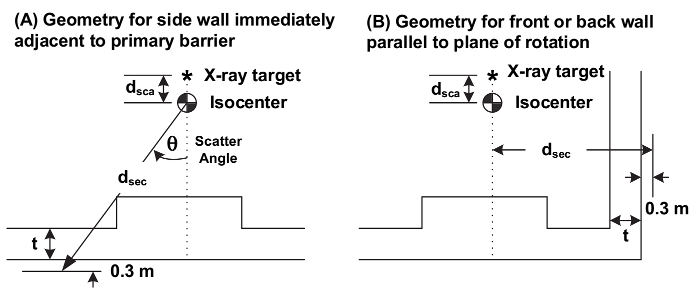

Figure 2-5 Secondary barrier geometry.

fraction (f_L) is customarily 10^{-3}, corresponding to the standard International Electrotechnical Commission (IEC) recommendation that the average x-ray leakage outside the beam must be less than 0.1% of the dose rate at isocenter. Note that measured x-ray leakage for traditional linear accelerators is typically at least a factor of 4 lower than 0.1% (one of the factors considered in *NCRP Statement 10*). Using a leakage fraction less than 0.1% is therefore appropriate only with manufacturer data illustrating typical leakage of at least a factor of 4 less than the assumed leakage fraction.

The leakage workload (W_{Li}) for a given energy (or MV) and treatment delivery category is the conventional workload multiplied by the intensity-modulated radiation therapy (IMRT) ratio (C_{Ii}), as shown in Equation (2-7). Typical values of the IMRT ratio range from 3 to 15 depending on the technique used for treatment.

$$W_{Li} = W_i \, C_{Ii} \tag{2-7}$$

As shown in Equation (2-8), the x-ray leakage workload (W_L) for a given MV is then given by the sum of the leakage workload for each treatment delivery category.

$$W_L = \sum_i W_{Li} \tag{2-8}$$

Example*: *x-ray leakage unshielded dose rate

2 stereotactic body radiation therapy (SBRT) patient treatments per day at 10 Gy each with $C_I = 3$

20 Volumetric Modulated Arc Therapy (VMAT)

IMRT patient treatments per day at 3 Gy each with $C_I = 3$

12 3D patient treatments per day at 3 Gy each with $C_I = 1$

Leakage workload: $5 \times (2 \times 10 \times 3 + 20 \times 3 \times 3 + 12 \times 3 \times 1) =$ 1380 Gy/week

Leakage fraction: 0.001

Distance from isocenter to protected location: 7.5 m

$H_{UL} = (1380)(10^{-3}) / 7.5^2 = 2.45 \times 10^{-2}$ Sv/week $= 2.45 \times 10^1$ mSv/week

The shielded x-ray leakage dose rate (H_L) is given by Equation (2-9).

$$H_L = H_{UL} \, B_L \tag{2-9}$$

Here B_L is the leakage transmission calculated from the barrier thickness and x-ray leakage tenth-value layers TVL_1 and TVL_e using the same procedure used to calculate the primary barrier transmission. Leakage TVL values for customary shielding materials are given in Table A-2.

Example*: *x-ray leakage barrier transmission and shielded dose rate

Barrier: 1067 mm normal weight concrete

TVL_1 = 340 mm

TVL_e = 290 mm at 6 MV from Table A-2

B = 10^(–340/340) × 10^[–(1067 – 340)/290] = 3.11×10^{-4}

$H_{UL} = 2.45 \times 10^1$ mSv/week

H_L = (2.45×10^1 mSv/week)(3.11×10^{-4}) = 0.0076 mSv/week

As illustrated in Figure 2-5, the path to the protected location may traverse the barrier at an angle, termed the slant angle (θ). In this case, the barrier thickness t is multiplied by the slant factor 1/cos(θ) to get the effective barrier thickness used to calculate barrier transmission. The effective barrier thickness is typically referred to as slant thickness.

Example*: *slant thickness

Barrier thickness: 1067 mm normal weight concrete

Slant angle = 26°

cos(26°) = 0.899

Slant thickness = 1067 mm / 0.899 = 1187 mm

For energies above 6 MV, neutron leakage is included in the calculated secondary shielded dose rate. Neutron leakage is calculated using the same approach as for x-ray leakage—Equations (2-5) through (2-8)—except with using neutron leakage fraction (see Table A-3) and neutron TVLs (see Table A-6). A lower neutron leakage workload may be assumed for a dual energy accelerator in which only the higher energy is used for the shielding calculations because much of the actual workload will be typically performed at 6 MV. If a separate calculation is performed for each MV, the neutron leakage workload is the same as the x-ray leakage workload.

The unshielded patient scatter dose rate (H_{UPS}) in sievert per week is given by Equation (2-10).

$$H_{UPS} = \frac{a(\theta)\,W\,U\,(F/400)}{d_{sca}^2\,d_{\sec}^2} \qquad (2\text{-}10)$$

As illustrated in Figure 2-5, d_{sca} (meters) is the target to isocenter distance (typically 1 m), d_{sec} (meters) is the secondary distance from isocenter to the point protected, U is use factor, and W is the workload in gray per week at 1 m from the x-ray target, where

$a(\theta)$ = scatter fraction or fraction of the primary beam absorbed dose at 1 m from the x-ray target that scatters from the patient at scatter angle θ at 1-m distance from isocenter for a 400-cm^2 field area (Table A-4), and

and

F = field area in square centimeters at isocenter (e.g., 1600 cm^2 for 40 × 40-cm field).

If d_{sca} is not 1 m, it may be more straightforward to normalize F to 1 m from the x-ray target instead of isocenter and remove the d_{sca} term from Equation (2-10). Assuming $U = 1$ for scatter is recommended. For secondary barriers immediately adjacent to a primary barrier, applying the primary barrier use factor (typically 0.25) to scatter is permissible, particularly for existing construction. Note the leakage fraction will exceed 10^{-3} near the central axis, so assuming $U = 1$ for scatter compensates for this to some extent.

Note that the average field area in clinical use may be substantially less than the maximum field area (e.g., 20 × 20 cm^2 might be considered typical). This conservatism is one of the reasons *NCRP Statement 10* permitted *NCRP 151* to use 1 mSv per year as the shielding design goal; hence, using the maximum field area is recommended for shielding calculations, especially for new construction.

Example*: *patient scatter unshielded dose rate

2 SBRT patient treatments per day at 10 Gy each
20 VMAT IMRT patient treatments per day at 3 Gy each
12 3D patient treatments per day at 3 Gy each
Workload: (5)(2 × 10 + 20 × 3 + 12 × 3) = 580 Gy/week
Use factor = 1 assumed.

Scatter fraction at 26° scatter angle (6 MV): 3.95×10^{-3} (interpolated from Table A-4 as the log of scatter fraction vs. linear angle)

Field area at 1 m d_{sca}: 1600 cm^2

Distance from isocenter to protected location: 6.2 m

$H_{UPS} = (3.95 \times 10^{-3})(580)(1)(1600/400) / 6.2^2 = 2.38 \times 10^{-1}$ Sv/week

$= 2.38 \times 10^2$ mSv/week

The patient scatter shielded dose rate (H_{PS}) is given by Equation (2-11).

$$H_{PS} = H_{UPS}\, B_{PS} \qquad (2\text{-}11)$$

Here B_{PS} is the patient scatter transmission calculated from the patient scatter TVL_1 and TVL_e values, using the same procedure used to calculate the primary barrier transmission. The patient scatter TVLs, which are given in Tables A-5, vary both with machine MV and scatter angle. The TVL values in Tables A-5 are based on *NCRP 151* Tables B.5 and B.6 and *NCRP 151* Figure A.1. For values of machine MV or scatter angle outside the region included in *NCRP 151* Table B.5, the TVL values are interpolated from Figure A.1 based on scatter energy from *NCRP 151* Table B.6. Note the scatter energy used to determine TVLs from *NCRP 151* Figure A.1 are increased slightly to make them consistent with the *NCRP 151* Table B.5 scatter TVLs for lead.

Example*: *patient scatter shielded dose rate

$H_{UPS} = 2.38 \times 10^2$ mSv/week
Barrier thickness: 1067 mm normal weight concrete
Slant angle: 26°, cos(26°) = 0.899
Slant thickness = 1067 mm / 0.899 = 1187 mm
Patient scatter TVL = 281.3-mm linear interpolation from Table A-5a
B = 10^(–281.3/281.3) × 10^[–(1187 – 281.3)/281.3] = 6.03×10^{-5}
$H_{PS} = (2.38 \times 10^2$ mSv/week$)(6.03 \times 10^{-5}) = 0.0144$ mSv/week
Note: the calculated H_{PS} final digit may vary depending on number of significant figures retained in the intermediate calculations.

The secondary shielded dose rate is the sum of H_L (including x-ray and neutron leakage) and H_{PS}. The total secondary shielded dose rate is the sum of the secondary shielded dose rate for all the machine MVs. The barrier must be sufficient for the total secondary shielded dose rate to be less than P/T.

With the current U. S. regulatory requirements, secondary barriers for conventional linear accelerators are typically the equivalent of 3- to 4-feet-thick normal weight concrete. The thickness varies with location, depending primarily on occupancy and workload. The 3-foot thickness would typically be suitable only for an exterior back wall, with no nearby high occupancy anticipated. The 4-foot thickness is typically compatible with full-occupancy uncontrolled access. The 4-foot thickness may also be used in a standardized design because it could typically be used without modification. A typical secondary barrier thickness is 3.5 feet, which would typically be compatible with a location designated $P = 0.1$, $T = 1$ or $P = 0.2$, $T = 0.2$, the most common combinations of shielding design goal and occupancy adjacent to a treatment room. For a control area, 4-foot wall thickness is preferred instead of 3.5-foot wall thickness because of the high occupancy and the other potential sources of scattered radiation (e.g., treatment room entrance and duct penetration above) present at that location. For linear accelerators with a very high leakage workload, the secondary barrier would need to be proportionally thicker, with 5-foot or more thickness possibly appropriate.

Flattening Filter Free (FFF) Accelerators

Linear accelerators have traditionally used flattening filters to provide a relatively uniform dose rate within the treatment field. The advent of sophisticated 3D treatment planning software reduced the importance of having uniform intensity in the field because the beam shape could be incorporated into the treatment planning software. The desire to provide higher instantaneous dose rate, along with the enabling treatment planning software, led to the development of linear accelerators that have a so-called flattening filter free (FFF) mode, with higher instantaneous dose rates. This is of particular importance for modalities, such as stereotactic radiosurgery (SRS) and Stereotactic Body Radiation Therapy (SBRT), to reduce treatment duration associated with the larger treatment fractions.

Except for countries that have regulations limiting the maximum instantaneous dose rate, the FFF mode does not directly impact shielding calculations. However, FFF can impact the shielding calculations indirectly through enabling higher average workloads per hour, week, or year. To mitigate the impact on shielding required, it is now common to distribute the workload used in the shielding calculations over all the accelerator energies available, as addressed in the next section, rather than simply assuming the entire workload at the maximum energy. There is an insignificant difference between the TVLs with and without the FFF mode at a given energy, so the workload does not need to distinguish between the flattening filter (FF) and FFF modes.

However, the apparent concrete primary TVL at 10 MV, which is commonly used for many FFF treatments, now appears to be larger than the value provided in *NCRP 151*. Consequently, the 389 mm

TVL value from *Institute of Physics and Engineering in Medicine (IPEM) 75* (IPEM 2002) is recommended as the TVL_e in Table A-1 because this provides closer agreement with recent survey data than the *NCRP 151* TVL_e value (370 mm).

Workload Examples

Most linear accelerators operate at multiple energies. This requires the primary and secondary barrier calculations to be performed separately for each energy, with the total shielded dose rate the sum of the shielded dose rates calculated for each energy.

Table 2-2 illustrates the workload described in *NCRP 151* Section 7.1. *NCRP 151* noted that the shielded dose rate contribution from the 6-MV workload is fairly minor in this example. *NCRP 151* indicated shielding calculations based solely on the 18-MV workload would be acceptable to simplify the shielding calculations.

Following the example of *NCRP 151*, an absorbed dose of 3 Gy is used for the conventional treatment fraction in Table 2-2. For a tissue-maximum ratio in the 0.7 to 0.8 range, this is equivalent to a patient fraction in the 210 to 240 cGy range versus a more typical patient fraction on the order of 200 cGy. Note, however, that the actual workload will include machine usage not associated with administering patient treatment (e.g., quality assurance [QA], maintenance, and physics developmental activities). The 3-Gy-per-patient treatment recommended by *NCRP 151* is intentionally higher than the typical average patient workload to allow for such machine usage.

Leakage workload (W_L) differs from workload at isocenter because it depends on the number of monitor units (MUs) required

Table 2-2 *NCRP 151* Section 7.1 workload example

Energy (MV)	*Patients per day*	*Workload (Gy/pt)*	*Workload (Gy/wk)*	*MU/cGy Ratio*	*Leakage Workload (Gy/wk)*	
18 IMRT	12	3	180	5	900	
18 3D	18	3	270	1	270	
18	30		450		1170	Total
6 IMRT	12	3	180	5	900	
6 3D	3	3	45	1	45	
6	15		225		945	Total

45 Total patient treatments per day

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Table 2-3 *Workload example for linear accelerator with three energies*

Energy (MV)	*Patients per day*	*Workload (Gy/pt)*	*Workload (Gy/wk)*	*MU/cGy Ratio*	*Leakage Workload (Gy/wk)*	
15 VMAT	2	3	30	3	90	
15 3D	8	3	120	1	20	
15	10		150		210	Total
10 SRS	1	20	100	3	300	
10 SBRT	2	10	100	3	300	
10 VMAT	5	3	75	3	225	
10 3D	5	3	75	1	75	
10	13		350		900	Total
6 SRS	2	20	200	3	600	
6 SBRT	5	10	250	3	750	
6 VMAT	15	3	225	3	675	
6	22		675		2025	Total

45 Total patient treatments per day

to deliver the dose at isocenter at a given energy. IMRT requires an increase in MUs compared with conventional radiation therapy. The IMRT ratio is the ratio of MU to cGy at isocenter. The IMRT ratio will vary with the treatment delivery and with MV.

Table 2-3 provides an example of workload-per-patient treatment and IMRT ratio for a variety of treatment modalities. The workload used in the shielding calculations should be selected by the facility staff to provide an upper bound on the anticipated total workload. The treatment modalities are included as an aid to estimating the total workload. As noted in *NCRP 151*, the entire workload can be assumed to be performed at the maximum MV. However, the trend toward increasing workload (caused by higher instantaneous dose rates, hypofractionation, and more extensive use of IMRT) may require unnecessary shielding that can be avoided by using a more realistic workload in the shielding calculations. For example, it is common for a large fraction of the leakage workload to be delivered at 6 MV. Performing shielding calculations at the highest MV for the workload actually delivered at 6 MV would likely require an unnecessary amount of neutron shielding in the door.

Primary Barrier Width Calculation

The primary barrier width (w) is recommended to have sufficient width to ensure at least a 0.3-m margin on either side of a field of maximum size rotated 45 degrees. For a square f × f-cm field at 1-meter distance from the target, w is given by:

$$w = (f / 100\,\text{cm})\sqrt{2}\, d_N + 0.6\,\text{meters} \qquad (2\text{-}12)$$

where d_N is the distance from the target to the far side of the narrowest part of the barrier (also in meters). Figure 2-6 illustrates the typical locations for the narrowest point of the barrier. The square-root of two factor is in included in Equation (2-12) to account for the 45-degree clocking of the field. If the linear accelerator does not allow clocking of the field, the square root of two factor should be removed from Equation (2-12).

The maximum field is typically a 40 × 40-cm square. If the corners of the field are clipped, which is typically the case, the effective field size to be used in Equation (2-6) is smaller than 40 cm. Figure 2-7 illustrates this with primary barrier width typically calculated with a 35-cm effective field size.

Note the diagonal measurement of the 35-cm effective field size is approximately 50 cm. If the 50-cm diagonal field size is used as the basis to calculate the minimum primary barrier width, the square root of two factor should be removed from Equation (2-12), since clocking of the field has already been included in the 50-cm value.

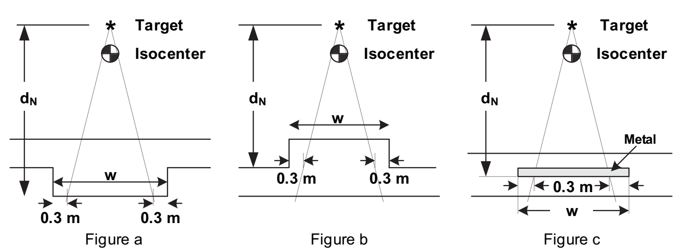

Figure 2-6 Primary barrier width.

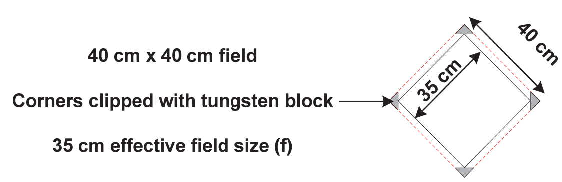

Figure 2-7 Effective field size.

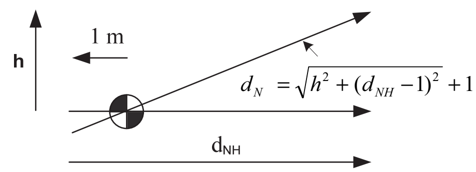

Figure 2-8 Distance measured to top of primary barrier.

NCRP 151 recommended that the distance from the target to the narrow point of the primary barrier is measured at the top of the barrier, not at the same height as isocenter. This recommendation is not physically meaningful when the primary barrier extends outward from the secondary barrier (Figure 2-6a); otherwise it is an appropriate recommendation to follow for new construction. If the top of the barrier is h meters above isocenter and the distance from the target to the narrow point of the barrier measured horizontally is d_{NH} meters, then d_N is calculated as illustrated in Figure 2-8.

For existing construction, it is generally impractical to increase the primary barrier width if the barrier is slightly too narrow, as calculated with the beam pointing at the top of the wall. Evaluating primary barrier width with the beam pointed horizontally (for walls) or vertically (for ceiling or floor if applicable) is therefore pragmatic for existing construction. The main criterion that determines whether the primary barrier width is adequate is the dose rate beyond the adjacent secondary barrier. A retrofit (if required) for existing construction is typically achieved by adding shielding to the adjacent secondary barrier, not increasing primary barrier width.

Example*: *recommended primary barrier width

Figure 2-6a, with $d_N = 6.2$ m

$w = (35/100) \times \sqrt{2} \times 6.2 + 0.6 = 3.67$ m

A slightly wider 3.96-m primary barrier width is recommended.

Figure 2-6b, new construction with $d_{NH} = 5.4$ m, $h = 2$ m

$d_N = \sqrt{2^2 + (5.4 - 1)^2} = 5.83$ m

$w = (35/100) \times \sqrt{2} \times 5.83 + 0.6 = 3.49$ m

A slightly wider 3.66-m primary barrier width is recommended.

However, situations requiring increased primary barrier width do occur if the field extends very close to (or beyond) the edge of the primary barrier. Examples include a change from the original treatment room design for isocenter or the plane of rotation. In such situations, in addition to evaluating the adjacent secondary barrier, a primary barrier calculation at the edge of the field may be appropriate. The next section provides a model that can be used in situations in which the primary barrier shielding at the edge of the primary barrier is less than provided along the central axis.

Primary Beam Dose Rate vs. Beam Angle

Normally a primary barrier has constant thickness over the entire field, with the highest dose rate beyond the barrier occurring on the central axis of the beam. If the barrier thickness or material changes near the edge of the field, a separate calculation may be appropriate at that location. Table 2-4 provides a model for the primary beam dose rate relative to the central axis dose rate for use in this calculation. The normal primary TVLs are conservatively assumed to apply.

The model in Table 2-4 is based on an 18-MV 21EX Varian linear accelerator with a 40 × 40-cm field clocked at 45 degrees, with measurements made out to 22 degrees off the central axis (Potts 2007). The data are then extrapolated out to 45 degrees, the mini-

Table 2-4 *Primary dose rate relative central axis vs. beam angle*

Angle	*Ratio*
0	1.000
8	0.950
11	0.900
13	0.800
14	0.550
16	0.250
18	0.150
20	0.100
22	0.070
24	0.050
26	0.030
28	0.020
32	0.010
38	0.003
45	0.001
180	0.001

mum angle from the central axis for which the 0.1% leakage fraction is specified. As with other primary barrier calculations, the dose rate in Table 2-4 assumes no phantom (or patient) is located at isocenter.

Tapered Primary Barrier Ceiling

When the space above the accelerator vault may be occupied, the ceiling must be shielded as a primary barrier. The weight and thickness required are more challenging for a ceiling than for a wall because of structural requirements. A tapered primary barrier reduces this weight by exploiting the fact that the required barrier thickness decreases with distance away from the point immediately above isocenter. The reduced thickness is primarily caused by slant thickness, but it is also partially caused by the lower use factor (U = 0.1) appropriate for gantry angles that are not a multiple of 90 degrees. Typically tapering is recommended only if the primary barrier includes high-density shielding material to decrease its thickness.

In Figure 2-9, the "width" and "length" dimensions of individual ceiling barrier sections are defined to be consistent with wall primary barrier width. The term width refers to the dimension perpendicular to the plane of rotation. The term length refers to the

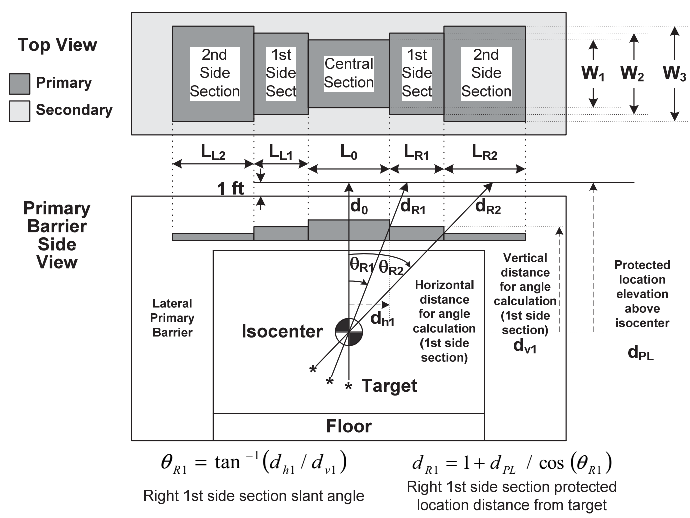

Figure 2-9 Tapered primary ceiling barrier.

horizontal dimension in the plane of rotation. The thickness required for the central section immediately above isocenter is identical to the conventional primary calculation described previously. The central section length (L_0) is based on the beam being within plus or minus the angle for central section length from vertical (i.e., near the vertical gantry angle for which $U = 0.25$ is applied). The minimum width of the central section W_0 must provide a 30-cm margin on each side with the beam pointed at the boundary between the central section and the first side section.

Typically, the width of the concrete in the primary ceiling barrier will be selected to match the wall primary barrier, with any metal embedded in the concrete possibly having a narrower width. The next length L_{R1} can be arbitrarily selected based on the dimensions of available material. An arbitrary number of segments can be used. The ceiling primary barrier must extend a sufficient distance to ensure the wall provides adequate shielding with the beam pointed just below the ceiling shielding. This may require the ceiling to extend to the far side of the wall primary barrier.

The shielded dose rate calculations for the side sections use the same method as the central section, except with a potentially lower use factor (e.g., U = 1/10) and increased distance d_{R1}, d_{R2}, etc. In addition, the barrier transmission calculations are based on the slant thickness of the barrier material (vertical material thicknesses along the path divided by $\cos(\theta_{R1})$, $\cos(\theta_{R2})$, etc.). As illustrated in Figure 2-9, the angles θ_i are calculated to provide the path with the minimum slant angle for a given section of material.

Obliquity Factor

For primary barriers, scatter can cause the barrier transmission to be higher than predicted based on slant factor alone. To compensate for this, the slant thickness $[t / \cos(\theta)]$ is divided by an obliquity factor (see Table A-7, with the result termed the oblique thickness. The obliquity factors in Table A-7 are based on Biggs (1996), with values at 45 degrees modified to comply with the *NCRP 151* recommendation to add 2 HVL at low MV and 1 HVL at high MV for slant angles of 45 degrees and higher. Interpolation is used at MVs between the values given in Table A-7.

Groundshine Calculations

If a primary barrier is extremely thin (e.g., only of lead), scattered radiation through a normal weight concrete floor may exceed the direct radiation through the wall when the beam is pointed at the

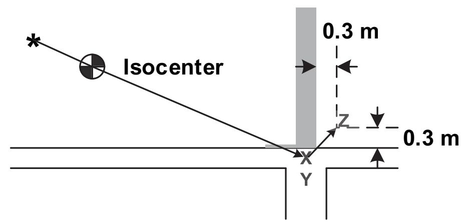

Figure 2-10 Basic groundshine geometry.

base of the wall. This radiation is referred to as groundshine. As depicted in Figure 2-10, groundshine is modeled by first determining the dose rate at Location X in the concrete floor beneath the wall along a path from the x-ray target passing beneath the base of the wall. A primary barrier calculation is used to determine the dose rate at Location X. The protected location (denoted Z in Figure 2-10) is considered to be 0.3 m above floor level and 0.3 m beyond the wall, with the dose rate at Location Z calculated from the dose rate at Location X using a secondary barrier scatter calculation.

The groundshine scatter calculation should use the maximum field size, which covers a significant area beneath the wall, not a specific point such as X or Y depicted in Figure 2-10. In reality the transmission through the floor varies significantly over the field. To assess the impact of the varying geometry over the field, groundshine should be calculated at a number of Location X elevations corresponding to the vertical extent of the field below the wall. The average of these calculations is the calculated groundshine. Location Y (the point yielding the same calculated dose rate as the average over the field) can then be used to illustrate the calculation.

Neutrons should not be a significant source of groundshine because the concrete floor should provide adequate neutron shielding.