

Design and Shielding of Radiotherapy Treatment Facilities

IPEM report 75, 2nd Edition

P W Horton and D J Eaton

Chapter 5

Empirical shielding calculations for treatment rooms with linear accelerators

P W Horton, D J Peet and R M Harrison

5.1 General principles

The purpose of radiation shielding is to attenuate the radiation from the treatment unit, its surroundings and the patient, to areas outside the room and its entrance to a level less than a dose and/or a dose rate constraint adopted by the hospital and based on requirements and recommendations set in national legislation or international guidance. Walls at which the beam can be pointed directly are called primary barriers. Other walls in the treatment room need to provide protection from radiation leakage from the head of the treatment unit and scatter from the patient, and are called secondary barriers. Generally secondary barriers are thinner than primary barriers due to the lower energy of the scattered radiation and lower dose rates. For primary and secondary barriers, the dose rate at an external point of interest will be reduced by the inverse square law and the attenuation provided by the intervening shielding, the latter diminishing with increasing x-ray or gamma ray energy.

The entrance to the treatment room may be through a door or along a corridor with a number of bends, termed a ‘maze’. Doors need to be substantial, especially for megavoltage treatment units, to provide the necessary shielding to attenuate the radiation, and are power operated. With maze entrances, multiple scattering and absorption along the length of the maze reduce the dose rate to an acceptable level at the entrance. The dose rate at the maze entrance during operation will diminish with increasing maze length due to the inverse square law and with the number of bends, which increase the number of scatter interactions with the walls of the maze. When space is limited, a combination of a short maze and a lighter door may be used to achieve acceptable dose rates. For linear accelerators operating at 8.5 MV and higher energies, neutrons will be produced in the treatment head of the accelerator and scattered by the walls down the maze. Again the inverse square law plays a part

but special measures such as neutron absorber sheets on the walls of the maze and a door may be required to achieve the dose and/or dose rate constraint. These processes and the calculation of the external annual dose and instantaneous dose rate using empirical methods are considered in greater detail below. Typical arrangements for a shielded room containing a linear accelerator, often termed a bunker or a vault, and having a maze are shown in plan and elevation in figure 5.1.

5.2 Primary barriers

5.2.1 General

Radiation falling directly on a primary barrier originates from the target of the treatment unit and all distances for the inverse square law component of shielding calculations should have this as their origin.

The attenuating power of shielding materials can be empirically specified in terms of tenth value layers (TVLs), i.e. the thickness of the material, to reduce the intensity at normal incidence to one tenth of its incident intensity for megavoltage radiation, and in terms of the half value layer (HVL), i.e. the thickness to reduce the incident

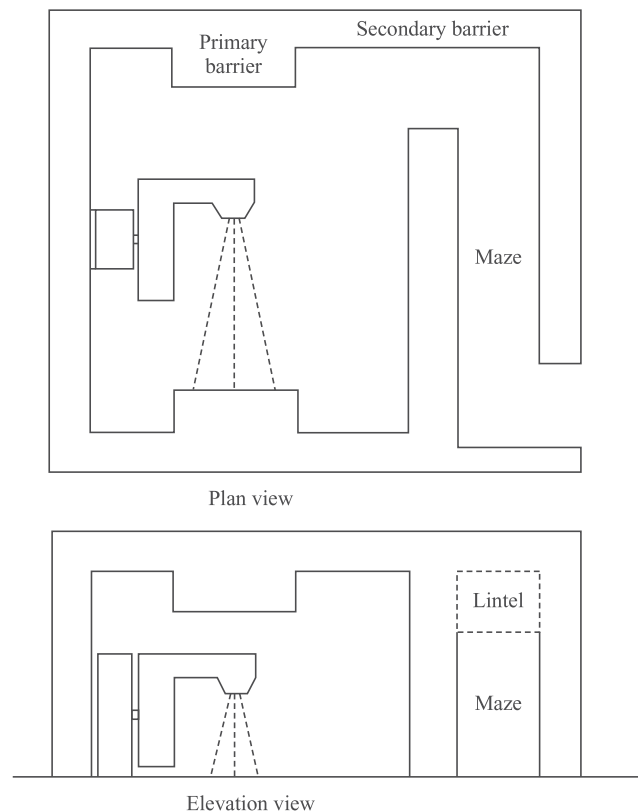


Figure 5.1. A typical linear accelerator bunker.

intensity by half, for kilovoltage radiation. The barrier transmission factor, B , is then given by

$$B = 10^{-n} \text{ or } 2^{-n},$$

where n is the number of TVLs or HVLs, respectively. To achieve a specific transmission factor, the number of TVLs or HVLs can be calculated using the expressions

$$n_{\text{TVL}} = -\log_{10} B \quad \text{or} \quad n_{\text{HVL}} = -\log_2 B.$$

The required thickness of the shielding can then be calculated by multiplying n by the relevant TVL or HVL value, i.e.

$$\text{thickness } (t) = n \times \text{TVL or } n \times \text{HVL.} \quad (5.1)$$

The TVL and HVL will decrease with increasing x-ray energy and n will need to be increased to achieve a specific dose rate on the exterior of the shielding for a given incident dose rate.

IPEM (1997) tabulates TVLs for standard concrete (2350 kg m^{-3}) for x-ray endpoint energies ranging from 4 to 24 MV, and also has a graphical presentation of the TVL variation in concrete, steel and lead over the energy range 50 kV–10 MV. However, these are average TVL values. In practice the x-ray beam will be hardened as it penetrates the shielding and the TVL will increase, especially after the first TVL. NCRP (2005) adopts this more scientific approach and gives values for the first TVL (TVL_1) and the subsequent equilibrium TVL (TVL_e). These are reproduced in table 5.1. The barrier thickness, t , is then given by

$$t = \text{TVL}_1 + (n - 1)\text{TVL}_e. \quad (5.2)$$

Table 5.1. Primary beam TVLs for concrete, steel and lead for a range of endpoint energies (adapted from NCRP (2005) table B2).

Density (kg m^{-3})	Concrete		Steel		Lead	
	2350		7870		11 350	
Endpoint energy (MeV)	TVL_1 (mm)	TVL_e (mm)	TVL_1 (mm)	TVL_e (mm)	TVL_1 (mm)	TVL_e (mm)
4	350	300	99	99	57	57
6	370	330	100	100	57	57
10	410	370	110	110	57	57
15	440	410	110	110	57	57
18	450	430	110	110	57	57
20	460	440	110	110	57	57
25	490	460	110	110	57	57
30	510	490	110	110	57	57
Co-60	210	210	700	700	40	40

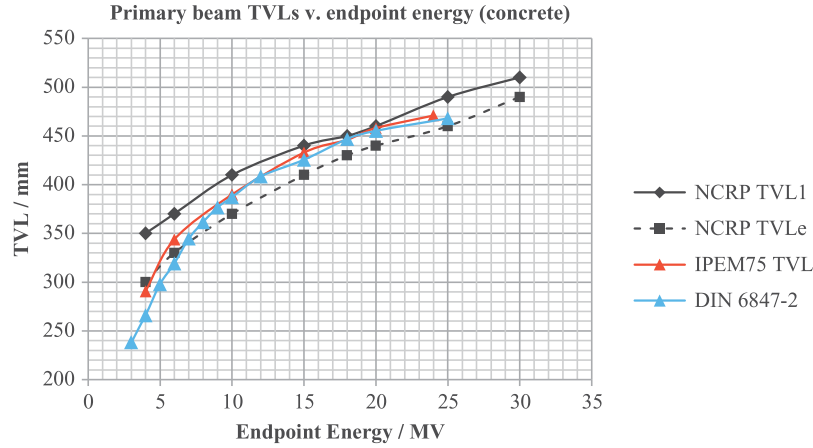


Figure 5.2. Variation of concrete TVLs with endpoint energy (density of concrete = 2350 kg m^{-3}). Data are taken from table 5.1, IPEM (1997) and DIN (2008).

Comparison of the two sets of TVL data shows that the IPEM (1997) values are closer to the equilibrium TVLs in the range 4–8 MV, and lie between the first and equilibrium TVLs at higher end point energies. This is illustrated in figure 5.2. It is recommended that the NCRP (2005) TVL values reproduced in table 5.1 are used in calculations.

5.2.2 Annual dose

The unattenuated annual dose (D_p) at a position outside the primary shielding around a treatment unit can be calculated from the annual radiation workload delivered to the isocentre (D_i) (see chapter 4) and the fraction of the treatment time (orientation or use factor) for which the beam is pointed at the barrier concerned (see section 4.1.3.4), i.e.

$$D_p = D_i \times U \times d_i^2 / (d_i + d_p)^2,$$

where U is the orientation factor, d_i is the target to isocentre distance and d_p is the distance from the isocentre to a point 0.3 m from the barrier on the far side of the barrier.

This point, 0.3 m beyond the barrier, is chosen as it is representative for the whole-body exposure of a person standing next to the external surface of the barrier at the calculation point selected.

The annual workload can be calculated from the number (N) of patient treatments per day, the average dose per patient (D_f) and the number of treatment days per year; the last is taken as 250 days for 5 days per week and 50 weeks per year, i.e.

$$D_i = D_f \times N \times 250.$$

The attenuated annual dose (D_a) to a person outside the primary shielding is then given by

$$D_a = (D_f \times N \times 250 \times U \times T \times B \times d_i^2) / (d_i + d_p)^2 \quad (5.3)$$

where T is the occupancy factor for the area concerned, i.e. the fraction of time the area is occupied by an individual (see section 3.7.2).

Re-arranging expression 5.3, the barrier transmission to achieve an annual dose constraint (D_{acc}) is given by

$$B = D_{\text{acc}} \times (d_i + d_p)^2 / (D_f \times N \times 250 \times U \times T \times d_i^2). \quad (5.4)$$

This will only be the case if a single energy is used for treatment. Commonly two energies are used, e.g. 6 MV and 10 MV or 6 MV and 15 MV, and for a given barrier thickness, the annual dose will be the sum of the annual doses at each of the energies taking into account the proportion of treatments at each energy. Calculation of the barrier thickness assuming all treatments take place at the higher energy will result in a safe situation, but will overestimate the thickness required in practice and calculation at the lower energy will result in an underestimate. A number of trial calculations between these two thicknesses taking into account the proportion of treatments at each energy may be required to arrive at an optimal thickness that meets the dose constraint. Some centres adopt the highest energy approach as a means of future-proofing the bunker for future developments but this adds to the costs. **Worked example 1** below shows the thicknesses of concrete required to achieve 0.3 mSv per year at 6, 10 and 15 MV for a typical radiation workload at a single energy for a fully occupied area outside the barrier. As stated above, more complex situations are met in practice.

Worked example 1

Suppose

$$\begin{aligned} D_{\text{acc}} &= 0.3 \text{ mSv per year} \\ d_i + d_p &= 5.0 \text{ m and } d_i = 1.0 \text{ m} \\ D_f &= 2 \text{ Gy} \\ N &= 50 \text{ patients per day} \\ U &= 0.25 \\ T &= 1 \end{aligned}$$

then

$$\begin{aligned} B &= 1.2 \times 10^{-6} \\ n &= -\log_{10} B = 5.92 \\ t &= \text{TVL}_1 + 4.92 \times \text{TVL}_e. \end{aligned}$$

The required barrier thicknesses in standard concrete (2350 kg m^{-3}) at 6, 10 and 15 MV using the TVL_1 and TVL_e values in table 5.1 are as follows:

Energy (MV)	Thickness (m)
6	1.99
10	2.23
15	2.46

5.2.3 Dose rate measures and verification of shielding

Whilst the annual dose constraint is the principal criterion for shielding design, it is recommended that external dose rates for each barrier are calculated to check that they are not excessive (see chapter 3). The external dose rate may also be a constraint in national legislation, usually expressed in $\mu\text{Sv h}^{-1}$. In the UK, the term ‘instantaneous dose rate’ is used to describe the dose rate averaged over one minute to take account of the response time of the measuring instrument and the pulse repetition rate if a linear accelerator is the radiation source. To check the adequacy of the shielding, the dose rate on the exterior of the barrier when the radiation beam is pointing directly at the barrier at normal incidence can be measured and compared with these predicted values.

For an existing barrier with a transmission factor B , the external dose rate, DR in $\mu\text{Sv min}^{-1}$, will be given by

$$\text{DR} = (\text{DR}_i \times 10^6 \times B \times d_i^2) / (d_i + d_p)^2, \quad (5.5)$$

where DR_i is the dose rate at the isocentre (Gy min^{-1}) and d_i and d_p have the meaning given above.

This value can be compared with a measured value at the same position to assess the adequacy of the shielding.

To calculate the barrier thickness to meet a dose rate constraint, DR_{act} in $\mu\text{Sv h}^{-1}$, equation (5.5) can be re-arranged to calculate the transmission factor required as follows:

$$B = (\text{DR}_{\text{act}} \times (d_i + d_p)^2) / (\text{DR}_i \times 60 \times 10^6 \times d_i^2). \quad (5.6)$$

The required thickness can then be calculated from B in TVLs as above and be converted to actual thickness using the relevant TVL values. In general a dose constraint based on dose rate over a short period of time will lead to thicker barriers as this does not take account of the absence of radiation between patient fields and between patients. This is illustrated in [worked example 2A](#), where an actual dose rate of $7.5 \mu\text{Sv h}^{-1}$ has been specified for 6 Gy min^{-1} operation. As can be seen, the thickness of concrete at each energy is slightly greater than in worked example 1. [Worked example 2B](#) shows the thickness of concrete required for an actual dose rate of $20 \mu\text{Sv h}^{-1}$ with flattening-filter-free (FFF) mode operation at 24 Gy min^{-1} . The thickness of concrete at each energy is slightly greater than in worked example 2A. US practice (NCRP 2005) has shielding design goals for controlled and uncontrolled areas based on equivalent dose limits per week.

Worked example 2A: Standard mode operation

Suppose

$$\text{DR}_{\text{act}} = 7.5 \mu\text{Sv h}^{-1}$$

$$d_i + d_p = 5.0 \text{ m and } d_i = 1.0 \text{ m (as before)}$$

$$\text{DR}_i = 6 \text{ Gy min}^{-1}$$

then

$$B = 5.21 \times 10^{-7}$$

$$n = -\log_{10} B = 6.28$$

$$t = \text{TVL}_1 + 5.28 \times \text{TVL}_e.$$

The required barrier thicknesses in standard concrete (2350 kg m^{-3}) at 6, 10 and 15 MV using the TVL_1 and TVL_e values in table 5.1 are as follows:

Energy (MV)	Thickness (m)
6	2.11
10	2.36
15	2.60

Worked example 2B: FFF mode operation

Suppose

$$\text{DR}_{\text{act}} = 20 \text{ } \mu\text{Sv h}^{-1}$$

$$d_i + d_p = 5.0 \text{ m and } d_i = 1.0 \text{ m (as before)}$$

$$\text{DR}_i = 24 \text{ Gy min}^{-1}$$

then

$$B = 3.47 \times 10^{-7}$$

$$n = -\log_{10} B = 6.46$$

$$t = \text{TVL}_1 + 5.46 \times \text{TVL}_e.$$

The required barrier thicknesses in standard concrete (2350 kg m^{-3}) at 6, 10 and 15 MV using the TVL_1 and TVL_e values in table 5.1 are as follows:

Energy (MV)	Thickness (m)
6	2.17
10	2.43
15	2.68

5.2.4 Primary barrier width

For bunkers containing linear accelerators where the radiation beam is confined to a rotational plane through the isocentre (sometimes termed ‘C-arm accelerators’), the primary barriers will be limited in width to reduce concrete volume and cost (see figure 5.1). The width of the barrier will primarily be set by the extent of the beam at the barrier distance using the diagonal of largest field size, commonly $400 \text{ mm} \times \sqrt{2} = 570 \text{ mm}$ at the isocentre distance. Whilst at the end point energies of linear accelerator beams, 6 MV and higher, the radiation scatter within the barrier will be predominantly in the forward direction, there will still be some lateral scatter, sometimes termed the ‘plume effect’. To absorb this scattered radiation and to allow for building tolerances, it is good practice to add 300 mm to each side of the projected maximum beam width at the barrier to give the barrier width for

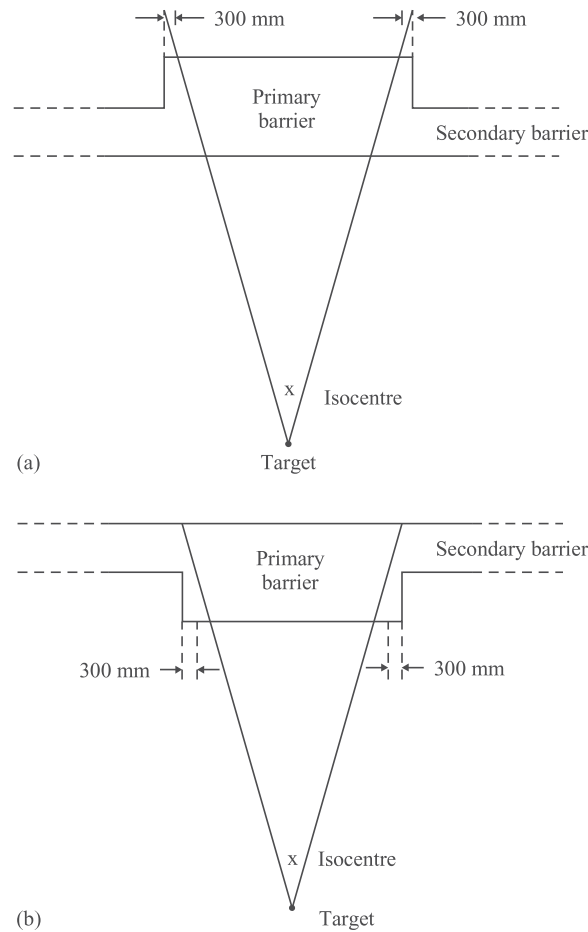


Figure 5.3. (a) Primary barrier external to treatment room. (b) Primary barrier intruding into treatment room.

construction. This is illustrated in figure 5.3 for barriers intruding into the treatment room, where 300 mm is added at the distance of inner wall provided by the secondary shielding, and extending outside the room, where 300 mm is added at the external wall. The width of the primary wall barrier will need to be maintained for the primary barrier in the roof of the bunker (figure 5.1) if the exterior is accessible.

5.3 Secondary barriers

5.3.1 General

Radiation falling on the secondary barriers originates from leakage radiation from the head of the treatment unit, scattered radiation from the patient and to a lesser extent scattered radiation from the walls. At large scatter angles, the intensity and energy of the radiation scattered from the patient is less than the leakage from the

treatment head, especially with small field sizes, and the latter is used alone in calculations of adequate secondary shielding. This practice is followed in the examples below. When the scatter angle is small, patient scatter should not be ignored. Scatter fractions from a human-size phantom are given in NCRP (2005, table B4); these are reproduced in table 5.8. When calculating the secondary barrier thicknesses for leakage and patient scattered radiation, the larger thickness should be used if the two thicknesses differ by more than a TVL. If the two thicknesses differ by less than a TVL, use the larger thickness and add an HVL of the shielding material to give the total thickness required (IAEA 2006).

International standards (IEC 2009) limit the leakage dose rate to 0.1% of the dose rate in the primary beam at the isocentre to restrict the patient's body dose in comparison with the tumour dose. Linear accelerator manufacturers achieve a lower leakage rate in practice and the rate is typically halved when the accelerator is in FFF mode due to the absence of the flattening filter as a source of scattered radiation.

All distances for the inverse square law component of secondary shielding calculations have the isocentre as their origin. This is assumed to be the mean position of the treatment head over a large number of treatments at different gantry angles for leakage radiation and is also the origin of the patient scatter.

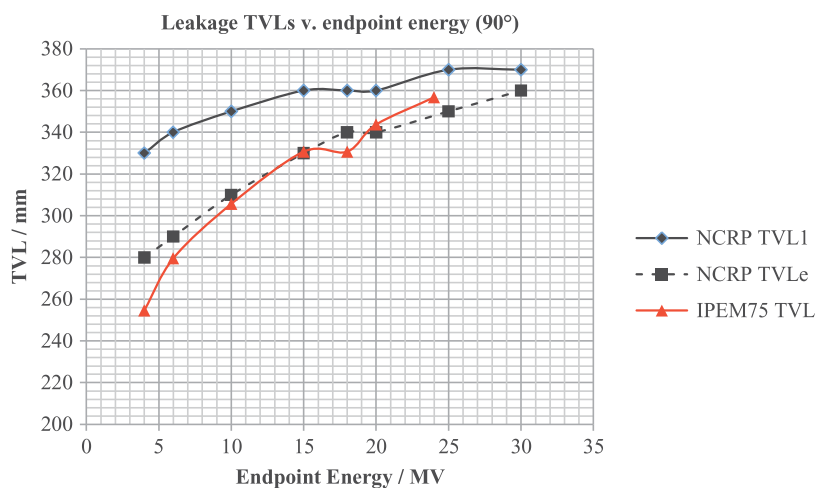
The scattered radiation is also assumed to be isotropic in its distribution around the isocentre, when averaged over all gantry angles. The orientation factor, U , is therefore taken as unity in all directions in dose calculations.

The end point energy of the leakage radiation will be degraded by the scatter interactions with components in the treatment head, and the mean energy of the scattered radiation will be less than the primary radiation. Consequently the TVL values for scattered radiation will be lower than those for the primary beam and generally secondary shielding will be thinner than primary shielding. Again, IPEM (1997) tabulates secondary TVLs for standard concrete (2350 kg m^{-3}) for x-ray end point energies ranging from 4 to 24 MV. These are an average value as the scattered x-ray beam will be hardened as it penetrates the shielding and the TVL will increase, especially after the first TVL. Again NCRP (2005) adopts a more scientific approach and gives values for the first TVL (TVL_1) and the subsequent equilibrium TVL (TVL_e) for leakage Co-60 radiation and x-radiation with end point energies in the range 4–30 MV. These are reproduced in table 5.2. Comparison of the two sets of TVL data shows that the IPEM (1997) values are broadly in agreement with the NCRP (2005) equilibrium TVLs although the IPEM (1997) values are lower at 4–6 MV. This is illustrated in figure 5.4. NCRP (2005, tables B.5a and B.5b) also gives mean TVL values for patient scattered radiation in concrete for Co-60 radiation and x-radiation with end point energies in the range 4–24 MV and in lead for 4, 6 and 10 MV for a range of scatter angles; these are reproduced in tables 5.3 and 5.4, respectively, for completeness. IPEM (1997) has extensive data for kilovoltage end point energies and limited data at 4 and 6 MV only in the megavoltage range; the latter data are typically 25% higher than the corresponding NCRP (2005) values.

As described in section 4.1, many current radiotherapy treatments employ intensity modulated radiotherapy (IMRT) or volumetric intensity modulated arc

Table 5.2. Leakage TVLs for concrete at 90° for a range of endpoint energies (adapted from NCRP (2005) table B7).

Endpoint energy (MeV)	TVL _L (mm)	TVL _e (mm)
4	330	280
6	340	290
10	350	310
15	360	330
18	360	340
20	360	340
25	370	350
30	370	360
Co-60	210	210

**Figure 5.4.** Variation of concrete leakage TVLs (90°) with endpoint energy (density of concrete = 2350 kg cm⁻³). Data are taken from table 5.2 and IPEM (1997).

therapy (VMAT) to build up complex non-uniform dose distributions within the tumour treatment volume. This requires the application of many small shaped fields of different intensity. The total dose will generally be the same as that in a conventional single large field of uniform intensity, and primary shielding calculations are unchanged unless the total dose is increased for clinical reasons. However, the build-up using small fields will require a much longer period of irradiation (beam-on time) for the same prescribed dose, and this longer period of radiation increases the amount of leakage and scattered radiation per treatment. An

Table 5.3. TVL values in concrete for patient scattered radiation versus scatter angle (adapted from NCRP (2005) table B.5a).

Scatter angle °	TVL (mm)					
	Co-60	4 MV	6 MV	10 MV	15 MV	18 MV
15	220	300	340	390	420	440
30	210	250	260	280	310	320
45	200	220	230	250	260	270
60	190	210	210	220	230	230
90	150	170	170	180	180	190
135	130	140	150	150	150	150

Table 5.4. TVL₁ and TVL_e in lead for patient scattered radiation versus scatter angle (adapted from NCRP (2005) table B.5b).

Scatter angle °	4 MV		6 MV		10 MV	
	TVL ₁ (mm)	TVL _e (mm)	TVL ₁ (mm)	TVL _e (mm)	TVL ₁ (mm)	TVL _e (mm)
30	33	37	38	44	43	45
45	24	31	28	34	31	36
60	18	25	19	26	21	27
75	13	19	14	19	15	19
90	9	13	10	15	12	16
105	7	12	7	12	9.5	14
120	5	8	5	8	8	14

IMRT factor is introduced into secondary shielding calculations to take account of this practice; it is defined as follows:

$$\text{IMRT factor (IF)} = \frac{\text{MU(IMRT)}}{\text{MU(conventional)}},$$

where MU(IMRT) is the number of monitor units (typically 1 MU~1 cGy) to give the prescribed dose using IMRT, and MU (conventional) is the number of monitor units to give the prescribed dose with a single uniform treatment field.

NCRP (2005) notes that the IMRT factor ranges from 2 to 10 for IMRT treatments and a factor of 5 is commonly used in calculations of secondary shielding. VMAT employs arc therapy to deliver similar doses to IMRT in a shorter treatment time and an IMRT factor of 2.5 has been determined for some treatments (see section 4.1.2.1). A value of 3 is considered conservative.

In planning adequate secondary shielding it is important that the proportion of patients having IMRT and VMAT is determined and the IMRT factor is derived from the range of existing or planned clinical procedures in the centre. For example

if the fraction of patients having IMRT and/or VMAT is P and the IMRT factor is IF, then the fractional increase, f , in the ‘beam-on time’ will be given by

$$f = 1 - P + P \times \text{IF}.$$

5.3.2 Annual dose

The unattenuated annual dose (D_p) at a position outside the secondary shielding around a treatment unit can be calculated from annual radiation workload delivered to the isocentre (D_i) and the fractional leakage dose rate (0.001) and the increase in beam-on time, i.e.

$$D_p = D_i \times 0.001 \times f / d_p^2,$$

where d_p is the distance from the isocentre to the far side of the barrier.

The annual radiation workload can be calculated from the number (N) of patient treatments per day, the average dose per patient (D_f) and the number of treatment days per year; the last is often taken as 250 days for 5 days per week and 50 weeks per year, i.e.

$$D_i = D_f \times N \times 250.$$

The attenuated annual dose (D_a) to a person outside the secondary shielding is then given by

$$D_a = (D_f \times N \times 250 \times 0.001 \times f \times T \times B) / d_p^2, \quad (5.7)$$

where T is the occupancy factor for the area concerned and B is the transmission factor.

Re-arranging equation (5.7), the barrier transmission to achieve an annual dose constraint (D_{acc}) is given by

$$B = D_{acc} \times d_p^2 / (D_f \times N \times 250 \times 0.001 \times f \times T). \quad (5.8)$$

This will only be the case if a single energy is used for treatment. Commonly two energies are used, e.g. 6 and 10 MV or 6 and 15 MV, and for a given barrier thickness, the annual dose will be the sum of the annual doses at each of the energies taking into account the proportion of treatments at each energy. Calculation of the barrier thickness assuming all treatments take place at the higher energy will result in a safe situation, but will overestimate the thickness required in practice and calculation at the lower energy will result in an underestimate. A number of trial calculations between these two thicknesses taking into account the proportion of treatments at each energy may be required to arrive at an optimal thickness that meets the dose constraint. [Worked example 3](#) below shows the thicknesses of concrete required to achieve 0.3 mSv per year at 6, 10 and 15 MV for a typical radiation workload at a single energy for a fully occupied area outside the barrier. As stated above, more complex situations are met in practice.

Worked example 3

Suppose

$$D_{\text{acc}} = 0.3 \text{ mSv per year}$$

$$d_p = 4.0 \text{ m}$$

$$D_f = 2 \text{ Gy}$$

$$N = 50 \text{ patients per day}$$

$$U = 1$$

$$T = 1$$

$$\text{IF} = 5$$

$$\text{fraction of patients having IMRT and/or VMAT} = 0.4$$

$$f = 0.6 + 0.4 \times 5 = 2.6,$$

then

$$B = 7.38 \times 10^{-5}$$

$$n = -\log_{10} B = 4.13$$

$$t = \text{TVL}_1 + 3.13 \times \text{TVL}_e.$$

The required barrier thicknesses in standard concrete (2350 kg m^{-3}) at 6, 10 and 15 MV using the TVL_1 and TVL_e values in table 5.2 are as follows:

Energy (MV)	Thickness (m)
6	1.25
10	1.32
15	1.39

5.3.3 Dose rate measures and verification of shielding

Whilst the annual dose constraint is the principal criterion for shielding design, it is recommended that external dose rates for each barrier are calculated to check that they are not excessive (see chapter 3). The external dose rate may also be a constraint in national legislation, usually expressed in $\mu\text{Sv h}^{-1}$. To check the adequacy of the shielding, the dose rate on the exterior of the barrier can be measured and compared with predicted values. This is normally done with a water phantom at the isocentre to mimic the patient scatter and is done at a number of gantry angles to cover all beam orientations.

For an existing barrier with a transmission factor B , the external dose rate, DR in $\mu\text{Sv min}^{-1}$, will be given by

$$DR = (DR_i \times 10^6 \times 0.001 \times B)/d_p^2, \quad (5.9)$$

where DR_i is the dose rate at the isocentre (Gy min^{-1}) and d_p has the meaning given above.

This value can be compared with a measured value at the same position to assess the adequacy of the shielding.

To calculate the barrier thickness to meet a dose rate constraint, DR_{acc} in $\mu\text{Sv h}^{-1}$, equation (5.9) can be re-arranged to calculate the transmission factor required as follows:

$$B = (\text{DR}_{\text{acc}} \times d_p^2) / (\text{DR}_i \times 60 \times 10^6 \times 0.001). \quad (5.10)$$

The required thickness can then be calculated from B in TVLs as above and converted to actual thickness using the relevant TVL values. This is illustrated in [worked example 4](#), where a dose constraint of $7.5 \mu\text{Sv h}^{-1}$ has been specified for 6 Gy min^{-1} operation and $20 \mu\text{Sv h}^{-1}$ has been specified for 24 Gy min^{-1} operation. US practice (NCRP 2005) has shielding design goals for controlled and uncontrolled areas based on equivalent dose limits per week.

Worked example 4A: Standard mode operation

Suppose

$$\text{DR}_{\text{acc}} = 7.5 \mu\text{Sv h}^{-1}$$

$$d_p = 4.0 \text{ m}$$

$$\text{DR}_i = 6 \text{ Gy min}^{-1}$$

then

$$B = 3.33 \times 10^{-4}$$

$$n = -\log_{10} B = 3.48$$

$$t = \text{TVL}_1 + 2.48 \times \text{TVL}_e.$$

The required barrier thicknesses in standard concrete (2350 kg m^{-3}) at 6, 10 and 15 MV using the TVL_1 and TVL_e values in [table 5.2](#) are as follows:

Energy (MV)	Thickness (m)
6	1.06
10	1.12
15	1.18

Worked example 4B: FFF mode operation

Suppose

$$\text{DR}_{\text{acc}} = 20 \mu\text{Sv h}^{-1}$$

$$d_p = 4.0 \text{ m}$$

$$\text{DR}_i = 24 \text{ Gy min}^{-1}$$

then

$$B = 2.22 \times 10^{-4}$$

$$n = -\log_{10} B = 3.65$$

$$t = \text{TVL}_1 + 2.65 \times \text{TVL}_e.$$

The required barrier thicknesses in standard concrete (2350 kg m^{-3}) at 6, 10 and 15 MV using the TVL_1 and TVL_e values in [table 5.2](#) are as follows:

Energy (MV)	Thickness (m)
6	1.11
10	1.17
15	1.23

5.4 Roofs and skyshine

Where the space above the bunker(s) is routinely accessible or occupied, the same annual dose and possibly dose rate constraints for x-rays will apply to these areas as apply to areas outside the walls of the bunker(s). In this situation the thicknesses of the primary and secondary shielding in the roof of the bunker are calculated using the methodology in sections 5.2 and 5.3, respectively, taking into account the occupancy of the areas concerned and the orientation factor U in the direction of the roof for the primary beam.

When there are no rooms above the bunker, access to the area over the roof can be prohibited during operation of the treatment unit and an instantaneous dose rate of 2 mSv h^{-1} adopted for the primary and secondary shielding calculations. This dose rate is accepted (IPEM 1997) as the threshold for a significant dose from radiation transmitted through the roof and scattered from the air above the bunker to reach people on the ground nearby or in adjacent buildings, this is called ‘skyshine’ (NCRP 1977). This can be especially important if radiation sensitive equipment, e.g. gamma cameras, is located in adjacent buildings. For a linear accelerator operating at 6 Gy min^{-1} and a distance of 3.5 m from the isocentre to the upper surface of the roof, this requires 3.95 TVLs of primary shielding and 1.17 TVLs of secondary shielding (not taking obliquity into account). For 15 MV operation, this corresponds to 1.65 m of conventional concrete for the primary barrier and 0.42 m for the secondary barrier.

If an assessment of x-ray skyshine is required, the following expression (McGinley 2002) can be used to estimate the dose rate (Gy h^{-1}) at ground level using the configuration in figure 5.5:

$$\text{DR}_{\text{sky}} = (2.5 \times 10^{-2} \times \text{DR}_0 \times B_{\text{roof}} \times \Omega^{1.3}) / ((d_r + 2) \times d_c^2) \quad (5.11)$$

where DR_0 is the dose rate at the isocentre (Gy h^{-1}), B_{roof} is the transmission factor of the roof with a vertical beam, Ω is the angle subtended by the primary beam at the

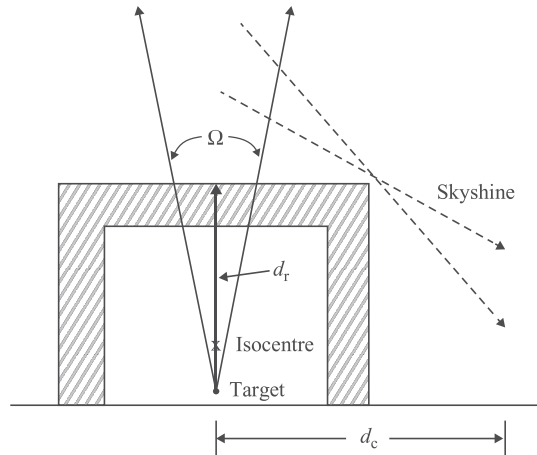


Figure 5.5. Elevation showing the position of the target and the position of the calculation point for the estimation of skyshine.

external surface of the roof, d_r is the distance from the radiation source to the external surface of the roof (m) and d_c is the horizontal distance from the radiation source to the point of interest (m).

McGinley (1993) has compared measurements of x-ray skyshine with calculated dose rates using the above methodology for an 18 MV accelerator with a roof having a transmission factor of 10^{-1} . The calculated dose rates are more than the measured dose rates close to the building because attenuation by the building is ignored but are lower farther away. The highest dose rates occur when d_c is similar to the height of the bunker wall. It is suggested that equation (5.11) should be used only to estimate an order of magnitude dose rate.

NCRP (2005) also considers the dose rate from x-rays scattered laterally from thin roof barriers and the skyshine dose rate from neutrons produced by linear accelerators operating at x-ray energies over 8.5 MV.

5.5 Groundshine

With a bunker built with conventional concrete the wall thickness will be at least 1 m and this will attenuate the radiation scattered upward when the beam is directed toward the floor at the bottom of a wall. However, with a thin wall made of high Z material, e.g. lead or steel, it is possible for scattered radiation to emerge on the far side of the wall when the primary beam is directed toward the bottom of the wall, e.g. in a CyberKnife[®] installation¹. One solution to this problem is to place additional shielding of lead or steel on the floor at the foot of the wall (figure 5.6) or let into the floor. Alternatively the wall can be extended below floor level to ensure the primary beam passes through the same thickness of material. The obliquity of the beam in this situation (see below) reduces the thickness of lead or steel required.

5.6 Obliquity factor

Generally bunkers made of conventional concrete are built with primary and secondary barriers of constant thickness for simplicity and ease of construction; the thickness of the barrier being calculated for radiation at normal incidence to give the attenuation required. Away from radiation beams passing horizontally or vertically through the isocentre, the beam will strike the barrier at an oblique angle. This will increase both the distance to the barrier and the path length in the barrier, termed the slant thickness. The slant thickness t_s is given by

$$t_s = t / \cos \theta,$$

where t is the thickness of the barrier and θ is the angle of obliquity between the radiation and the normal to the surface of the barrier.

In practice, the use of t_s in transmission calculations will underestimate the barrier thickness required because scattered photons will originate inside the barrier and will have a path length less than t_s . This will vary with the angle of incidence and the

¹ CyberKnife is a registered mark of Accuray.

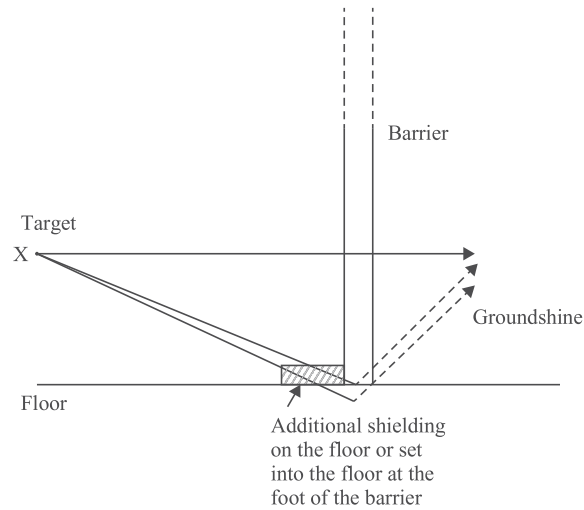


Figure 5.6. Groundshine at a physically thin barrier.

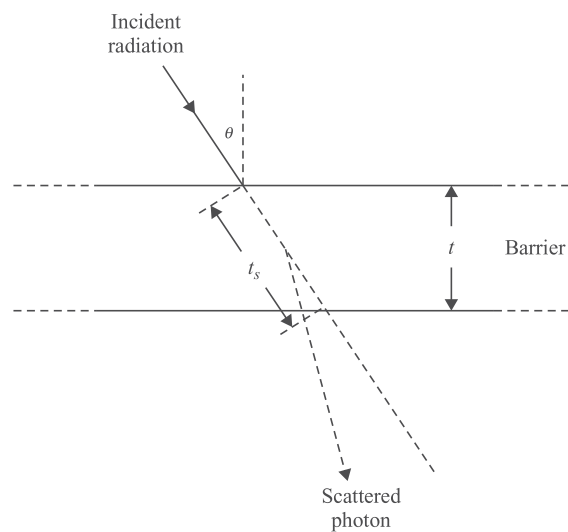


Figure 5.7. Calculation of slant thickness and origin of scattered radiation.

beam energy. This is illustrated in figure 5.7. The effective path length can be calculated by dividing the slant thickness by an obliquity factor (Biggs 1996). These are listed in table 5.5. As can be seen, the factors only become significant with incidence at 45° or greater. In practice obliquity is most often employed to reduce the wall thickness and cost when expensive high Z materials, e.g. lead, steel or high density concrete, are used when space is limited or when floor to floor height is limited and/or areas above are occupied.

Table 5.5. Obliquity factors for calculating effective slant thickness (Biggs 1996).

Angle	Concrete				Lead	Steel
	Co-60	4 MV	10 MV	18 MV	4–18 MV	4–18 MV
30	1.04	1.02	1.00	1.00	1.03	1.02
45	1.20	1.07	1.04	1.04	1.08	1.07
60	1.34	1.20	1.13	1.08	1.22	1.20
70	1.86	1.47	1.28	1.22	1.50	1.45

5.7 X-ray scatter down the maze

The dose rate due to x-rays at the external entrance to the bunker maze arises from four sources which need to be summed to give the total dose rate. These are:

- scatter of the primary beam from the bunker and maze walls,
- scatter from the patient,
- scatter of the head leakage radiation from the bunker walls and
- transmission of head leakage radiation through the inner maze wall.

These components will be considered individually. In general calculations assume that the intensity of the scattered radiation is linearly related to the irradiated wall area of the maze at each wall scatter and diminishes according to the inverse square law. This leads to multiple terms of the form $\alpha_n A_n / d_n^2$, where α_n is the reflection coefficient dependent upon the x-ray energy, wall material, and the angles of incidence and reflection, A_n is the area of wall irradiated and d_n is the distance to the next scatter or the exit in the case of the last scatter. It should be noted that barrier thicknesses calculated to adequately attenuate head leakage will also be adequate to satisfactorily attenuate all components of scattered radiation incident on a barrier and not reflected. The scattered radiation from the floor and roof of the bunker is not usually considered significant as both require an additional reflection at the floor or roof to reach the inner maze entrance. Typically this will add 0.1% to the intensity striking the inner maze walls in the examples in the following sections.

It is also generally assumed in these calculations that the radiation scattered by the patient and reflected at the walls after the first and subsequent scatters has an energy of 500 keV (NCRP 2005, IAEA 2006). However, Al-Affan (2000) using Monte Carlo modelling to simulate scatter down a two-leg maze from a 6 MV accelerator found that the scattered photon energy fell from about 350 keV at the inner maze entrance to about 100 keV at the outer maze entrance. McGinley and James (1997) also found that the average x-ray energy at the outer maze entrance of a similar maze was 150 keV for a 6 MV accelerator and 200 keV for a 10 MV accelerator. The lower energies will increase the reflection coefficients (see tables 5.6 and 5.7) for reflections close to the outer maze entrance. The lower energy from these calculations has been used to advocate less shielding in the door at the end of the maze if one is required. However, this suggestion should be treated with caution as higher energy x-rays from leakage radiation transmitted through the inner maze wall (see section 5.7.4) may also be present.

Table 5.6. Reflection coefficients for normal incidence on concrete as a function of angle of reflection for several endpoint energies (taken from NCRP (2005) table B8a). A table entry of 6.7 (e.g. for 4 MeV with normal reflection) means a reflection coefficient of 6.7×10^{-3} .

Endpoint energy (MeV)	Reflection coefficient $\times 10^3$ for normal incidence on concrete				
	Angle of reflection (degrees)				
	Measured from the normal				
	0	30	45	60	75
4	6.7	6.4	5.8	4.9	3.1
6	5.3	5.2	4.7	4	2.7
10	4.3	4.1	3.8	3.1	2.1
18	3.4	3.4	3	2.5	1.6
24	3.2	3.2	2.8	2.3	1.5
30	3	2.7	2.6	2.2	1.5
Co-60	7	6.5	6	5.5	3.8
Effective energy (MeV)					
0.25	32	28	25	22	13
0.5	19	17	15	13	8

Table 5.7. Reflection coefficients for 45° incidence on concrete as a function of angle of reflection for several endpoint energies (taken from NCRP (2005) table B8b). A table entry of 7.6 means a reflection coefficient of 7.6×10^{-3} .

Endpoint energy (MeV)	Reflection coefficient $\times 10^3$ for 45° incidence on concrete				
	Angle of reflection (degrees)				
	Measured from normal				
	0	30	45	60	75
4	7.6	8.5	9	9.2	9.5
6	6.4	7.1	7.3	7.7	8
10	5.1	5.7	5.8	6	6
18	4.5	4.6	4.6	4.3	4
24	3.7	3.9	3.9	3.7	3.4
30	4.8	5	4.9	4	3
Co-60	9	10.2	11	11.5	12
Effective energy (MeV)					
0.25	36	34.5	31	25	18
0.5	22	22.5	22	20	18

Table 5.8. Scatter fractions at 1 m from a human phantom for a reference field size of 400 cm² and target to phantom distance of 1 m (adapted from NCRP (2005) table B4). A table entry of 10.4 means a scatter fraction of 10.4×10^{-3}

Scatter fraction $\times 10^3$				
Angle (degrees)	6 MV	10 MV	18 MV	24 MV
10	10.4	16.6	14.2	17.8
20	6.73	5.79	5.39	6.32
30	2.77	3.18	2.53	2.74
45	1.39	1.35	0.864	0.830
60	0.824	0.746	0.424	0.386
90	0.426	0.381	0.189	0.174
135	0.300	0.302	0.124	0.120
150	0.287	0.274	0.120	0.113

5.7.1 Scatter of the primary beam from the bunker walls

This is illustrated in figure 5.8(a) for a two-leg maze and in (b) for a three-leg maze, where the radiation beam is incident on the primary shielding and the plane of beam rotation is parallel to the inner maze wall in both cases.

In general, the dose rate at the maze entrance, S_1 , will be given by:

$$S_1 = S^* \alpha_1 A_1 \alpha_2 A_2 \dots \alpha_n A_n / (d_i d_1 d_2 \dots d_n)^2, \quad (5.12)$$

where S^* is the dose rate at the isocentre; d_i is the distance from the target to the primary barrier (m); α_1 is the reflection coefficient at the first scatter dependent upon the x-ray energy, wall material, and the angles of incidence and reflection; A_1 is the beam area at the first scatter (m²); d_1 is the distance from the first scatter to the second scatter (m); α_2 is the reflection coefficient at the second scatter dependent on the energy of the scattered radiation (generally assumed to be 0.5 MeV), and the angles of incidence and reflection; A_2 is the irradiated area at the second scatter (m²); d_2 is the distance from the second to the third scatter (m); α_n is the reflection coefficient at the maze wall (n th scatter) dependent on the energy of the scattered radiation (generally assumed to be 0.5 MeV), and the angles of incidence and reflection; A_n is the area of the maze wall from which scatter is able to travel down the maze after the n th scatter; and d_n is the distance from the n th scatter to the maze entrance (m).

In figure 5.8(a) and (b), the first scatter takes place at the primary barrier and the distance d_i from the target to the primary barrier is 4.4 m and the area irradiated on the primary barrier is $1.8 \text{ m} \times 1.8 \text{ m} = 3.2 \text{ m}^2$ for the largest field size. The second scatter takes place at the inner maze entrance and the distance d_1 from the primary barrier to the inner maze entrance is 6.3 m. Suppose we have a linear accelerator operating at 10 MV with a dose rate at the isocentre of 6 Gy min^{-1} . The reflection coefficient α_1 at the primary barrier will be 2.1×10^{-3} (table 5.6) assuming a typical scattering angle of 75° , and α_2 at the inner maze entrance will be 8×10^{-3} assuming a