Basic Principles of Radiation Therapy Shielding Design

Peter J. Biggs Ph.D.,
Massachusetts General Hospital,
Harvard Medical School,
Boston, MA 02114
Outline

1. Basic principles and definitions
2. Calculations
3. Workload, use and occupancy factors
4. Shielding materials
5. Tenth value layers (TVL)
6. Room layout & features, construction details
7. Neutrons & laminated barriers
8. Mazes and doors
9. Ducts
Definitions

P: Weekly design dose limit (Sv/wk)
d: Distance from target to measurement point
W: Workload (Gy/wk)
U: Use Factor
T: Occupancy factor
a: Scatter fraction; (θ, E)
d_{sec}: Distance from scatterer to measurement point
d_{sca}: Distance from target to scatterer
d_{f}: Distance from the target to measurement point
F: Area of the beam in the plane of the scatterer (cm²)
B: Barrier transmission factor
Basic Principles

The purpose of radiation shielding is to reduce the effective equivalent dose from a linear accelerator to a point outside the room to a level that is determined by individual states.

Public or uncontrolled area - 0.02 mSv per week
- 0.02 mSv in any one hour

Controlled area - 1 mSv/wk (in practice 0.1 mSv/wk)
Basic Shielding Equations: NCRP
#151 Methodology

Primary:

\[ B_p = \frac{P d^2}{WUT} \]

Scatter:

\[ B_s = \frac{P}{aWT} d_{sec}^2 d_{sca}^2 \frac{400}{F} \]

Leakage:

\[ B_l = \frac{1000 \times P d_t^2}{WT} \]

The factor 1000 is due to the 0.1% leakage requirement

\[ B_x = \frac{I_{out}}{I_{in}} \]

B_x is the barrier transmission factor
Number of Tenth Value Layers (Primary & Leakage)

The number, \( n \), of tenth value layers (TVLs) required to reduce the dose to the value \( P \) is given by:

\[
n = -\log_{10}(B)
\]

and the thickness for primary and leakage radiation is given by:

\[
T = p,l\,TVL_1 + (n-1)p,l\,TVL_e
\]

NCRP report No. 151 Table B.2
Number of Tenth Value Layers for Scattered Radiation

Scatter TVLs are dependent only on energy and scattering angle, so:

\[ T_s = n_s \ TVL_s(\mathcal{G}) \]

NCRP report No. 151, Table B.5a
# Tenth Value Layers

## Primary TVLs (cm)*

<table>
<thead>
<tr>
<th>Energy (MV)</th>
<th>4</th>
<th>6</th>
<th>10</th>
<th>15</th>
<th>18</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>35(30)</td>
<td>37(33)</td>
<td>41(37)</td>
<td>44(41)</td>
<td>45(43)</td>
<td>46(44)</td>
</tr>
<tr>
<td>Steel</td>
<td>9.9</td>
<td>10</td>
<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>Lead</td>
<td>5.7</td>
<td>5.7</td>
<td>5.7</td>
<td>5.7</td>
<td>5.7</td>
<td>5.7</td>
</tr>
</tbody>
</table>

## Leakage TVLs at 90°* (cm)

<table>
<thead>
<tr>
<th>Energy (MV)</th>
<th>4</th>
<th>6</th>
<th>10</th>
<th>15</th>
<th>18</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>33(28)</td>
<td>34(29)</td>
<td>35(31)</td>
<td>36(33)</td>
<td>36(34)</td>
<td>36(34)</td>
</tr>
<tr>
<td>Steel**</td>
<td>8</td>
<td>8.5</td>
<td>8.7</td>
<td>8.7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lead**</td>
<td>4.5</td>
<td>4.6</td>
<td>4.7</td>
<td>4.7</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* First term is 1st TVL and term in brackets is for all other TVLs.

Data from NCRP #151

** Data from McGinley
Obliquity Factor - I

\[ t = \frac{s}{\cos \theta} \]

\[ s = \text{shield thickness} \]
Rule of thumb:
- for $\theta > 45^\circ$
- and $B < 0.001$
- Add $\sim 2$ HVL for low-energy photons
- And $\sim 1$ HVL for high-energy photons
Obliquity factor - III

- Experimental data by Kirn et. al. (1954)
- verified by Biggs (1996) using the Monte Carlo for a large range of clinical energies

- Monte Carlo results are in good agreement with previous recommendations at low energy, but more detail is given

- Caveat: beware of applying obliquity factor corrections for large angles!!
Conventional Workload

- Number of patients treated per week multiplied by the average dose (MU)/patient at isocenter
- Include calibration, service, if indicated
- Recommended values: 500 or 1000 Gy wk$^{-1}$
- Survey shows values from 250 to 450 Gy wk$^{-1}$
- Balance between high energy and low energy use? Using high energy is conservative approach
- Electron-only (IORT) machines?
Workload TBI

- Workload for TBI >> workload for conventional therapy due to the extended distances:

\[ W_{TBI} = D_{TBI} d_{TBI}^2 \]

- Leakage workload is also higher, but patient- and wall-scattered workload is not.

- Radiation is usually directed at one barrier
Workload IMRT (1)

- Workload for IMRT is complicated by the fact that the #MU is much larger than for conventional therapy. The IMRT factor is defined as:

\[
C_I = \frac{MU_{IMRT}}{MU_{conv}}
\]

and varies between 2 and 10 or more

- This only affects leakage radiation, not primary or scattered radiation.
Workload IMRT (2)

- Helical tomotherapy has the highest “C” values, >10.
- Linac based IMRT at MGH gives an average “C” value of about 5
- Impact of IMAT on MUs (VMAT, Rapid Arc) – reduction of MUs
- Anecdote: For a 6/18 MV machine the energy use prior to IMRT was 20%/80% (MU). With 28% IMRT patient load, the use was 70%/30%. Hence need to consider balancing the workload for two energies
Conventional Use Factors

90° interval:
- 0° (31%); 90° and 270° (21.3 % each); 180° (26.3 %)
  - previously, all barriers were assigned 0.25

45° interval:
- 0° (25.6 %); 45° and 315° (5.8 % each); 90° and 270° (15.9 % each); 135° and 225° (4 % each); 180° (23 %)
Use Factor for Conventional Therapy
Use Factors – Special Cases

- A significant TBI load will require one wall to have an increased use factor

- IMRT may also require a change in the values assigned to the use factor for the primary barrier
Use Factor – Dedicated Machines

- One should pay attention to the types of procedures to be carried out in new room

- A room dedicated to SRS and SRT requires different considerations from a general therapy room

- A room dedicated to breast treatments will use specific ranges of primary beam angles
Example: Use Factor for Stereotactic Radiosurgery
**Workload - Summation (1)**

**Primary:**

\[ W_{U_p} = W_{U_{wall\ scat}} = (W_{conv \ U_{conv}} + W_{TBI \ U_{TBI}} + W_{IMRT \ U_{IMRT}} + W_{QA \ U_{QA}} + \ldots) \]

**Patient scatter:**

\[ W_{scatter,iso} = (W_{conv} + W_{IMRT} + W_{QA} + \ldots) \]

(note that the TBI contribution is calculated separately – source not at isocenter)
**Workload - Summation (2)**

Leakage:

\[
W_L = (W_{\text{conv}} + W_{\text{TBI}} + C_{I} W_{\text{IMRT}} + C_{QA} W_{QA} + \ldots)
\]
Occancy Factors

- Occupancy factors down to 1/40 are now allowed.

- This is the limiting factor to permit 0.02 mSv in any one hour using an MPD of 0.02 mSv/wk.

- Area beyond vault door can now have an occupancy of 1/8.

- Caveat: be sure to check not only the occupancy of the immediately adjacent area, but also the area beyond. For example, an office beyond a corridor becomes the dominant factor in the calculation. Also future development plans foreseen.
If the Dose Rate is High, Should I Freak Out?

Note that even for a weekly limit of 0.02 mSv/wk, the dose rate outside a barrier could be quite high.

e.g. for a primary barrier, an occupancy of 1/40 would imply a weekly dose of 3.8 mSv and for a beam on time of 2.8 hr, the instantaneous dose rate is 1.34 mSv/hr!!

Moral: Choose factors wisely!!
**Instantaneous Dose Rate (IDR)**

- NCRP recommends use of 1 hr as the minimum period for measuring IDR
- Compares with many places (e.g., Europe) where the instantaneous dose rate at the highest dose delivery rate is used
- Not an issue for occupancy of 1 for uniformly spaced treatments
- Only an issue when treatments are not given uniformly throughout the 40 hr week or occupancy is <1
# Shielding Materials

<table>
<thead>
<tr>
<th>Materials</th>
<th>Density (g/cm²)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>2.35; 3.85</td>
<td>High density concrete is very expensive</td>
</tr>
<tr>
<td>Concrete blocks</td>
<td>2.35; 3.85; 4.62</td>
<td>Lack structural integrity of concrete</td>
</tr>
<tr>
<td>Lead</td>
<td>11.35</td>
<td>Great for photons; bad for neutrons. Needs structural support</td>
</tr>
<tr>
<td>Steel</td>
<td>7.87</td>
<td>Not as efficient as lead for photons, but better for neutrons</td>
</tr>
<tr>
<td>Earth</td>
<td>1.5</td>
<td>Cheap! Therefore, build underground</td>
</tr>
<tr>
<td>Brick</td>
<td>1.65 - 2.05</td>
<td></td>
</tr>
<tr>
<td>Polyethylene; borated polyethylene</td>
<td>~1.0</td>
<td>Used to shield against neutrons in doors, ducts etc.</td>
</tr>
</tbody>
</table>
Width of Primary Barrier - I

- Allow 1 foot (0.3 m) either side of the primary beam
  \[ w = 0.4 \sqrt{2d} + 0.6 \]

- allow for fixed primary collimator diameter (0.5 m)
  \[ w = 0.5d + 0.6 \]

- Allow for greater width at the top of the wall
  \[ w = 0.5d' + 0.6 \]
Width evaluated in elevated plane
Contouring the Primary Shielding in the Ceiling
Lead-Only Room: Groundshine

“McGinley” effect
for primary barriers, laser support should be attached to the steel channel
Neutron Spectra from Medical Linacs

- Neutrons produced in the head of the linac are first moderated by the x-ray shielding
- Neutrons are further moderated by scattering off the concrete walls of the therapy room
- Walls with only regular density concrete that are sufficient for x-ray protection will be adequate for neutrons.
Neutron Spectra from Medical Linacs

- The total neutron fluence therefore consists of direct (‘fast’) neutrons, scattered neutrons and thermal neutrons

\[ \Phi_{\text{total}} = \Phi_{\text{dir}} + \Phi_{\text{sca}} + \Phi_{\text{th}} \]

- Fast neutrons obey the inverse law, but scattered and thermal neutrons are isotropically distributed; hence the neutron fluence drops off less fast than inverse square
Shielding Thickness Required to Halve the Average Neutron Energy

![Graphs showing the relationship between neutron energy and shielding thickness.](image)

- **Half Energy Layer (cm)**
- **E (MeV)**

**Most probable energy**
Production of Neutrons by Primary Beam in a Laminated Barrier

For high energy x-ray beams, the x-ray dose is enhanced by a factor of 2.7 to be conservative.
Production of Neutrons by Primary Beam in a Laminated Barrier

\[ H = \frac{D_0 R F_{\text{max}}}{\left( \frac{t_m}{2} + t_2 + 0.3 \right)} \times 10^{-t_1/TVL_x} \times 10^{-t_2/TVL_n} \]

where \( H \) is the neutron dose equiv. (\( \mu \text{Sv wk}^{-1} \))

\( D_0 \) is the x-ray dose at isocenter (\( \text{cGy wk}^{-1} \))

\( R \) is the neutron prod\( \text{n} \). rate (\( \mu \text{Sv cGy}^{-1} \text{ m}^{-2} \))

and \( F_{\text{max}} \) is the max. beam area at isocenter (\( \text{m}^2 \))
Total Dose Behind a Laminated Barrier

\[ H_{tot} = H_n + H_{ph} = H_n + 2.7*H_{tr} \]

The 2.7 factor accounts for the production of capture gamma rays by the photo-produced neutrons. This is an conservative, empirical figure given by McGinley.
Contributions to the Dose at the End of a Maze

1. Primary scatter
2. Patient scatter
3. Leakage along maze
4. Leakage through maze wall
Secondary Radiation at Door due to Wall Scatter of Primary Beam

\[ S_s = \frac{W U_B \alpha_1 A_1 \alpha_2 A_2}{(d_i d_{r1} d_{r2})^2} \]
Secondary Radiation at Door due to Patient Scatter

\[ S_p = \frac{aW U_B (F / 400) \alpha_1 A_1}{(d_{\text{sca}} d_{\text{sec}} d_s)^2} \]
Secondary Radiation at Door due to Leakage

\[ L = \frac{L_0 W U_B \alpha_1 A_1}{(d_s d_1)^2} \]
Secondary Radiation at Door due to Leakage Through Maze Wall

\[ L_d = \frac{L_0 \, W \, U_B \, 10^{-(t/TVL)}}{(d_{l-d})^2} \]

Note that this radiation is more energetic than radiation along the maze.
The total dose when the beam is directed towards the wall is the sum of the four components:

\[ D_t = f S_s + S_p + L + L_d \]

Note that the \( S_s \) component is reduced by a factor “\( f \)” to account for patient attenuation. Assuming use factors of \( \frac{1}{4} \) for the 4 gantry angles, McGinley gives an average total dose of:

\[ D_T = 2.64 \ D_t \]
Several authors† have noted that the foregoing formalism underestimates the true dose at the door.

This problem has been partly rectified by redefining the geometry of the scatter and assuming lower energies for the scattered radiation which, in turn, increase the scatter coefficients.

† Numark & Kase; Al-Affan; McGinley & James
Reflection Coefficients for Monoenergetic X-Rays on Concrete
Door Inside Room

- Target
- Isocenter
- Plane of Gantry Rotation
- Primary Barrier
- Door Overlap
- Pb/Poly Door
- Concrete Secondary Barrier
Door Outside Room

Target

Isocenter

Primary Barrier

Plane of Gantry Rotation

Concrete Secondary Barrier

Pb/Poly Door

AAPM Physics Review – July 19, 2014
Edge Effect for Direct Shielded Doors

C

B

A

Lead

Polyethylene

Lead
Parameters for Calculation of Neutron Dose at Door
Neutron Fluence Entering the Maze

The total neutron fluence is given by (McCall et. al, 1999)

\[ \Phi = \frac{\beta Q_n}{4\pi d_1^2} + \frac{5.4 \beta Q_n}{2\pi S_r} + \frac{1.3 Q_n}{2\pi S_r} \]

The addition of \((2\pi)\) in the scattered and thermal terms accounts for the directionality of the neutrons and \(Q_n\) is the \#neutrons/photon Gy
Neutron Dose at Door of Maze

Kersey formula:

$$H = H_0 \frac{S_0}{S} \frac{1}{d_1^2 10^{-d_2/5}}$$

where $H_0$ is the total neutron head leakage at 1.4 m from the target, $d_1$ is the distance from the target to the maze entrance and $d_2$ is the length of the maze. $S_0/S$ is the ratio of the inner to outer maze areas (rationale for lintel). The TVL for neutrons along the maze is 5 m.
Wu & McGinley’s formula:

\[ H_{n,D} = 2.4 \times 10^{-15} \varphi_A \sqrt{\frac{S_0}{S_1}} \left[ 1.64 \times 10^{-10} \left( \frac{d_2}{1.9} \right) + 10 \left( \frac{d_2}{TVD} \right) \right] \]

is a modification of McGinley’s 2-component model and is based on an analysis of a number of facilities.
Dose at Maze Door due to Capture $\gamma$ Rays

Capture rays follow the same formalism for photoneutron attenuation in the maze. For mazes >3 m, the first term disappears and a single exponential term is left.

$$D = K\Phi_{total} \cdot 10^{-d_2/TVD}$$

where $K$ is the $\gamma$ dose/nfluence ratio at the maze entrance

$\Phi$ is the neutron fluence at the maze entrance

$d_2$ is the distance along the maze

and $TVD$ is the TVL for $\gamma$’s down the maze
Combined Dose at Maze Door

The neutron and capture γ-ray components are calculated and shielding thicknesses to meet the required effective dose equivalent are derived using the following TVLs:

- Neutrons (100 keV) - 4.5 cm polyethylene
- Capture γ-rays - 6.1 cm lead

As a rule, for high energy machines only these components and the photon leakage components need be considered. Generally, for 15 & 18 MV photons, $D_n > D_{\text{capture} \gamma \text{rays}}$
Practical Problems with NCRP #151

- Use of dual energy workloads, dual TVLs, laminated barriers creates confusion in the calculations

- Use of the obliquity factor for scattered radiation (not leakage) is unclear – two examples in the text give opposing views. Experts are divided on this issue, but it can be used, but with caution!
Handling Dual Energies in NCRP #151

- A dual energy machine having say 6 and 18 MV will have different workloads for (P,S) and L radiation for 3D CRT and IMRT (6 MV assumed). In general, a conservative approach assumes:

- use of the maximum energy in a full 3D CRT environment for the primary and …

- the IMRT workload for the secondary barrier orthogonal to the plane of gantry rotation
Handling Dual Energies in NCRP #151

- in the secondary barrier region adjacent to the primary, the dominance of 3D CRT vs 3D CRT+IMRT depends on the explicit workloads and room geometry

- one should be careful to consider $20^\circ$ scatter radiation for laminated barriers since the primary beam angle is only $14^\circ$ (exclusive of extra 2’ barrier width recommended by NCRP)
Handling Dual Energies in NCRP #151

- In that same angular zone in the secondary barrier, there will be TVLs for two energies for scattered and leakage radiation.

- Rule is that:
  - scatter should be added to scatter to determine if an extra HVL is required
  - leakage should be added to leakage to determine if an extra HVL is required
  - Scatter is then compared to leakage to determine if an additional HVL is required
Handling Dual Energies in NCRP #151

- To recap:
  (i) $S_1 + S_2 \rightarrow S$
  (ii) $L_1 + L_2 \rightarrow L$
  (iii) $S + L \rightarrow$ Total secondary thickness

- Question remains as to which of the TVLs to use; higher or lower for L (ii); S or L for (iii)

- However, because of these multiple additions, this may overestimate the required shielding
Example: Barrier Adjacent to Primary

<table>
<thead>
<tr>
<th>Energy</th>
<th>Radiation</th>
<th>Workload (Gy)</th>
<th>Thickness</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 MV</td>
<td>Leakage</td>
<td>225</td>
<td>36.1”</td>
<td></td>
</tr>
<tr>
<td>6 MV</td>
<td>Leakage</td>
<td>1775</td>
<td>42.9”</td>
<td></td>
</tr>
<tr>
<td>Combined 6 +15 MV</td>
<td>Leakage</td>
<td>2000</td>
<td>47.2”</td>
<td>Use TVL₁ for 15 MV</td>
</tr>
<tr>
<td>15 MV</td>
<td>Scatter</td>
<td>225</td>
<td>45.6”</td>
<td></td>
</tr>
<tr>
<td>6 MV</td>
<td>Scatter</td>
<td>525</td>
<td>42.0”</td>
<td></td>
</tr>
<tr>
<td>Combined 6 +15 MV</td>
<td>Scatter</td>
<td>750</td>
<td>49.3”</td>
<td>Use TVLₛₑₐ for 15 MV</td>
</tr>
<tr>
<td>Combined 6 + 15 MV</td>
<td>Leakage + scatter</td>
<td>53.3”</td>
<td></td>
<td>Use TVL₁ for 15 MV</td>
</tr>
</tbody>
</table>

Note: … and only one shielding material is used!
### Example: Barrier Orthogonal to Gantry Rotation Plane

<table>
<thead>
<tr>
<th>Energy</th>
<th>Radiation</th>
<th>Workload (Gy)</th>
<th>Thickness</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 MV</td>
<td>Leakage</td>
<td>225</td>
<td>37.3”</td>
<td></td>
</tr>
<tr>
<td>6 MV</td>
<td>Leakage</td>
<td>1775</td>
<td>43.9”</td>
<td></td>
</tr>
<tr>
<td>Combined 6 +15 MV</td>
<td>Leakage</td>
<td>2000</td>
<td>47.8”</td>
<td>Use TVL$_1$ for 15 MV</td>
</tr>
<tr>
<td>15 MV</td>
<td>Scatter</td>
<td>225</td>
<td>19.8”</td>
<td></td>
</tr>
<tr>
<td>6 MV</td>
<td>Scatter</td>
<td>525</td>
<td>22.6”</td>
<td></td>
</tr>
<tr>
<td>Combined 6 +15 MV</td>
<td>Scatter</td>
<td>750</td>
<td>24.7”</td>
<td>Use TVL$_{sca}$ for 15 MV</td>
</tr>
<tr>
<td>Combined 6 + 15 MV</td>
<td>Leakage + scatter</td>
<td>47.8”</td>
<td></td>
<td>Use TVL$_1$ for 15 MV</td>
</tr>
</tbody>
</table>
Thank you for your attention!

Al-Affan, I.A.M. “Estimation of the dose at the maze entrance for x-rays from radiotherapy linear accelerators” Med. Phys. 27:231-238;2000

Almond, P. Neutron leakage from current machines. Proceedings of a conference on neutrons from medical accelerators (NBS Special Publication 554, Gaithersburg, MD, 1979), pp. 129-138.

Barish, R.J. “Evaluation of a new high-density shielding material” Health Physics 64:412-416;1993

Biggs, P.J. “An interactive computer graphics program for determining the shielding for a megavoltage radiotherapy facility” Health Physics 43:601-607; 1982

Biggs, P.J. “Shielding design for the ceiling of a 6-MV accelerator in an existing facility” Health Physics 52:491-493; 1987

Biggs, P.J. “Calculation of shielding door thicknesses for radiation therapy facilities using the ITS Monte Carlo program” Health Physics 61:465-472; 1991
Biggs, P.J. “Obliquity factors for $^{60}$Co and 4, 10 and 18 MV x-rays for concrete, steel and lead and angles of incidence between 0° and 70°” Health Physics 70:527-536; 1995


McGinley, P.H. “Photoneutron production in the primary barriers of medical accelerator rooms” Health Physics 62:359-363;1992


