Radiation Oncology treatment room design

Linear accelerator bunkers
Radiation Oncology

- Linear accelerator
- Brachytherapy
- CT simulator
- simulator
Basic shielding concepts

• Establish a target dose-rate at a certain point behind a barrier

• Calculate barrier thickness necessary to achieve the target dose rate
Shielding considerations

- Type of radiation
- Primary beam incidence
- Primary beam scatter
- Patient scatter
- Leakage radiation
Shielding considerations

• Type of space
  – Basement
  – Mountain
  – 3rd floor

• Space availability
  – New facility
  – Retro-fit

• Future workload
• Capital funding
Shielding considerations

• Machine workload

• Type of person to protect
  – NEW
  – Public

• Type of space to protect
  – Public access area
  – Restricted access
ALARA

- As Low As Reasonably Achievable
- ICRP 60 recommendations are limits
- Facilities should not be designed to the limits as they are not designed to be exceeded
- So ALARA factor of 10 - 20 can be applied
Types of barriers

• Primary barriers
  – Attenuate primary (direct) beam
  – Very thick (1.5-2.5m)

• Secondary barriers
  – Leakage
  – Patient scatter
  – Wall scatter
Treatment room

- **Secondary barrier**
- **Primary barrier**
- **Isocenter**
- **Linac rotation plane**
Primary beam

• Barrier thickness depends on:
  – Distance to POI from source (d)
  – Target dose rate (P)
  – Workload (W)
  – Occupancy (T)
  – Usage (U)

*Patient and table attenuation not taken into account
Basic situation

source

isocenter

1 m

s

1 m

d
Reduction factor $B$

- $B$ is the factor by which the intensity of radiation ($P_0$) must be reduced to achieve the target dose rate $P$

$$B = \frac{P}{P_0}$$
Transmission Curves

- NCRP 49, 51
- B as a function of material thickness

![Graph showing transmission curves for concrete thickness and B as a function of material thickness.](image-url)
TVL - Tenth Value Layer

\[ n = \log \left( \frac{1}{B} \right) \]

\[ S = TVL_1 + (n-1)TVL_e \]
TVL - Tenth Value Layer

- Thickness of material required to allow 10% transmission

- TVL depends on:
  - Photon beam energy
  - Barrier material
  - Barrier thickness
## TVL - materials

<table>
<thead>
<tr>
<th>Energy</th>
<th>Material</th>
<th>TVL₁ (m)</th>
<th>TVLₑ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 MV</td>
<td>concrete</td>
<td>0.350</td>
<td>0.350</td>
</tr>
<tr>
<td></td>
<td>steel</td>
<td>0.099</td>
<td>0.099</td>
</tr>
<tr>
<td></td>
<td>lead</td>
<td>0.055</td>
<td>0.057</td>
</tr>
<tr>
<td>18 MV</td>
<td>concrete</td>
<td>0.470</td>
<td>0.430</td>
</tr>
<tr>
<td></td>
<td>steel</td>
<td>0.108</td>
<td>0.108</td>
</tr>
<tr>
<td></td>
<td>lead</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>24 MV</td>
<td>concrete</td>
<td>0.510</td>
<td>0.460</td>
</tr>
<tr>
<td></td>
<td>steel</td>
<td>0.109</td>
<td>0.109</td>
</tr>
<tr>
<td></td>
<td>lead</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*values from NCRP 51
# Shielding materials

<table>
<thead>
<tr>
<th>material</th>
<th>density g/cm³</th>
<th>Z</th>
<th>Relative cost</th>
<th>Tensile strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>concrete</td>
<td>2.3</td>
<td>11</td>
<td>1.0</td>
<td>500</td>
</tr>
<tr>
<td>heavy concrete</td>
<td>3.7-4.8</td>
<td>26</td>
<td>5.8</td>
<td>-</td>
</tr>
<tr>
<td>low C steel</td>
<td>7.87</td>
<td>26</td>
<td>2.2</td>
<td>40000</td>
</tr>
<tr>
<td>Pb</td>
<td>11.35</td>
<td>82</td>
<td>22.2</td>
<td>1900</td>
</tr>
<tr>
<td>dry packed earth</td>
<td>1.5</td>
<td>-</td>
<td>cheap</td>
<td>-</td>
</tr>
</tbody>
</table>
Primary beam

\[ B = \frac{Pd^2}{WUT} \]
Distance

• $d$ is the distance from the source to the point of interest (POI) in meters.

• The POI is located at least 30 cm from the surface of the outside of the barrier.
Basic situation

source  isocenter

1 m

d

s
## Target dose rate P

<table>
<thead>
<tr>
<th>Group</th>
<th>ICRP 60 Dose limit (mSv/y)</th>
<th>ALARA Target limit (mSv/y)</th>
<th>Maximum hourly dose rate* (µSv/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEW</td>
<td>20</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Public</td>
<td>1</td>
<td>0.1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

*1 year has 50 weeks of 40 hrs/week or 2000 hr/year
Workload W

• How much is the machine used
• Expressed in Gy/wk @ isocenter
• Good to overestimate

40 patients/day x 2 Gy/patient x 5 days/wk = 400 Gy/wk

• Typical values (NCRP 49, 51):
  – Low X machine (<10 MV) - 1000 Gy/wk
  – High X machine (> 10 MV) - 500 Gy/wk
# Occupancy factor T

<table>
<thead>
<tr>
<th>T</th>
<th>Type of area</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Full</td>
</tr>
<tr>
<td></td>
<td>Offices, shops, labs, living area</td>
</tr>
<tr>
<td>1/4</td>
<td>Partial</td>
</tr>
<tr>
<td></td>
<td>Corridors, restrooms, parking</td>
</tr>
<tr>
<td>1/16</td>
<td>Occasional</td>
</tr>
<tr>
<td></td>
<td>Waiting room, stairway, janitor closet</td>
</tr>
</tbody>
</table>
Usage factor U

- Accounts for beam orientation
- Isocentric units have same usage for floors, ceiling, and walls.
- $U = 0.25$
- There are some exceptions
  - Dedicated rooms eg. TBI
  - Non-isocentric machines
Primary barrier

- At isocenter max FS is 40 x 40 cm²
- Largest dimension is diagonal (56 cm)
- At barrier this will project to larger size

at iso ~ 56 cm  at barrier ~ 200 cm
Primary barrier

• Primary barrier will be approximately 3X thicker than all other walls

• Max with of beam at barrier must be calculated
Primary beam: Example

• Calculate the $B$ for a 6 MV photon facility primary barrier if:
  
  $P = 0.1 \text{ mSv/year}$
  
  $d = 4 \text{ m}$
  
  $W = 50 \text{ patients per day}$
  
  $U = 0.25$
  
  $T = 1 \text{ (control area)}$
Primary beam: Example

- \( W = 50 \text{ pt/day} \times 2 \text{ Gy/pt} \times 270 \text{ day/y} \)
- \( W = 27,000 \text{ Gy/y} = 27,000,000 \text{ mSv/y} \)

\[
B = \frac{P_d^2}{W_U T} = \frac{0.1 \text{ mSv/y} \times (4m)^2}{27 \times 10^6 \text{ mSv/y} \times 0.25 \times 1} = 2.37 \times 10^{-7}
\]
Primary beam: Example

- What would be the required thickness of concrete?

\[ B = 2.37 \times 10^{-7} \]

\[ n = \log \left( \frac{1}{B} \right) = \log \left( \frac{1}{2.37 \times 10^{-7}} \right) = 6.62 \text{ TVL} \]
Primary beam: Example

- 6.62 TVL are required

\[ S = TVL_1 + (n-1)TVL_e \]

\[ S = 0.35 + (6.62-1) 0.35 = 2.32m \]
Secondary barriers

- Head leakage
- Patient scatter
- Wall scatter

- For energy > 10 MV head leakage is dominant
Leakage radiation

- Photon beam produced in many directions
Leakage radiation

- Head shielding designed to reduce intensity by factor of 1000
- $d$ is distance from target to POI
- Leakage assumed to be isotropic: $U = 1$

$$B = \frac{1000 \ Pd^2}{WT}$$
Patient scatter

\[ B = \frac{P d_1^2 d_2^2}{a W T} F - 400 \]
\[ B = \frac{P d_1^2 d_2^2}{a W T} \cdot 400 \]

**F** is the incident field size on the patient
Patient scatter

- **a** is the scatter fraction
- Ratio of scattered radiation at a point 1m from the patient to the primary beam dose rate at isocenter
  - Taylor and Rodgers, 1999
  - Rule of thumb 0.1-0.2%

<table>
<thead>
<tr>
<th>Angle (deg)</th>
<th>6 MV</th>
<th>10 MV</th>
<th>18 MV</th>
<th>24 MV</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.04 x10^{-2}</td>
<td>1.66 x10^{-2}</td>
<td>1.42 x10^{-2}</td>
<td>1.78 x10^{-2}</td>
</tr>
<tr>
<td>20</td>
<td>6.73 x10^{-3}</td>
<td>5.79 x10^{-3}</td>
<td>5.39 x10^{-3}</td>
<td>6.32 x10^{-3}</td>
</tr>
<tr>
<td>30</td>
<td>2.77 x10^{-3}</td>
<td>3.18 x10^{-3}</td>
<td>2.53 x10^{-3}</td>
<td>2.74 x10^{-3}</td>
</tr>
<tr>
<td>45</td>
<td>1.39 x10^{-3}</td>
<td>1.35 x10^{-3}</td>
<td>8.64 x10^{-4}</td>
<td>8.30 x10^{-4}</td>
</tr>
<tr>
<td>60</td>
<td>8.24 x10^{-4}</td>
<td>7.46 x10^{-4}</td>
<td>4.24 x10^{-4}</td>
<td>3.86 x10^{-4}</td>
</tr>
<tr>
<td>90</td>
<td>4.26 x10^{-4}</td>
<td>3.81 x10^{-4}</td>
<td>1.89 x10^{-4}</td>
<td>1.74 x10^{-4}</td>
</tr>
<tr>
<td>135</td>
<td>3.00 x10^{-4}</td>
<td>3.02 x10^{-4}</td>
<td>1.24 x10^{-4}</td>
<td>1.20 x10^{-4}</td>
</tr>
<tr>
<td>150</td>
<td>2.87 x10^{-4}</td>
<td>2.74 x10^{-4}</td>
<td>1.20 x10^{-4}</td>
<td>1.13 x10^{-4}</td>
</tr>
</tbody>
</table>
Wall scatter

\[ B = \frac{P d_1^2 d_2^2}{\alpha A W T U} \]
Wall scatter

\[ B = \frac{P \, d_1^2 d_2^2}{\alpha \, A \, W \, T \, U} \]
Wall scatter

• $\alpha$ is the reflection coefficient
• Function of material, energy, and angle of incidence
• Generally between 0.001-0.1
Reflection coefficients
Rule of thumb

- 6 TVL required for primary barrier
- 3 TVL required for secondary barrier
Room Mazes

- Mazes used to reduce door size
- Disadvantage is that the maze takes up considerable space
- Remember to build maze wide enough to pass equipment and patients on stretchers
Room Mazes

- Radiation reaching the maze door is from the scattering from room surface and the patient, and leakage transmission through the maze.

- maze + wall thickness is at least calculated secondary barrier thickness
Low energy < 10 MV

- Secondary barrier
- Primary barrier
- Isocenter
- Linac rotation plane
- Maze
- Little door
Room mazes

• Scatter is comprised of 3 components:
  – Scattered primary beam from room surfaces ($S_s$)
  – Head leakage photons scatted (L)
  – Primary scatter from patient ($S_p$)
  – Scattered photon energy $\sim 0.2-0.3$ MeV
Dose at room door

\[ D_c = f S_{\text{prim}} + S_{\text{pat}} + L + T \]

- \( f \) fraction of scattered photons transmitted through patient (0.25)
- \( S_{\text{prim}} \) dose from scattered primary beam
- \( S_{\text{pat}} \) dose from scattered patient scatter
- \( L \) scattered leakage dose
- \( T \) transmitted leakage dose
Equations for the door

\[ S_{\text{prim}} = \frac{D_o \alpha_1 A_1 \alpha_2 A_2}{(d_1 d_{r1} d_{r2})^2} \]

\[ S_{\text{pat}} = \frac{aD_o \alpha_1 A_1 (F/400)}{(d_1 d_2 d_{r1})^2} \]

\[ L = \frac{D_o L_o \alpha_1 A_1}{(d_1 d_s)^2} \]
Leakage photons

• Care must be taken to shield non-scattered leakage photons

\[ T = \frac{D_0 \cdot L_0 \cdot B}{d^2} \]
Doors and mazes: Low X

• Typical door size is 6-10 mm Pb in 5 cm of wood
High energy installations

• Energy > 10 MV

• Photo-neutrons

• Neutron capture (activation)
Photo-neutrons

- Photo-nuclear interactions can result in the production of neutrons

$$^{AX}(\gamma,n)^{A-1}X$$

- Neutrons can be created from the heavy metal components in the head of the LINAC

- Electrons make photons that make neutrons
### Photo-neutrons

Relative yield of photo-neutrons as a function of incident electron energy. Values normalized to W at 25 MeV. (NCRP, 1984)

<table>
<thead>
<tr>
<th>Element</th>
<th>Threshold (MeV)</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>13.1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0.03</td>
</tr>
<tr>
<td>Cu</td>
<td>9.91</td>
<td>0</td>
<td>0</td>
<td>0.11</td>
<td>0.25</td>
</tr>
<tr>
<td>Fe</td>
<td>13.4</td>
<td>0</td>
<td>0</td>
<td>0.07</td>
<td>0.17</td>
</tr>
<tr>
<td>Pb</td>
<td>6.74</td>
<td>0</td>
<td>0.25</td>
<td>0.7</td>
<td>0.93</td>
</tr>
<tr>
<td>W</td>
<td>6.19</td>
<td>0</td>
<td>0.25</td>
<td>0.7</td>
<td>1.0</td>
</tr>
</tbody>
</table>
Neutron activation

- $(n,\gamma)$ reactions can activate heavy metal components of LINAC head

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Decay mode</th>
<th>Half life</th>
<th>Photon energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{27}\text{Al}(n,\gamma)^{28}\text{Al}$</td>
<td>$\beta^-$</td>
<td>2.3min</td>
<td>1.78</td>
</tr>
<tr>
<td>$^{63}\text{Cu}(\gamma,n)^{62}\text{Cu}$</td>
<td>$\beta^+$</td>
<td>9.7min</td>
<td>0.511</td>
</tr>
<tr>
<td>$^{55}\text{Mn}(n,\gamma)^{56}\text{Mn}$</td>
<td>$\beta^-$</td>
<td>2.6min</td>
<td>0.847</td>
</tr>
<tr>
<td>$^{63}\text{Cu}(n,\gamma)^{64}\text{Cu}$</td>
<td>$\beta^+ \beta^-$</td>
<td>12.7hr</td>
<td>1.346</td>
</tr>
<tr>
<td>$^{65}\text{Cu}(\gamma,n)^{64}\text{Cu}$</td>
<td>$\beta^+ \beta^-$</td>
<td>12.7hr</td>
<td>1.346</td>
</tr>
<tr>
<td>$^{186}\text{W}(n,\gamma)^{187}\text{W}$</td>
<td>$\beta^-$</td>
<td>23.9hr</td>
<td>0.479/0.686</td>
</tr>
<tr>
<td>$^{58}\text{Ni}(\gamma,n)^{57}\text{Ni}$</td>
<td>$\beta^+$</td>
<td>36hr</td>
<td>1.387/1.920</td>
</tr>
</tbody>
</table>
Neutron activation

- Average neutron E is 2 MeV (fast)

- ~15% are attenuated or scattered in linac head (~7 cm Pb)

- Average neutron E leaving linac head is ~1.7 MeV

- Room scattered neutron E is ~ 0.5 MeV

- There is also a thermal neutron energy group present (~ 0.025 eV)
Neutron shielding

- Fast neutrons are efficiently attenuated by materials rich in Hydrogen (concrete)
  - $TVL_n$ in concrete is 22 cm
  - $TVL_{18MV}$ in concrete 44 cm
- Fast neutrons are adequately shielded by room shielding
Neutron shielding

- Fast neutrons are moderated by hydrogen collisions and become slow neutrons

- Capture reactions with slow neutrons can yield high energy $\gamma$
  - $E_{\gamma\text{ave}} = 3.6$ MeV
  - $E_{\gamma\text{max}} > 8.0$ MeV

- Boron moderates slow neutrons effectively (few mm)

- Slow neutron capture results in 0.478 MeV $\gamma$–emission
High energy > 10 MV

- primary barrier
- secondary barrier
- isocenter
- maze
- big door
- linac rotation plane
Doors and mazes: High X

- Door has to stop neutrons, scatter photons, and, activation gammas.

Borated polyethylene (5% B wt.)

Pb

6 mm steel

10.2 cm

10 - 15 mm
High energy > 10 MV

- Primary barrier
- Secondary barrier
- Linac rotation plane
- Isocenter
- Maze
- Bigger door
Doors and no maze: High X

- Direct shielded door

Borated polyethylene (5% B wt.)
Surveys

• A complete survey of the facility should be carried out immediately following the installation of the linear accelerator

• The survey should be encompass all primary and secondary barriers as well as above the ceiling

• If a high energy Linac is involved, a complete neutron survey must be carried out
miscellaneous

• High energy machines can create ozone

• The requirement is for 6 complete air exchanges per hour

• HVAC holes are large and must be constructed in such a way as to not compromise the shielding. (are usually located above the door)
ducting
CL6EX-A/B and CL18
Let’s design a room

- Inside 8 x 8 m²
- High energy - 6/18 MV
- Concrete and high density concrete available
- Design with maze
- Max f/s @ iso is 40 x 40 cm²
- Max dose rate at isocenter is 500 cGy/min
Let’s design a room

Corridor (public)

Waiting room
Public

T, U

Corridor (public)

Console area
NEW

T, U

isocenter

linac rotation plane
Let’s design a room

- What is the workload of the linac?
- What is the target dose-rate?
- What are the relevant factors? (U,T,d)
- What is the B?
- What barrier thickness is required?
- Maze and door (neutrons)?