Radiation Oncology treatment facility design

Simulators, CT scanners, HDR Brachytherapy
UNITS

For this class only:

$1 \text{ R} = 1 \text{ cGy} = 1 \text{ cSv} = 10 \text{ mSv}$
Reference book

- McGinley
- NCRP 49
- NCRP 51
- *Health Physics notes*, Robert Corns
- Safety code 20A, Health Canada
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

• Machine workload

• Type of person to protect
  – NEW
  – Public

• Type of space to protect
  – Public access area
  – Restricted access
Shielding considerations

- Type of radiation
- Primary beam incidence
- Primary beam scatter
- Patient scatter
- Leakage radiation
Simulator

- Operates with same geometry as LINAC
- Radiation source is diagnostic x-ray tube
- Capable of radiographic and fluoroscopic functions
Simulator

• Most exposures made in fluoroscopy mode

• X-ray beam collimated, always incident on image intensifier (II)

• Primary beam significantly attenuated by patient and II
Shielding materials

- Lead (Pb) backed gypsum board (dry wall)
- Shielding provided to height of 7 feet unless space above is occupied
- Viewing window with lead glass is used at console area
Types of barriers

- Primary barriers
  - Attenuate primary (direct) beam

- Secondary barriers
  - Leakage
  - Patient scatter
  - Wall scatter
Simulator room

Simulator room

- Simulator control area
- Lead glass window
- Target rotational plane
- Isocenter

Primary
- Shielded door

Secondary
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

d

s
Primary barrier

- At isocenter max FS is 40 x 40 cm$^2$
- Largest dimension is diagonal (56 cm)
- At barrier this will project to larger size

at iso ~ 56 cm
at barrier ~ 200 cm
Simulators: Primary beam

- $K_{ux}$ is transmission factor
- Expressed in (R/mA min) at 1m
- NCRP 49 (1976)

$$K_{ux} = \frac{Pd^2}{WUT}$$
## Target dose rate P

<table>
<thead>
<tr>
<th>Group</th>
<th>ICRP 60 Dose limit (mSv/y)</th>
<th>Exposure rate (R/week)</th>
<th>Exposure rate (R/y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NEW</td>
<td>20</td>
<td>0.04</td>
<td>~ 2</td>
</tr>
<tr>
<td>Public</td>
<td>1</td>
<td>0.002</td>
<td>~ 0.1</td>
</tr>
</tbody>
</table>

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

** diagnostic X-ray installations are not licensed by CNSC but may fall under provincial regulations
Workload

- **W** workload expressed in mA-min/wk:

- Radiography
  - 50 patient/wk x 500 mAs/patient x 1 s/60 min = 400 mA min/wk

- Fluoroscopy
  - 50 patient/wk x 5 mA/patient x 1 min = 250 mA min/wk

\[ K_{ux} = \frac{Pd^2}{W \ UT} \]

\[ W = 1000 \text{ mA-min/wk} \]
### Table 3
**Typical Workloads (W) For Busy Department**

<table>
<thead>
<tr>
<th>Daily Patient Load</th>
<th>#100 kVp</th>
<th>125 kVp</th>
<th>150 kVp</th>
<th>Workload mA-min/week</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chest (36 cm x 43 cm) (14&quot; x 17&quot;)</td>
<td>60</td>
<td>150</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Cystoscopy</td>
<td>8</td>
<td>600</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Fluoroscopy including spot filming</td>
<td>24</td>
<td>1500</td>
<td>600</td>
<td>300</td>
</tr>
<tr>
<td>Fluoroscopy without spot filming</td>
<td>24</td>
<td>1000</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>Fluoroscopy with image intensification including spot filming</td>
<td>24</td>
<td>750</td>
<td>300</td>
<td>150</td>
</tr>
<tr>
<td>General Radiography</td>
<td>24</td>
<td>1000</td>
<td>400</td>
<td>200</td>
</tr>
<tr>
<td>Special Procedures</td>
<td>8</td>
<td>700</td>
<td>280</td>
<td>140</td>
</tr>
</tbody>
</table>
Usage factor U

- **U** Accounts for beam orientation

- Isocentric units have same usage for floors, ceiling, and walls.

- **U = 0.25**

\[ K_{ux} = \frac{Pd^2}{W U T} \]
### Occupancy factor T

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

\[
K_{ux} = \frac{Pd^2}{W U T}
\]
Transmission factor $K_{ux}$
Transmission - lead

The image contains graphs showing the relationship between lead thickness (LEAD, millimetres) and the specific transmission factor (K, R per mA min at 1 m) for different kvp values (50, 70, 85, 100, 125, 150 kvp) on the left side, and for higher kvp values (200, 250, 300 kvp) on the right side. The graphs are used to determine the effectiveness of lead in attenuating radiation at various kvp settings.
Transmission - concrete

[Graph showing transmission through concrete with various curves for different voltages.]
Simulators: Leakage

- Assumption leakage is 0.1 R/hr at 1m
- Shielded to a factor of 600 per minute

\[
B = \frac{600 \times \text{Pd}_s^2}{\text{WT}}
\]
Simulators: Leakage

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

\[
B = \frac{P}{P_0}
\]

\[
B = \frac{600 \times 1 \times \text{Pd}_s^2}{\text{WT}}
\]
Simulators: Leakage

- \( I \) is the tube current (mA)
- \( d_s \) is the distance from source to POI

\[
B = \frac{600 \, I \, P \, d_s^2}{WT}
\]
TVL - Tenth Value Layer

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

HVL - Half Value Layer

1 TVL = 3.32 HVL
TVL and HVL

\[
\frac{1}{2^x} = \frac{1}{10}
\]

\[
2^x = 10
\]

\[
x \log 2 = \log 10
\]

\[
x = 3.32
\]
<table>
<thead>
<tr>
<th>Tube Potential</th>
<th>Lead (mm)</th>
<th>Concrete (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>kVp</td>
<td>HVL</td>
<td>TVL</td>
</tr>
<tr>
<td>50</td>
<td>0.06</td>
<td>0.17</td>
</tr>
<tr>
<td>70</td>
<td>0.17</td>
<td>0.52</td>
</tr>
<tr>
<td>85</td>
<td>0.22</td>
<td>0.73</td>
</tr>
<tr>
<td>100</td>
<td>0.27</td>
<td>0.88</td>
</tr>
<tr>
<td><strong>125</strong></td>
<td><strong>0.28</strong></td>
<td><strong>0.93</strong></td>
</tr>
<tr>
<td>150</td>
<td>0.30</td>
<td>0.99</td>
</tr>
<tr>
<td>200</td>
<td>0.52</td>
<td>1.70</td>
</tr>
<tr>
<td>250</td>
<td>0.88</td>
<td>2.90</td>
</tr>
<tr>
<td>300</td>
<td>1.47</td>
<td>4.80</td>
</tr>
</tbody>
</table>
Simulators: Scatter

• Scattered x-rays have same barrier penetration as primary beam

• NCRP 49 (1976)

\[ K = \frac{400 \ P \ D^2 \ d^2}{F \ aWT} \]
Simulators: Scatter

- D is the distance from the source to scatterer
- d is the distance from scatterer to POI
- F is the field area on patient
- a is the scatter fraction

\[ K = \frac{400 \ P \ D^2 \ d^2}{F \ aWT} \]
### Scatter fraction

#### Table 6
Ratio, $a$, of Scattered to Incident Exposure

<table>
<thead>
<tr>
<th>Tube Potential KvP</th>
<th>30°</th>
<th>45°</th>
<th>60°</th>
<th>90°</th>
<th>120°</th>
<th>135°</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.0005</td>
<td>0.0002</td>
<td>0.00025</td>
<td>0.00035</td>
<td>0.0008</td>
<td>0.0010</td>
</tr>
<tr>
<td>70</td>
<td>0.00065</td>
<td>0.00035</td>
<td>0.00035</td>
<td>0.0005</td>
<td>0.0010</td>
<td>0.0013</td>
</tr>
<tr>
<td>85</td>
<td>0.0012</td>
<td>0.0007</td>
<td>0.0007</td>
<td>0.0009</td>
<td>0.0015</td>
<td>0.0017</td>
</tr>
<tr>
<td>100</td>
<td>0.0015</td>
<td>0.0012</td>
<td>0.0012</td>
<td>0.0013</td>
<td>0.0020</td>
<td>0.0022</td>
</tr>
<tr>
<td>125</td>
<td><em>0.0018</em></td>
<td><em>0.0015</em></td>
<td><em>0.0015</em></td>
<td><em>0.0015</em></td>
<td><em>0.0023</em></td>
<td><em>0.0025</em></td>
</tr>
<tr>
<td>150</td>
<td>0.0020</td>
<td>0.0016</td>
<td>0.0016</td>
<td>0.0016</td>
<td>0.0024</td>
<td>0.0026</td>
</tr>
<tr>
<td>200</td>
<td>0.0024</td>
<td>0.0020</td>
<td>0.0019</td>
<td>0.0019</td>
<td>0.0027</td>
<td>0.0028</td>
</tr>
<tr>
<td>250</td>
<td>0.0025</td>
<td>0.0021</td>
<td>0.0019</td>
<td>0.0019</td>
<td>0.0027</td>
<td>0.0028</td>
</tr>
<tr>
<td>300</td>
<td>0.0026</td>
<td>0.0022</td>
<td>0.0020</td>
<td>0.0019</td>
<td>0.0026</td>
<td>0.0028</td>
</tr>
</tbody>
</table>
Lead Glass

- Leaded glass may be used for patient observation window

<table>
<thead>
<tr>
<th></th>
<th>thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lead</strong></td>
<td>1.9 (1/16”)</td>
</tr>
<tr>
<td></td>
<td>2.6 (3/32”)</td>
</tr>
<tr>
<td></td>
<td>3.1 (1/8”)</td>
</tr>
<tr>
<td><strong>Glass</strong></td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>14</td>
</tr>
<tr>
<td><strong>X-ray kV&lt;sub&gt;p&lt;/sub&gt;</strong></td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>200</td>
</tr>
<tr>
<td><strong>Cost/m&lt;sup&gt;2&lt;/sup&gt;</strong></td>
<td>145</td>
</tr>
<tr>
<td></td>
<td>190</td>
</tr>
<tr>
<td></td>
<td>220</td>
</tr>
</tbody>
</table>
Doors

• Doors contain the lead equivalent thickness required for secondary barrier shielding

• 1 - 2 mm Pb in wood

• Make sure door is not in primary beam
Determine wall thickness (concrete and Pb) required for POI A and B. What would be the thickness of the lead glass required for the console area?

d iso to POI is 4m

A is an office T = 1

B is a waiting room T = 1/16

U = 0.25 for simulators

W = 1000 mA min/week
Simulator room

• Determine target P
  – At A, office with NEW (+ALARA ?)
  – 20 mSv/year (ICRP 60)
  – Target dose rate is 20 mSv/yr = 2 R/yr = 0.04 R/wk
Simulator room

- \( P = 0.04 \) R/week
- \( d = 4m \)
- \( W = 1000 \) mA min/week
- \( U = 0.25, \, T = 1 \)

\[
K_{ux} = \frac{Pd^2}{WUT} = 0.00256
\]
Simulator room

$$K_{ux} = \frac{0.04 \, \text{R/wk} \times 4^2}{1000 \, \text{mA min/wk} \times 0.25 \times 1}$$

$$K_{ux} = 0.00256 \, \text{R/mA min at 1m}$$

~ 12 cm concrete or 1 - 2 mm Pb
Leakage barrier

- Leakage barrier (at $B$)
  - $I = 5 \text{ mA}$, $T = 1/16$, $d_s = 4m$

$$B = \frac{600 \, I \, Pd_s^2}{WT}$$
Simulator room

• Leakage barrier (at B)

\[ B = \frac{600 \text{ l Pd}_s^2}{\text{WT}} \]

\[ = \frac{600 \times (5) \times 0.002 \text{ R/wk} \times 4^2}{1000 \times 1/16} \]

\[ = 0.186 \text{ TVLs or 0.618 HVLs} \]
Simulator room

- Concrete @ 125 kVp = 0.186 x 6.6 cm = 1.2 cm
- Lead @ 125 kVp = 0.186 x 0.93 = 1.7 mm
- Lead glass equivalent = 8 mm
• Scatter barrier (at B)

- \( F = 20^2 \text{ cm}^2, \ T = 1/16, \ D = 1\text{m}, \ d = 4\text{m} \)
- \( a = 0.002 \)

\[
K = \frac{400 \ P \ D^2 \ d^2}{F \ aWT} = 0.256
\]

- Equivalent to about 1 cm concrete so use leakage calculation
CT simulator room

- Dedicated CT scanner for radiotherapy
- Flat table, lasers, big bore
- X-ray tube operating at 125 kVp and 250 mAs
- Primary beam is inherently shielded and $U = 1$
CT simulator room

control area

waiting room
CT simulator

• Workload
  – $W = 50 \text{ pt/wk} \times 100 \text{ slices/pt} = 5000 \text{ slices/wk}$

• Isodose plots are provided from the manufacturer to estimate the dose rate in different parts of the room
CT scanner dose

\[ \mu \text{Gy per scan} \]

NOTE:
125kV, 200mA, 1.5 Second per scan
Body Phantom
CT scanner dose

- The workload at any unprotected point in the room:

\[ D = W D_0 T \]

- \( D_0 \) is the isodose value, \( T \) is the occupancy
The required transmission is:

$TR = \frac{P}{D} = \frac{P}{W \ D_o \ T}$

and $TR = \frac{X_s}{X_o}$

$X_s = X_o \ TR$

$X_s = X_o \ \frac{P}{W \ D_o \ T}$

- $X_s$ is the shielded intensity
- $X_o$ is conversion R per mA min at 1m
CT simulator room

- R per mA min at 1 m from the x-ray target

<table>
<thead>
<tr>
<th>kV</th>
<th>X₀</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>0.95</td>
</tr>
<tr>
<td>125</td>
<td>0.90</td>
</tr>
<tr>
<td>100</td>
<td>0.86</td>
</tr>
<tr>
<td>70</td>
<td>0.73</td>
</tr>
<tr>
<td>50</td>
<td>0.50</td>
</tr>
</tbody>
</table>
CT simulator room

Calculate the barrier thickness required at point X.

10 patients are scanned a day, 100 slices each patient.

The area to be protected is a public access area with occupancy T=1.

The scanner operates at 125 kV and 200 mA for 1.5s per slice.

a) Calculate the Workload
b) Calculate the P
c) Determine the thickness of lead required
\[ X_s = X_o \frac{P}{W D_o T} \]

- **Workload** \( W \)
  - \( 10 \text{ pt/day} \times 100 \text{ slices/pt} \times 5 \text{ day/wk} = 5000 \text{ slices/wk} \)

- **Target dose rate** \( P \)
  - Public limit 1 mSv/year is 0.02 mSv/wk

- **Dose from isodoses** \( D_o \)
  - \( D_o = 0.03 \)

- **R per mA min conversion** \( X_o \)
  - \( X_o = 0.95 \)
CT simulator room

\[ X_s = X_o \frac{P}{W} D_o T \]

\[ = \frac{(0.95 \times 0.02 \text{ mSv/wk})}{5000 \text{ slices/wk} \times 0.02 \times 10^{-3} \text{ mGy}} \]

\[ X_s = 0.19 \]
\[ X_s = \frac{X_o}{P \cdot D} \]

\[ 5000 \text{ slices/week} \times 0.03 \times 10^{-3} \text{ mGy} = \text{cm} \]
HDR brachytherapy

- Ir-192
- 10 Ci, welded to flexible steel cable
- Remotely controlled
- Source driven out of safe through a catheter to patient
- Typical room ~ 60 cm concrete
HDR brachytherapy

- Shielding calculations based on transmission factor $B$, where:

$$B = \frac{Pd^2}{WT}$$

- $d$ is distance from source to POI
HDR brachytherapy

- Workload based on the total dose delivered to all patients to be treated per week

- $W$ is also function of source activity and treatment time

- $W = \Gamma f A t$
HDR brachytherapy

\[ W = \Gamma f A t \]

- \( \Gamma \) exposure rate constant
  - Relates exposure rate to activity at 1m
  - For Ir-192 \( \Gamma = 0.48 \text{ m}^2 \text{ R/hr Ci} \)

- F factor
  - relates cGy to R and is 0.96 cGy/R for Ir-192

- t treatment time per week
  - \( T = \text{dose} \times \#\text{patients} / \text{doserate @ 1cm} \)
HDR brachytherapy

• Calculate thickness of concrete required for a 10 Ci Ir-192 installation that treats 25 pt/wk to a dose of 10 Gy per patient. The dose is delivered at 1 Gy per minute. d = 2 m, and the POI is a control area T = 1, we want to protect NEWs.

• Workload
• Target dose rate
HDR brachytherapy

\[ W = \Gamma f A t \]

- **Workload**
  - Time = dose / doserate
    - \( = 25 \text{ patients x } 10 \text{ Gy} / 1 \text{ Gy/min} \)
    - \( = 250 \text{ min } = 4.16 \text{ hr/wk} \)

  \[ W = 0.48 \text{ R/hr Ci} \times 0.96 \text{ cGy/R} \times 10 \text{ Ci} \times 4.16 \text{ hr/wk} = 19.2 \text{ cGy/wk @1m} \]

- **Target dose rate**
  - NEW \( 0.04 \text{ cGy/wk} \text{ (or cSv)} \)
HDR brachytherapy

\[ B = \frac{Pd^2}{WT} = 0.008 \]

- From graph ~ 48 cm concrete
Brachytherapy - concrete
Brachytherapy - lead
Lead underwear

Radiation Guard for prostate cancer patients

Direct Scientific now offers the Radiation Guard designed specifically for patients who have undergone permanent radioactive seed implantation for prostate cancer. The radioactive seeds are either Iodine-125 or Palladium-103. The Radiation Guard stops more than 99% of the Palladium radiation and 95% of the Iodine radiation. Loved ones will now be able to spend unrestricted time near you while you are wearing the Radiation Guard. The Radiation Guard is comfortable.

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<table>
<thead>
<tr>
<th>Shipping-UPS</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>ground</td>
<td>$10.00</td>
</tr>
<tr>
<td>orange 3 day</td>
<td>$13.00</td>
</tr>
<tr>
<td>blue 2 day</td>
<td>$18.00</td>
</tr>
<tr>
<td>red next day</td>
<td>$30.00</td>
</tr>
</tbody>
</table>

Radiation Guard $120.00
Radiation Guard w/ extension straps $125.00

Visa and MasterCard accepted
MGH brachytherapy/SIM
MGH CT simulators 1
MGH CT simulators 2