Diagnostic X-Ray Shielding

Radiographic/Fluoroscopic Rooms
Multi-Slice CT Rooms
Using NCRP 147 Methodology

Melissa C. Martin, M.S., FAAPM, FACR
Therapy Physics Inc., Torrance, CA

AAPM Annual Meeting, Orlando, FL
Refresher Course
Thursday, July 26, 2007 7:30 am

Acknowledgement

Radiographic /Fluoroscopic Room
Slides Courtesy of:

Ben Archer, Ph.D, FACR, FAAPM
Baylor College of Medicine, Houston, TX

Required Information for Shielding Designs

- Architectural drawings of equipment layout in room
- Architectural drawings of surrounding areas indicating usage of these areas - offices, restrooms, corridor, exterior, etc.
- Elevation view of room or construction of floor and ceiling and distance between floors

Nomenclature for Radiation Design Criteria

Required thickness = \( \frac{NT}{Pd^2} \)

where:
N = total no. of patients per week
T = Occupancy Factor
P = design goal (mGy/wk)
d = distance to occupied area (m)
**Shielding Design Goal (Air Kerma):**

**Uncontrolled Areas**
- Annual: $P = 1 \text{ mGy per year}$
- Weekly: $P = 0.02 \text{ mGy per week}$

**Controlled Areas**
- Annual: $P = 5 \text{ mGy per year}$
- Weekly: $P = 0.1 \text{ mGy per week}$

---

**New Formalism for Radiation Design Criteria**

Required thickness = $NT/Pd^2$

where:
- $N =$ total no. of patients per week
- $T =$ Occupancy Factor
- $P =$ design goal (mGy/wk)
- $d =$ distance to occupied area (m)

Easy to use graphs for R and RF rooms developed by Simpkin are included in Report.

---

**Shielding Design Goal (Air Kerma):**

**Uncontrolled Areas**
- Annual: $P = 1 \text{ mGy per year}$
- Weekly: $P = 0.02 \text{ mGy per week}$

**Controlled Areas**
- Annual: $P = 5 \text{ mGy per year}$
- Weekly: $P = 0.1 \text{ mGy per week}$
**Distance (d)**

The distance in meters from either the primary or secondary radiation source to the occupied area.

New recommendations in Report 147 for areas above and below source.

---

**Where in the occupied area do you calculate the dose?**

- **0.3 m = 1 ft**
- **1.7 m = 5.5 ft**

---

**Recommended Occupancy Factors for Uncontrolled Areas:**

<table>
<thead>
<tr>
<th>( T = 1 )</th>
<th>Clerical offices, labs, fully occupied work areas, kids’ play areas, receptionist areas, film reading areas, attended waiting rooms, adjacent x-ray rooms, nurses’ stations, x-ray control rooms</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T = 1/2 )</td>
<td>Rooms used for patient examinations and treatments</td>
</tr>
<tr>
<td>( T = 1/5 )</td>
<td>corridors, patient rooms, employee lounges, staff rest rooms</td>
</tr>
<tr>
<td>( T = 1/8 )</td>
<td>corridor doors</td>
</tr>
</tbody>
</table>

---

**Recommended Occupancy Factors for Uncontrolled Areas:**

| \( T = 1/20 \) | public toilets, vending areas, storage rooms, outdoor area with seating, unattended waiting rooms, patient holding areas                                                                                   |
| \( T = 1/40 \) | minimal occupancy areas; transient traffic, attics, unattended parking lots, stairways, janitor’s closets, unattended elevators                                                                       |
**Pre-shielding ($x_{pre}$) for Radiographic Room Workload Distributions**

*(Dixon RL, Med Phys 1994)*

- Grid + cassette: (cross table)
  - Equivalent to: 0.3 mm Pb
  - or 3 cm concrete

- Grid + cassette + table/chest bucky supports: (over table and chest)
  - Equivalent to: 0.85 mm Pb
  - or 7.2 cm concrete

---

**Equivalency of Shielding Materials**

*Table 4.8 Page 67*

- **Steel thickness requirement:**
  - 8 $\times$ Pb thickness requirement

- **Gypsum wallboard thickness requirement:**
  - 3.2 $\times$ concrete thickness requirement

- **Plate Glass thickness requirement:**
  - 1.2 $\times$ concrete thickness requirement

- **Light-weight concrete thickness requirement:**
  - 1.3 $\times$ std-weight concrete thickness requirement

---

**Figure 5.2 Radiographic Room page 75**

**PRIMARY BARRIER Cross-Table Wall in Rad Room**
Required thickness $\Rightarrow$ NT/Pd$^2$

where:
- $N = 125$ patients/week
- $T = 1$
- $P = 0.02$ mGy/wk
- $d = 2.8$ m

$$NT/Pd^2 = 797 \text{ mGy}^{-1} \text{ m}^2$$

1. Go to page 54, Fig. 4.5a
   (Primary, lead, with no pre-shielding)
2. Look up NT/Pd$^2 = 797$
   (Cross-table Wall)

Pb required = 1.03 mm
Specify: 4/64” (1/16”); 4 lb/sq ft

---

OR

1. Go to page 55, Fig. 4.5b
   (Primary, lead, with pre-shielding)
2. Look up NT/Pd$^2 = 797$
   (Cross-table Wall)

Pb required = 0.83 mm
Specify: 5/128”; 2.5 lb/sq ft (minimum)
Recommended: 1/16”; 4 lb/sq ft
Using the NCRP 49 attenuation data and recommendations of \( W = 1000 \text{ mA-min per wk}, U = \frac{1}{4}, T=1 \), the new dose limit of \( P = 0.02 \text{ mGy (0.002 R) per wk} \), and assuming all exposures are made at 100 kVp, the required barrier thickness is 2.6 mm Pb (1/8 in. or 8 lbs per sq ft).

**Wall Containing Chest Image Receptor**

- Required thickness \( \Rightarrow \) \( NT/Pd^2 \)
  - \( N = 125 \text{ patients/ week} \)
  - \( T = 1/5 \) (staff rest room)
  - \( P = 0.02 \text{ mGy/wk} \)
  - \( d = 2.5 \text{ m} \)
  - \( NT/Pd^2 = 200 \text{ mGy}^{-1} \text{ m}^{-2} \)
Wall Containing Chest Image Receptor
Primary Barrier - Chest Receptor Area
- From Fig 4.5 a, page 54
  - (no pre-shielding)
  - Requires 1.32 mm Pb
- From Fig 4.5 b, page 55
  - (with pre-shielding)
  - Requires 0.50 mm Pb

Wall Containing Chest Image Receptor
Secondary Barrier - Chest Receptor Wall
- From Fig 4.5 c, page 56
  - Rest Room
  - Requires 0.37 mm Pb

Shielding Required for Entire Wall
Since the primary shielding is greater than the secondary wall requirements, the entire wall can be shielded with the minimum primary requirement.

No Pre-shielding
Pb required = 1.32 mm
Specify: 1/16”; 4 lb/sqft

With Pre-shielding
Pb required = 0.50 mm
Specify: 1/32”; 2 lb/sqft

Control Wall in the Radiographic Room
Secondary Barrier
Controlled Area: P = 0.1 mGy/wk
T = 1

d_{sec} = 1.8 m
Primary Barrier
**Simplified Graphical Solution**

**Control Wall in the Radiographic Room**

\[ \frac{NT}{Pd^2} = 125 \times \frac{1}{0.1} \times (1.8)^2 = 386 \]

1. Go to page 56, Figure 4.5c
   "Secondary Wall" curve
2. Look up \( \frac{NT}{Pd^2} = 386 \)

\[ \text{Pb required} = 0.27 \text{ mm} \]

Specify: 1/32"; 2 lb/sqft (Minimum)

**Recommended Specification:** 1/16 inch lead in all control booth walls with lead equivalent windows of at least 1.5 mm.

---

**Floor of the Rad Room**

**Primary Barrier Beneath the Rad Table**

- Required thickness \( \Rightarrow \frac{NT}{Pd^2} \)
  where:
  - \( N = 125 \) patients/week
  - \( T = 1 \)
  - \( P = 0.02 \text{ mGy/wk} \)
  - \( d = 4.1 \text{ m} \)

\[ \frac{NT}{Pd^2} = 372 \text{ mGy}^{-1} \text{ m}^2 \]

---

**Floor of the Rad Room**

**Primary Barrier Beneath the Rad Table**

1. Go to page 58, Fig. 4.6b
   (Primary, concrete, with pre-shielding)
2. Look up \( \frac{NT}{Pd^2} = 372 \)

If Specifying: Standard-Weight Concrete:
Minimum Concrete required = 37 mm = 1.5 in.

If Specifying: Light-Weight Concrete:
Minimum Concrete required = 37 mm x 1.3 = 48.1 mm = 1.9 in.
**Floor of the Rad Room**

Secondary Barrier Calculation for Floor

- **Required thickness** \( \Rightarrow \ NT/Pd^2 \)
  
  where:
  
  - \( N = 125 \) patients/ week
  - \( T = 1 \)
  - \( P = 0.02 \) mGy/wk
  - \( d = 3.0 \) m
  
  \( NT/Pd^2 = 694 \) mGy\(^{-1}\) m\(^2\)

---

**Floor of the Rad Room**

Secondary Barrier Calculation for Floor

1. Go to page 59, Fig. 4.6c (Secondary, concrete)
2. Look up \( NT/Pd^2 = 694 \)

**Minimum Concrete required** = \( 33 \) mm = \( 1.3 \) in.

This is less than the \( 37 \) mm thickness required for the primary barrier. Thus \( 37 \) mm of standard-weight concrete will suffice for the entire floor.

---

**Shielding References**


---

**Acknowledgement**

Multi Slice CT Shielding

Slides Courtesy of:

S. Jeff Shephard, M.S., DABR
M.D. Anderson Cancer Center, Houston, TX

Ben Archer, Ph.D, FACR
Baylor College of Medicine, Houston, TX
Multi-Slice Helical CT Shielding

- Larger collimator (slice thickness) settings generate more scatter
- Offsets advantages of multiple slices per rotation
- Environmental radiation levels typically increase
- Ceiling and floor deserve close scrutiny

Method

- Calculate the unshielded weekly exposure rate at area of interest
- Find the maximum weekly exposure at 1 m from isocenter and inverse-square this out to the occupied area beyond the barrier.
- Apply traditional barrier thickness calculations to arrive at an answer.
- Occupancy, permissible dose, attenuation of concrete, etc.

NCRP 147 DLP Method

- Weekly Air Kerma at 1m ($K_{1sec}^1$)

  \[ K_{1sec}^1 (\text{head}) = \kappa_{\text{head}} \times DLP \]
  \[ K_{1sec}^1 (\text{body}) = 1.2 \times \kappa_{\text{body}} \times DLP \]

  \[ \kappa_{\text{head}} = 9 \times 10^{-5} \text{ /cm} \]
  \[ \kappa_{\text{body}} = 3 \times 10^{-4} \text{ /cm} \]

  Use inverse square to find unshielded weekly exposure at barrier from $K_{1sec}^1$

NCRP 147 DLP Method

DLP (Dose-Length Product)

\[ = \text{CTDI}_{\text{vol}} \times L \]

- $\text{CTDI}_{\text{vol}} = \text{CTDI}_{\text{w/Pitch}}$
- $\text{CTDI}_{\text{w}} = \frac{1}{3} \text{ Center CTDI}_{100}$
  + $\frac{2}{3} \text{ Surface CTDI}_{100} (\text{mGy})$
- $L =$ Scan length for average series in cm
- Units of mGy-cm

\[ = \left[ \frac{1}{3} \text{ CTDI}_{100, \text{ Center}} + \frac{2}{3} \text{ CTDI}_{100, \text{ Surface}} \right] \times L/p \]
NCRP 147 DLP Method

<table>
<thead>
<tr>
<th>Procedure</th>
<th>CTDI_{vol} (mGy)</th>
<th>Scan Length (L) (cm)</th>
<th>DLP* (mGy-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>60</td>
<td>20</td>
<td>1200</td>
</tr>
<tr>
<td>Body</td>
<td>15</td>
<td>35</td>
<td>525</td>
</tr>
<tr>
<td>Abdomen</td>
<td>25</td>
<td>25</td>
<td>625</td>
</tr>
<tr>
<td>Pelvis</td>
<td>25</td>
<td>20</td>
<td>500</td>
</tr>
<tr>
<td>Body (Chest, Abdomen, or Pelvis)</td>
<td>25</td>
<td>20</td>
<td>550</td>
</tr>
</tbody>
</table>

* Double the value shown for w/o contrast

Example - Ceiling Calculation

- 180 Procedures/week
- 150 Abdomen & Pelvis
- 30 Head
- 40% w&w/o contrast
- 13’ (4.2 m) ceiling height (finished floor to finished floor)
- GE LightSpeed 16

Preliminary Information

- Architectural drawings (Plan view) of exam room, floor above, and floor below
- Elevation sections through scanner location for floor and ceiling
- Occupancy factors for floors above and below
- Two rooms away for possibility that remote areas may be more sensitive than adjacent areas
- Composition of walls, ceilings and floors
- Materials and thickness
- Scanner placement from vendor
- Distance from scanner to protected areas beyond barriers

![Diagram of CT Control and Mechanical areas]
Unshielded Weekly Exposure at Barrier

- **Weekly Air Kerma (K_{sec})** at Ceiling:
  - 30 head procedures/wk
  - 150 body procedures/wk
  - $D_{sec} = 4.2 \text{ m} + 0.5 \text{ m} - 1 \text{ m} = 3.7 \text{ m}$

  \[
  K_{sec} \text{ (head)} = 30 \times 4.9 \text{ mGy} \times (1\text{m}/3.7\text{m})^2 \\
  = 0.36 \text{ mGy}
  \]

  \[
  K_{sec} \text{ (body)} = 150 \times 41.6 \text{ mGy} \times (1\text{m}/3.7\text{m})^2 \\
  = 3.04 \text{ mGy}
  \]

- **Air Kerma/procedure at 1m ($K_{sec}$)**
  - 40% w/w/o contrast

  \[
  K_{sec} \text{ (head)} = \kappa_{head} \times \text{DLP} \\
  = 1.4 \times 9 \times 10^{-5} \text{ cm}^2 \times 1200 \text{ mGy-cm} \\
  = 4.9 \text{ mGy}
  \]

  \[
  K_{sec} \text{ (body)} = \kappa_{body} \times \text{DLP} \\
  = 1.4 \times 1.2 \times 3 \times 10^{-4} \text{ cm}^2 \times 550 \text{ mGy-cm} \\
  = 41.6 \text{ mGy}
  \]

- **Weekly Air Kerma (K_{sec})** at Ceiling:
  \[
  K_{sec} \text{ (Total)} = K_{sec} \text{ (head)} + K_{sec} \text{ (body)} \\
  = 0.36 \text{ mGy} + 3.04 \text{ mGy} \\
  = 3.40 \text{ mGy}
  \]
Required Transmission (B)

\[ B = \frac{P}{K_{sec} \times T} \]

P = Maximum permissible weekly exposure
T = Occupancy Factor

\[ 0.02 \text{ mGy} = 3.87 \times 10^{-3} \]

\[ 3.40 \text{ mGy} = 1 \]

Total Shielding Required

Use Simpkin curve fit equations or look up on published attenuation diagrams (NCRP 147 Fig. A-2)

Existing Shielding

- Floors and ceilings
  - Find lead equivalence from documentation of concrete thickness.
  - Find thickness by drilling a test hole and measuring.
  - Always assume light weight concrete, unless proven otherwise (30% less dense than standard density, coefficients used in NCRP 147)

3" light concrete = 2.1" std concrete
= 53 mm std concrete
B = 9 x 10^{-2}
= 0.45 mm Pb-eqiv
Existing Shielding

- Subtract existing lead-equivalence from total required
- Convert to 1/32 inch multiples (round up)

Total lead to add = (Total required) – (Existing)
= 1.54 mm – 0.45 mm
= 1.1 mm

Round up to 1/16" Pb Additional Lead required

CTDI Method

Unshielded weekly exposure calculation:
Secondary exposure per procedure at one meter $K_s^1$

$$K_s^1 = k \times \left( \frac{L}{p} \right) \times \left[ \frac{mAs/Rotation}{CTDI_{100, peripheral}} \right] \times \left[ \frac{\text{Scan KV}}{CTDI_{KV}} \right] \times \frac{1}{2}$$

Where:
- $k$ is the scatter fraction at one meter per cm scanned.
- $L$ is the length of the scanned volume.
- $p$ is pitch.

$K_s^1$ (head) = $9 \times 10^{-5}$ cm$^{-1}$
$K_s^1$ (body) = $3 \times 10^{-5}$ cm$^{-1}$

CTDI Method

ImPACT (the UK's CT evaluation center) website has measured axial and peripheral CTDI$_{100}$ for most scanners on the market in Excel format.

www.impactscan.org

Calculate $K_s^1$ for head and body separately, then combine with weighting factors depending on percentage of total workload.

$$K_s^1_{(total)} = \frac{\% \text{ heads} \times K_s^1_{(head)} + \% \text{ body} \times K_s^1_{(body)}}{100\%}$$

Finally, inverse-square this exposure out to each area to be protected.
Isodose Map Method

- Assume an isotropic exposure distribution based on the maximum exposure rate in the vendor-supplied exposure distribution plots (approx. 45° to the scanner axis).
- Overestimates shielding needed in the gantry shadows and the shadows of the patient.
Comparison of Methods

<table>
<thead>
<tr>
<th></th>
<th>DLP</th>
<th>CTDI_{100}</th>
<th>Isodose</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>4.9</td>
<td>0.2</td>
<td>12</td>
</tr>
<tr>
<td>Body</td>
<td>41.6</td>
<td>5.0</td>
<td>151</td>
</tr>
</tbody>
</table>

Combined Weekly Exposure at Ceiling

- 3.4 mGy
- 0.38 mGy
- 10 mGy

Add Lead

- 1/16"
- 1/32"
- 3/32"

Shielding References