Diagnostic X-Ray Shielding

Multi-Slice CT Scanners Using NCRP 147 Methodology

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

AAPM Annual Meeting, Orlando, FL
Refresher Course
Thursday, August 3, 2006  8:30 am
Acknowledgement

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
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:* \( P = 0.1 \text{ mGy per week} \)
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?

To the closest sensitive organ!

0.5 m

0.3 m = 1 ft

1.7 m = 5.5 ft
# Recommended Occupancy Factors for Uncontrolled Areas:

| \( T = 1 \) | 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 |
| \( T = 1/2 \) | Rooms used for patient examinations and treatments |
| \( T = 1/5 \) | Corridors, patient rooms, employee lounges, staff rest rooms |
| \( T = 1/8 \) | Corridor doors |
### Recommended Occupancy Factors for Uncontrolled Areas:

<table>
<thead>
<tr>
<th>$T=1/20$</th>
<th>public <em>toilets</em>, vending areas, storage rooms, outdoor area with seating, unattended waiting rooms, patient holding areas</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T=1/40$</td>
<td><em>minimal occupancy areas</em>; transient traffic, attics, unattended parking lots, stairways, janitor’s closets, unattended elevators</td>
</tr>
</tbody>
</table>
Equivalency of Shielding Materials

Table 4.8  Page 67

Steel thickness requirement:
8 × Pb thickness requirement

Gypsum wallboard thickness requirement:
3.2 × concrete thickness requirement

Plate Glass thickness requirement:
1.2 × concrete thickness requirement

Light-weight concrete thickness requirement:
1.3 × std-weight concrete thickness requirement
Nominal Thickness of Lead (mm and inches)
and Nominal Weight (lb ft$^{-2}$) at bottom of each bar
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
Problem

Question:

Do I really need to put lead in the ceiling of a 16-slice CT scanner room?
Method

- Calculate the unshielded weekly exposure rate at 0.5 m beyond the floor above.
  - 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 ($K^{1}_{\text{sec}}$)

$$K^{1}_{\text{sec}} \ (\text{head}) = k_{\text{head}} \times \text{DLP}$$

$$K^{1}_{\text{sec}} \ (\text{body}) = 1.2 \times k_{\text{body}} \times \text{DLP}$$

$$k_{\text{head}} = 9 \times 10^{-5} \ \text{1/cm}$$

$$k_{\text{body}} = 3 \times 10^{-4} \ \text{1/cm}$$

Use inverse square to find unshielded weekly exposure at barrier from $K^{1}_{\text{sec}}$. 
NCRP 147 DLP Method

DLP (Dose-Length Product)

\[ \text{DLP} = \text{CTDI}_{\text{VOL}} \times L \]

- \( \text{CTDI}_{\text{VOL}} = \text{CTDI}_{\text{W}} / \text{Pitch} \)
- \( \text{CTDI}_{\text{W}} = \frac{1}{3} \text{Center CTDI}_{100} + \frac{2}{3} \text{Surface CTDI}_{100} \text{ (mGy)} \)
- \( L = \text{Scan length for average } \textbf{series} \text{ in cm} \)
- Unit of mGy-cm

\[ \text{Units of mGy-cm} \]

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

<table>
<thead>
<tr>
<th>Procedure</th>
<th>CTDI\textsubscript{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></td>
<td>550</td>
</tr>
</tbody>
</table>

* Double the value shown for w/wo contrast
Example

- 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
Unshielded Weekly Exposure at Barrier

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

\[ K_{sec}^1 (\text{head}) = k_{\text{head}} \times \text{DLP} \]
\[ = 1.4 \times 9 \times 10^{-5} \text{ cm}^{-1} \times 1200 \text{ mGy-cm} \]
\[ = 4.9 \text{ mGy} \]

\[ K_{sec}^1 (\text{body}) = k_{\text{body}} \times \text{DLP} \]
\[ = 1.4 \times 1.2 \times 3 \times 10^{-4} \text{ cm}^{-1} \times 550 \text{ mGy-cm} \]
\[ = 41.6 \text{ mGy} \]
Unshielded Weekly Exposure at Barrier

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

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

\[
K_{sec} \text{ (body)} = 150 \times 41.6\, mGy \times \left(\frac{1m}{3.7m}\right)^2 = 3.04\, mGy
\]
Unshielded Weekly Exposure at Barrier

- Weekly Air Kerma ($K_{sec}$) at Ceiling:

$$K_{sec} \text{ (Total)} = K_{sec} \text{ (head)} + K_{sec} \text{ (body)}$$

$$K_{sec} \text{ (Total)} = 0.36 \text{ mGy} + 3.04 \text{ mGy}$$

$$K_{sec} \text{ (Total)} = 3.40 \text{ mGy}$$
Required Transmission (B)

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

- \( P \) = Maximum permissible weekly exposure
- \( T \) = Occupancy Factor

\[ \begin{align*}
0.02 \text{ mGy} & = \frac{3.87 \times 10^{-3}}{3.40 \text{ mGy} \times 1}
\end{align*} \]
Total Shielding Required

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

Transmission of CT Scanner Secondary Radiation Through Lead (120 kV)

- Transmission: $3.87 \times 10^{-3}$ at 1.54 mm lead thickness

**Graph Details:**
- X-axis: Lead Thickness (mm)
- Y-axis: Transmission
- Grid for data visualization

---

**Equation:**
$$0.001 = 1 - e^{-\frac{120}{1000} \times \text{Thickness} \times \text{Attenuation Coefficient}}$$

**Note:**
- The graph shows the transmission of secondary radiation through lead as a function of thickness.
- The attenuation coefficient is derived from curve fit equations provided by Simpkin or published diagrams.
Existing Shielding

- Measure existing attenuation in walls with Tc-99m source and Na-I detector (determine lead-equivalence – usually 0.1 mm Pb-eq)

- 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)
Transmission of CT Scanner Secondary Radiation
Through Concrete (120 kV)

Transmission of CT Scanner Secondary Radiation
Through Lead (120 kV)

3” light concrete = 2.1” std concrete
= 53 mm std concrete
B = 9x10^-2
= 0.45 mm Pb-eqv

3” light concrete = 2.1” std concrete
= 53 mm std concrete
B = 9x10^-2
= 0.45 mm Pb-eqv
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 $K_s^1$

$$K_s^1 = \kappa \times \left( \frac{L}{p} \right) \times \left( \frac{\text{mAs/Rotation}}{2} \right) \times \left( \text{CTDI}_{100, \text{peripheral}} / \text{mAs} \right) \times \left( \frac{\text{Scan kV}}{\text{CTDI kV}} \right)^2$$

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

<table>
<thead>
<tr>
<th>$\kappa$ (head)</th>
<th>$9 \times 10^{-5}$ cm$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\kappa$ (body)</td>
<td>$3 \times 10^{-4}$ cm$^{-1}$</td>
</tr>
</tbody>
</table>
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.

![Excel spreadsheet with CTDI values for various scanners](www.impactscan.org)
CTDI Method

Calculate $K^1_{sec}$ for head and body separately, then combine with weighting factors depending on percentage of total workload.

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

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.
Sensation 64/ Cardiac 64

Scanning was performed using a maximum slice thickness of 20 x 1.2 mm (24 mm) at 140 kV through the system axis in the horizontal plane. A cylindrical PMMA phantom measuring 32 cm in diameter and 16 cm in length was used for the scatter radiation test. The phantom was centered in the tomographic plane.

Measurement values in μGy/1 mAs
BODY SCATTER PHANTOM

ISO CONTour LEVELS: 0.075, 0.15, 0.3 AND 0.6 mR/SCAN

100 mAs/scan, 140 kV, 4 x 5.00mm Scan Acquisition
0.5 m aff

Acceptable exposures outside of this line

BODY SCATTER PHANTOM
ISO-COUNTOR LEVELS: 0.53, 1.07, 2.13 AND 4.26 mR/SCAN
710 mAs/scan, 140 kV, 16 x 0.25mm Scan Acquisition

8th floor

Drop Ceiling

9'

2.13

4.26

7th floor

0 50 Inches
Acceptable exposures outside of this line

6 Feet AFF (below)

6’
## Comparison of Methods

<table>
<thead>
<tr>
<th></th>
<th>DLP</th>
<th>CTDI&lt;sub&gt;100&lt;/sub&gt;</th>
<th>Isodose</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Head</td>
<td>Body</td>
<td>Head</td>
</tr>
<tr>
<td><strong>K&lt;sup&gt;1&lt;/sup&gt;_sec</strong></td>
<td>4.9</td>
<td>41.6</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Combined Weekly Exposure at Ceiling</strong></td>
<td>3.4 mGy</td>
<td>0.38 mGy</td>
<td>10 mGy</td>
</tr>
<tr>
<td><strong>Add Lead</strong></td>
<td>1/16”</td>
<td>1/32”</td>
<td>3/32”</td>
</tr>
</tbody>
</table>
Shielding References


Contact Information

Melissa C. Martin, M.S., FACR, FAAPM
Certified Medical Physicist
Therapy Physics Inc.
9156 Rose St., Bellflower, CA 90706
Office Phone: 562-804-0611
Office Fax: 562-804-0610
Cell Phone: 310-612-8127
E-mail: MelissaMartin@Compuserve.com