Welcome To The Next Generation*

- NCRP Report No. 147: Structural Shielding Design for X-ray Imaging
- AAPM Task Group 108: Shielding for PET/CT Facilities
- NCRP Report No. 151: Structural Shielding Design for Megavoltage Radiotherapy Facilities

*Of shielding design, that is!

Notes

- NCRP Report No. 147 was a committee report
  - I take credit for the good stuff, blame the others for the bad
- NCRP Report No. 147 was our take on “best practice” at one moment in time…
  - It’ll need constant revision
    - But we hope that our methods will be rigorous enough to last a few years!
    - I’ll point out those areas that I recognize as requiring a “fresh view”

History of Diagnostic X-ray Shielding Design

- NBS Handbook 60 (1955) & Braestrup & Wykoff Health Physics Text (1958)
- NCRP Reports 34 (1972) & 49 (1976)
  - Standard for specifying shielding for past 30 years
  - Limitations noted by mid ‘70s
- AAPM Task Group 9 formed 1989
- NCRP/AAPM Task Group 1992


- Measured/confirmed fundamental shielding data
  - Workloads
  - Transmission
- Refined shielding theory
- Published results along the way
  - 16 refereed publications, including 5 in Medical Physics & 6 in Health Physics
  - >31 invited lectures given by the members at AAPM, HPS, CRCPD, RSNA, AAPM & HPS Chapters, etc

NCRP-147 Cochairs

- Joel Gray
  - clinical/industry medical physicist
- Ben Archer
  - clinical medical physicist
NCRP-147 Membership

- Robert Dixon - clinical medical physicist
- Robert Quillin - Colorado state regulator (ret.)
- William Eide - architect
- Ray Rossi - clinical medical physicist (deceased)

NCRP-147 Membership

- Lincoln Hubbard - clinical medical physicist
- Douglas Shearer - clinical medical physicist
- Douglas Simpkin - clinical medical physicist
- Eric Kearsley -
  - 2nd NCRP staff scientist (1998-2001), first outside reviewer

NCRP-147 Consultants

- Marv Rosenstein, NCRP
- Andrew Poznanski, M.D. (who?)
- Ken Kase
  - Helped shepherd the report through its final reviews
- Wayne Thompson
  - Kept us honest in the past couple of years, independently redoing sample calculations, checking for self-consistency, & asking “Why?”
- Jack Krohmer (deceased)

NCRP-147 Consultants

- Eric Kearsley

History - NCRP Report #147

- Draft completed ~2001; held up by internal NCRP arguments over P
- Finally published November 2004
- Shielding information for diagnostic x-ray imaging devices only;
  - No dental units (cf. NCRP Report No. 145; x-ray shielding written by Marc Edwards)
  - No therapy machines (cf. NCRP Report #151)
  - No radionuclides… (cf. AAPM Task Group #108 Rept for PET)

Who can do shielding calculations?

- Per the Report, only Qualified Experts should perform these calculations and surveys
- A Qualified Expert (QE) is “… is a person who is certified by the American Board of Radiology, American Board of Medical Physics, American Board of Health Physics, or Canadian College of Physicists in Medicine.”
- Regulators?... They’re learning from us!

Exponential Attenuation of X rays

- No barrier will completely eliminate the radiation dose outside a diagnostic x-ray room
- What is safe?
Controlled & Uncontrolled Areas

- **Controlled areas** are occupied by employees/staff whose occupational radiation dose is monitored.
- **Uncontrolled areas** are occupied by individuals such as patients, visitors to the facility, and employees who do not work routinely with or around radiation sources. Areas adjacent to, but not part of, the x-ray facility are also uncontrolled areas.

Design Goal, $P$

- $P$ = permitted radiation level in the occupied area.
- $P$ must be consistent with NRCP Report 116, which limits the effective dose equivalent:
  - Which can’t be measured
  - Is highly photon energy-dependent
- $P$ for NCRP-147 is a kerma value
- $P$ for NCRP-151 (with neutrons) is a dose equivalent

Design Goal, $P$

<table>
<thead>
<tr>
<th>Controlled Area</th>
<th>Uncontrolled Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>NCRP-49 1976</td>
<td></td>
</tr>
<tr>
<td>50 mGy/y</td>
<td>5 mGy/y</td>
</tr>
<tr>
<td>= 1 mGy/wk</td>
<td>= 0.1 mGy/wk</td>
</tr>
<tr>
<td>NCRP-147 2004</td>
<td></td>
</tr>
<tr>
<td>Fraction (~1/2) of 10 mGy/y limit for new operations</td>
<td>1 mGy/y (matches fetal dose limit)</td>
</tr>
<tr>
<td>= 5 mGy/y</td>
<td>= 0.1 mGy/wk</td>
</tr>
<tr>
<td>= 0.02 mGy/wk</td>
<td></td>
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<tr>
<td>Effect</td>
<td>Factor of 10 decrease</td>
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<tr>
<td></td>
<td>Factor of 5 decrease</td>
</tr>
</tbody>
</table>

NCRP 0.25 mSv/y General Public Limit?

NCRP-116 sayeth unto us:

“...whenever the potential exists for exposure of an individual member of the public to exceed 25 percent of the annual effective dose limit as a result of irradiation attributable to a single site, the site operator should ensure that the annual exposure of the maximally exposed individual, from all man-made exposures (excepting that individual’s medical exposure), does not exceed 1 mSv on a continuous basis. Alternatively, if such an assessment is not conducted, no single source or set of sources under one control should result in an individual being exposed to more than 0.25 mSv annually.”

NCRP Statement 10 (2004)

- In Statement No. 10 *Recent Applications of the NCRP Public Dose Limit Recommendation for Ionizing Radiation* (December ’04) the NCRP reinforced that “An effective dose ... that does not exceed 1 mSv y⁻¹ is justified for the conservatively safe assumptions used in the recommended shielding design methodology.”
- Statement No. 10 is available at www.ncrp.com

Uncontrolled $P$=0.1 mGy/y will satisfy 0.25 mSv/y

- Ignoring patient attenuation
- Assuming perpendicular beam incidence
- Ignoring attenuating items in room (e.g. Pb aprons and fluoro drapes, etc.)
- Assuming worst-case leakage levels
- Assuming conservatively large beam areas for worst-case scatter calculations
Uncontrolled $P=0.1$ mGy/y will satisfy 0.25 mSv/y

- Assuming conservatively high occupancy factors
- Pb sheets come in quantized thicknesses (e.g. 1/32 inch, 1/16 inch, etc). Using the next greater thickness will shield to much lower levels than $P$
- Assuming minimum distances from source to personnel in occupied areas

• At <50 keV, the Effective Dose Equivalent is a small fraction of the kerma (due to shielding of deep organs by overlying tissues)

Occupancy Factor, $T$

- Traditionally, shielding designers have allowed for partial occupancy in shielded areas, with $T$ the “occupancy” factor
- $T$ is the fraction of the beam-on time a shielded area is occupied by an individual
- Shielding task: a barrier is acceptable if it decreases the kerma behind the barrier to $P/T$
- If $T<1$, the “full-time dose” will be $P/T$

Recommended Occupancy Factors

<table>
<thead>
<tr>
<th>Environment</th>
<th>Occupancy Factor $T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offices, labs, pharmacies, receptionist areas, attended waiting rooms, x-ray rooms, film reading areas, nursing stations, x-ray control rooms</td>
<td>1</td>
</tr>
<tr>
<td>Patient exam &amp; treatment rooms</td>
<td>1/2</td>
</tr>
<tr>
<td>Corridors, patient rooms, employee lounges, staff rest rooms</td>
<td>1/8</td>
</tr>
<tr>
<td>Corridor doors</td>
<td>1/8</td>
</tr>
<tr>
<td>Public toilets, vending areas, storage rooms, outdoor areas w/ seating, unattended waiting rooms, patient holding</td>
<td>1/20</td>
</tr>
<tr>
<td>Outdoors, unattended parking lots, attics, stairways, unattended elevators, janitor’s closets</td>
<td>1/40</td>
</tr>
</tbody>
</table>

X-ray Beam Transmission

- For a given x-ray spectrum, the Transmission, $B$, through a barrier of thickness $x$ is the ratio of kerma with & without the barrier

$$B(x) = \frac{K(x)}{K(0)}$$
Transmission Data in NCRP-147

- Measured or calculated \( B(x) \) data of modern three phase / constant potential Al-filtered beams:
  - Archer et al. (1994) for Pb, gypsum wallboard, steel, plate glass
  - Légaré et al. (1977) / Rossi (1997) for concrete
  - Simpkin (1987) for mammography
- Transmission data for a wide variety of materials were interpolated to yield \( B(x) \) every 5 kVp (Simpkin 1995)

Archer Equation for Transmission Curves

- Archer et al. presented a very useful equation for describing transmission data \( B \) fit to barrier thickness \( x \) in 3 parameters \((\alpha, \beta, \gamma)\)

\[
B = \left[ \left( 1 + \frac{\beta}{\alpha} \right) e^{\alpha x} - \frac{\beta}{\alpha} \right]^{-\frac{1}{\gamma}}
\]

Archer Equation for Transmission Curves

- Note: \( \alpha \) is the slope of the transmission curve at large \( x \). Therefore, \( \alpha = (\ln 2) / \text{“Hard HVL”} \)

Archer Equation for Transmission Curves

- This can be inverted to solve for \( x \)

\[
x = \frac{1}{\alpha \gamma} \ln \left[ \frac{B^{-\gamma} + B}{1 + \frac{\beta}{\alpha}} \right]
\]

Workload, \( W \)

- \( W \) is a measure of the x-ray tube’s use
- \( W = \) the time integral of the tube current
- Units: mA·min per wk (= mAs/60)
- \( W \propto \) # electrons hitting x-ray tube anode
- To be useful, must know or assume the operating potential (kVp) at which the workload occurs

Workload, \( W \)

- At a given x-ray tube accelerating potential, the magnitude of \( W \) determines the kerma generated by the tube
- The kVp distribution of \( W \) determines both the kerma and the transmission of the beam through the barrier.
  - Primary beam kerma \( \propto kVp^2 \)
  - Kerma transmitted through typical shielding barriers increases by factors of hundreds going from 60 kVp to 120 kVp
Workload, $W$

- To determine $W$ used clinically, a survey of modern medical facilities was undertaken by AAPM TG 9 in the early 1990s and published in *Health Phys* 1996 (Simpkin).
- Objectives of survey:
  - $W$ per patient in various types of diagnostic settings (general radiography, cath lab, etc.)
  - the weekly average number of patients, $N$
  - the kVp distribution of $W$
  - use factors in radiographic rooms

Workload Survey

- Found total workload $W$:
  - Radiographic Rooms: 277 mA·min/wk
  - Chest Rooms: 45 mA·min/wk
  - Cardiac Angio Rooms: 3050 mA·min/wk
- Found kVp distribution of workloads to be at potentials significantly below the single kVp operating value usually assumed

Workload Distribution, $W(kVp)$

- e.g. Cardiac Angio Lab
  - $W_{\text{tot}} = 3047$ mA·min/wk for $N = 20$ patients/wk

![Cardiac Angio Lab](chart)

- General Radiographic Room; all barriers in room
  - $W_{\text{tot}} = 277$ mA·min/patient for $N = 112$ patients/wk

![General Radiographic Room](chart)

- But this is composed of radiographic views taken against the wall-mounted “Chest Bucky”
  - $W_{\text{tot}} = 67.9$ mA·min/patient for $N = 112$ patients/wk

![General Radiographic Room](chart)

- And radiographic views taken against all other barriers (floor, other walls, etc)
  - $W_{\text{tot}} = 209$ mA·min/patient for $N = 112$ patients/wk

![General Radiographic Room](chart)
Update on Workload Data

- Since the workload survey was published over a decade ago, the digital revolution has occurred in radiographic imaging
  - See higher radiographic exposure per image =
    - Greater workload per patient (maybe by 50 to 100%)
    - Expect kVp distribution of workloads to remain unchanged from film/screen (since that effects contrast)
  - Greater through-put in number of patients in each room =
    - More patients per week in each room
    - Fewer radiographic rooms (!)

- Interventional systems (and some general fluoro systems) now use Cu-filtered x-ray beams
  - Workload (mA·min) appears much higher since Cu-filtered tubes operate at a much higher mA
  - But radiation output (kerma/μA·min) is much lower
  - Moral:
    - The two probably cancel. Assume Al filtered workloads, outputs, and transmissions, and we should be OK.
    - Requires a more complete evaluation…

Where in the occupied area do you calculate the kerma?

- To the closest sensitive organ!

The Three Models for Diagnostic X-ray Shielding In NCRP 147

1. First-principle extensions to NCRP 49
2. Given calculated kerma per patient, scale by # patients and inverse squared distance, and then use transmission curves designed for particular room types
3. \( NT/(Pd^2) \)

Models for Diagnostic X-Ray Shielding Calculations

- cf Table 5.1 for a “road map” on how to use the data in NCRP 147 to solve shielding problems of the various room types
1st principle extensions to NCRP 49

- (Underlies the other two methods)
- The kerma in the occupied area may have contributions from
  - primary radiation
  - scatter radiation
  - leakage radiation \{ Secondary radiation \}

Primary, Scatter, and Leakage

- Must protect from scatter & leakage radiation
- Must protect from primary radiation

Primary, Scatter, and Leakage

- These primary, scatter, and leakage radiations may be from multiple x-ray sources (or tube positions)
- So, simply add up all these contributions to the kerma from all these sources in the occupied area behind a barrier of thickness \( x \),

\[
K(x) = \sum_{\text{tubes}} \sum_{\text{kVp}} (K_p(x) + K_s(x) + K_l(x))
\]

1st principle extensions to NCRP 49

- Then iteratively find a barrier thickness \( x \) that decreases that kerma to \( P/T \), the design goal modified by the occupancy factor $c f. \ http://www.geocities.com/djsimpkin/$ for shareware XRAYBARR to do this
  - “Dose” in XRAYBARR = “Kerma” in NCRP-147
**Primary Radiation Model**

- In primary beam, know kerma per workload at 1 m, $K_W(kVp)$, for 3 phase units (W/Al beam data of Archer et al. 1994, Mo/Mo data of Simpkin)

**Unshielded Primary Beam Kerma**

- At a given $kVp$, $K_p(0) = \frac{K_W(kVp) W(kVp)}{d_p^2}$

- If only a fraction $U$ of the tube’s workload is directed at this barrier, then

$$K_p(0) = \frac{K_W(kVp) U W(kVp)}{d_p^2}$$

- $U$ is the use factor for this barrier

**Kerma Behind a Primary Barrier**

- The kerma behind a primary barrier of transmission $B(x, kVp)$ is

$$K_p(x, kVp) = \frac{K_W(kVp) U W(kVp) B(x, kVp)}{d_p^2}$$

- For the whole distribution of workloads, total kerma is

$$K_p(x) = \sum K_W(kVp) U W(kVp) \frac{B(x, kVp)}{d_p^2}$$

**Primary Radiation: The NCRP49 Model**

Barrier of thickness $x$ decreases raw primary radiation kerma to $P/T$

**Primary Radiation: A Realistic Model**

Primary radiation is significantly attenuated before reaching barrier

**Primary Radiation: A Conservative, Realistic Model**

Even without the patient, primary radiation is still significantly attenuated before reaching barrier
Primary Radiation: NCRP-147 Model

Assume primary beam attenuation in image receptor is due to a pseudo-barrier whose equivalent thickness \( x_{pre} \) gives same transmission as that seen for actual image receptors.

\[
\begin{align*}
\text{x}_{\text{pre}} &= x + x_{\text{pre}} \\
\text{No patient!}
\end{align*}
\]

Grid, cassette, maybe supporting structures

\[
\text{No patient!}
\]

Primary Transmission Through Patient, Image Receptor, and Supports

\[
\begin{align*}
\text{No patient & grid & cassette & cassette support structures & radiographic table:} \\
B &= 9.36 \times 10^{-13} kVp^{4.917} \\
\text{No patient & grid & cassette:} \\
B &= 4.7 \times 10^{-6} kVp^{2.181} \\
\text{Data of Dixon (1994)}
\end{align*}
\]

Needs validating for CR/DR image receptors

Values of \( x_{pre} \) for Radiographic Room Workload Distributions

- From Table 4.6:
  - Grid + cassette:
    - 0.3 mm Pb
    - 30 mm concrete
  - Grid + cassette + table/chest bucky supports:
    - 0.85 mm Pb
    - 72 mm concrete

Calculation of Primary Kerma

- Same as model in NCRP49 except
  - account for workload distribution in kVp
  - QE may account for image receptor shielding \( x_{pre} \)
- Primary kerma in occupied area is then

\[
K_p(x + x_{pre}) = \\
\frac{1}{d_p kVp} \sum_{kVp} K_{W}(kVp) U W(kVp) B(x + x_{pre}, kVp)
\]

Scatter Radiation
Scaled Normalized Scatter Fraction

\[ K_d = \frac{S}{P} \]

1 cm² area primary beam at 1 m

Scatter Radiation

- Same theory as NCRP-49
  - scatter fraction data of Kelley & Trout reevaluated by Simpkin & Dixon (1998)
  - pri beam area \( F \) (cm²) measured at pri distance \( d_F \) conveniently taken as image receptor area @ SID
  - explicitly show kVp dependence and sum over workload distribution to yield shielded scatter kerma

\[ K_S(\theta, \phi) = \sum_{kVp} d' \times K_w(\phi) W(\phi) \frac{F}{d'_F} B(x,\phi) \]

Leakage Radiation

- Radiation originating from x-ray tube focal spot but not emanating from the tube port

- Intensity can’t exceed \( L = 100 \text{ mR/hr} \) at 1 m when tube is operated at its leakage technique factors
  - maximum potential for continuous operation \( kVp_{\text{max}} \) (typically 135-150 kVp, or 50 kVp for mammography)
  - \( I_{\text{max}} \) is the maximum continuous tube current possible at \( kVp_{\text{max}} \)

- These leakage technique factors specify how thick the shielding in the tube housing should be
- NCRP49 suggested leakage technique factors of 3.3 mA at 150 kVp, 4 mA at 125 kVp, 5 mA at 100 kVp; remain fairly typical today
Leakage radiation

• NCRP-147 calculations (and shielding methods 2 and 3) use
  – 3.3 mA at 150 kVp
  – worst case leakage rates
  – (Subsequently, we’ve found that assuming 4 mA at 125 kVp leakage technique factors specifies barriers that are 10-20% thicker than in the report)
  – However, typical leakage rates are 0-30% of the maximum leakage so we don’t see a problem

New Leakage Model

• For tube operating at techniques \((kVp, I)\) with transmission through the tube housing \(B_{\text{housing}}\) assume leakage kerma rate at 1 m through tube housing is

\[ \dot{K}_L(kVp) \propto kVp^2 I B_{\text{housing}}(kVp) \]

• Assume worst case scenario: leakage kerma rate = limit \(L\) for tube operation at leakage technique factors (conservative by factors of 3 to \(-\infty\))

New Leakage Model

• Estimate thickness of tube housing by using primary beam output at leakage technique factors as model for unhoused leakage radiation.

- Tube operated at 150 kVp, 3.3 mA
- Transmission through tube housing

New Leakage Model

• Write ratio of leakage kerma rates at any \(kVp\) to \(L\) at \(kVp_{\text{max}}\). Integrating over time, and knowing that at a given \(kVp\), workload \(W(kVp)\) is the time integral of the tube current: \(W(kVp) = \int I \, dt\)

- then unshielded leakage kerma \(\dot{K}_L\) (at 1 m) at that \(kVp\) is

\[ \dot{K}_L(kVp) = \frac{L \, kVp^2 \, (1-U) \, W(kVp) \, B_{\text{housing}}(kVp)}{kVp_{\text{max}}^2 \, I_{\text{max}} \, B_{\text{housing}}(kVp_{\text{max}})} \]

How far off is NCRP-49’s leakage model?
Secondary Transmission Curves

- NCRP-147 App. C gives transmission of secondary radiation
- Transmission of secondary radiation includes transmitted:
  - Scatter
  - Leakage
- Secondary transmission will always exceed the primary transmission at the same kVp because since it includes the more penetrating leakage radiation

For single kVp operation

- Must go to Simpkin and Dixon Health Phys. 74(3), 350–365, 1998, for secondary kerma per workload at 1 m at single kVp operation
- Go to Simpkin Health Phys. 68(5), 704-709, 1995, for primary beam transmission data
- All other data is available in NCRP 147
  - But be careful reading the tables in the report: $1.234 \times 10^1 = 12.34$

Single kVp Example

- Put a C-arm in pain clinic.
- Do we need shielding?
- Assume
  - 15 patients/wk, 2 minutes of fluoro per patient at 100 kVp, 2 mA operation
  - $W = 15 \text{ pat} \times 2 \text{ mA} \times 2 \text{ min/pat} = 60 \text{ mA/min/wk}$
  - $P/T = 0.02 \text{ mGy/wk}, d = 4 \text{ m}, 12'' II = 730 \text{ cm}^2$
  - II at 36'' = 0.91 m SID

- Total unshielded sec kerma in occupied area is
- Required transmission is
- Which (from fits in NCRP-147 App. C tables) reqs
  - 0.18 mm = 1/141'' Pb
  - 18 mm = 0.7'' standard density concrete
  - 53 mm = 2.1'' gypsum wallboard
Shielding Model No. 2

- For each clinical workload distribution, of total workload \( W_{\text{norm}} \) per patient, for both primary and secondary barriers, NCRP 147 provides:
  - \( K_1 \), the kerma per patient at 1 m distance
    - Primary kerma per patient \( K_P \) is in Table 4.5
    - Secondary kerma per patient \( K_{\text{sec}} \) is in Table 4.7
  - \( B \), the transmission of the radiation generated by this workload distribution for primary or secondary barriers (cf App B & C)

Shielding Model No. 2

- Ratio of \( P/T \) to \( K(0) \) is the required transmission
  \[
  B(x) = \frac{P/T}{K(0)} = \frac{P d^2}{N T UD} = \frac{P d^2 W_{\text{norm}}}{W_{\text{tot}} T UD}
  \]
  (again, \( U \) is replaced by 1 for secondary barriers)

- Transmission \( B \) is now a function of
  - barrier material and thickness
  - workload distribution
  - primary or secondary

Cath Lab Example: Wall

- Assume \( d=4 \) m, uncontrolled area \( P = 0.02 \) mGy wk\(^{-1}\), \( T=1 \), 12” =30.5 cm diameter image receptor, 90° scatter, \( N=25 \) patients wk\(^{-1}\)
- From Table 4.7, look up secondary kerma at 1 m per patient for Cath Lab distribution: \( K_{\text{sec}} = 2.7 \) mGy patient\(^{-1}\)
- Total unshielded weekly kerma is then
  \[
  K(0) = \frac{K_1 U N}{d^2} = \frac{K_1 U W_{\text{tot}}}{d^2 W_{\text{norm}}}
  \]
  (where \( U \) is replaced by 1 for secondary barriers)

- The unshielded kerma, \( K(0) \), for
  - \( N \) patient procedures (suggested values of \( N \) are in Table 4.3) or, equivalently
  - total workload \( W_{\text{tot}} \) (where workload/pat = \( W_{\text{norm}} \))
  - can tweak \( W_{\text{tot}} \) by a QE-specified different workload per patient, \( W'_{\text{tot}} \)
- Kerma is then
  \[
  K(0) = \frac{K_1 U N}{d^2} = \frac{K_1 U W_{\text{tot}}}{d^2 W_{\text{norm}}}
  \]

- Required transmission is
  \[
  B = \frac{P/T}{K(0)} = \frac{0.02 \text{ mGy wk}^{-1}}{4.22 \text{ mGy wk}^{-1}} = 0.0047
  \]
- Look on graph for transmission curve for secondary radiation from Cardiac Angiography Lab (Fig. C.2)→ Requires 1.2 mm Pb.

- Required transmission is
  \[
  B = \frac{P/T}{K(0)} = \frac{0.02 \text{ mGy wk}^{-1}}{4.22 \text{ mGy wk}^{-1}} = 0.0047
  \]
- Look on graph for transmission curve for secondary radiation from Cardiac Angiography Lab (Fig. C.2)→ Requires 1.2 mm Pb.
Example: Mammography Wall

- From §5.5, $K_{sec} = 0.036 \text{ mGy patient}^{-1}$ in any direction (for typical 4 view mammograms)
- Example: $N=150 \text{ patients wk}^{-1}$
- Shield adjacent office: $d = 7' = 2.1 \text{ m}$, $P = 0.02 \text{ mGy wk}^{-1}$, $T=1$
  - Then $K(0) = \frac{0.036 \text{ mGy pat}^{-1} \times 150 \text{ pat wk}^{-1}}{(2.1 \text{m})^2} = 1.2 \text{ mGy wk}^{-1}$
  - Requires: $B = \frac{P/T}{K(0)} = \frac{0.02 \text{ mGy wk}^{-1}}{1.2 \text{ mGy wk}^{-1}} = 0.017$
  - Look up barrier requirement on graph
    - 10 mm gypsum drywall

Example: Mammography Door

- $N=150 \text{ patients wk}^{-1}$
- Shield doorway: $d = 7' = 2.1 \text{ m}$, $P = 0.02 \text{ mGy wk}^{-1}$, $T=1/8$
  - Then $K(0) = \frac{0.036 \text{ mGy pat}^{-1} \times 150 \text{ pat wk}^{-1}}{(2.1 \text{m})^2} = 1.2 \text{ mGy wk}^{-1}$
  - Requires: $B = \frac{P/T}{K(0)} = \frac{0.02 \text{ mGy wk}^{-1}}{1.2 \text{ mGy wk}^{-1}}(1/8) = 0.13$
  - Look up barrier requirement on graph
    - 42 mm wood door

Shielding Model No. 3 for “Representative Rooms”

- Scheme No. 2 can’t handle complicated assemblages of x-ray tubes/positions/workload distributions, such as in a radiographic or radiographic/fluoroscopic room
- NCRP-147 calculates barrier thickness requirements for representative rooms:
  - Assume conservatively small room layout
    - assures maximum contribution from all sources
  - Presumes that the kinds of exposures made amongst the various x-ray tubes/positions follow those observed by the AAPM TG-9 survey
  - But user can tweak the workload by adjusting the number of patients/week
Consider *All* X-ray Sources in Room

Assume workload kVp distributions and use factors seen from 1996 Survey

Cram it into the world’s smallest possible x-ray room!*

Include all sources in the calculation

“Representative R&F Room”

“Representative R&F Room”

*to conservatively maximize the contributions of the various x-ray beams

Vary \( N \), and find required control booth barriers as function of \( NT/(Pd^2) \). Graph results.

\*e.g. For this Control Booth calculation as a “2% primary barrier”, include:
1. Primary radiation with 2% of the workload
2. Secondary radiation from over-table and cross-table lateral work
3. Secondary radiation from wall bucky work
(Assume workload distributions and use factors from TG9 survey.)
“Representative Room”
Barrier Requirements

- From Model 2, transmission requirement is
  \[ B(x) = \frac{P d^2}{NTUK^2} \]
- so the barrier thickness requirement must scale as:
  \[ \frac{NT}{P d^2} \]

There are 12 \( NT/Pd^2 \) graphs

- For Representative Radiographic and R&F Rooms:
  - For Lead and Concrete:
    - Primary barriers with preshielding
    - Primary barriers without preshielding
    - Secondary barriers
From where is \( d \) measured?*

<table>
<thead>
<tr>
<th>Primary Barriers</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor</td>
<td>overhead radiographic tube</td>
</tr>
<tr>
<td>Chest Bucky wall</td>
<td>chest tube (72(^\circ) SID)</td>
</tr>
<tr>
<td>Crossable Lateral Wall</td>
<td>cross-table tube (40(^\circ) SID)</td>
</tr>
<tr>
<td>2% U wall</td>
<td>center of table</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Secondary Barriers</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor</td>
<td>patient on table</td>
</tr>
<tr>
<td>Chest Bucky secondary wall</td>
<td>chest tube (72(^\circ) SID)</td>
</tr>
<tr>
<td>Secondary Wall</td>
<td>patient on table</td>
</tr>
<tr>
<td>Ceiling</td>
<td>patient on table</td>
</tr>
</tbody>
</table>

*Not in NCRP-147

Equivalency of Shielding Materials

- For “representative room” calculations, conservatively conclude
  - **Steel** thickness requirement = \( 8 \times \text{Pb} \) thickness requirement
  - **Gypsum wallboard** thickness requirement = \( 3.2 \times \text{concrete} \) thickness requirement
  - **Glass** thickness requirement = \( 1.2 \times \text{concrete} \) thickness requirement
- But ONLY for these representative room calculations!

Example: Radiographic Room

\( N = 113 \text{ pat/wk} \)

Slab on-grade

Single story

Sample Rad Room

Control Booth

- Assume Control Booth = “\( U=2\% \) wall”
- Assume \( d = 8 \text{ ft} = 2.44 \text{ m} \), \( P = 0.02 \text{ mGy wk}^{-1} \) (to be conservative), \( T=1 \), with \( N = 113 \) patients/wk
- Then
  \[
  NT = \frac{113 \text{ pat wk}^{-1} \times 1}{0.02 \text{ mGy wk}^{-1} \times (2.44 \text{ m})^2} = 950 \text{ mGy}^{-1} \text{ m}^{-2}
  \]
- Look up Pb barrier requirement on graph

\( T=1, \text{ uncontrolled} \)
**Example: Radiographic Room**

Doorway, $T=$1/8, uncontrolled

**Sample Rad Room**

Room Door; Protect Corridor

- Assume door = “$U=2\%$ wall”
- Assume $d=$7 ft $=2.13$ m (conservatively measure from chest bucky tube), $P=0.02$ mGy wk$^{-1}$, $T=1/8$, with $N=113$ patients wk$^{-1}$
- Then
  \[ NT = \frac{113 \text{ pat wk}^{-1} \times 1/8}{0.02 \text{ mGy wk}^{-1} \times (2.13 \text{ m})^2} = 155 \text{ mGy}^{-1} \text{ m}^{-2} \]
- Look up Pb barrier requirement on graph

**Example: Radiographic Room**

Office, $T=$1, uncontrolled

**Sample Rad Room**

Room Door; Protect Distant Office

- Assume Door = “$U=2\%$ wall”
- Assume $d=$16 ft $=4.88$ m (conservatively measure from chest bucky tube), $P=0.02$ mGy wk$^{-1}$, $T=1$, with $N=113$ patients wk$^{-1}$
- Then
  \[ NT = \frac{113 \text{ pat wk}^{-1} \times 1}{0.02 \text{ mGy wk}^{-1} \times (4.88 \text{ m})^2} = 237 \text{ mGy}^{-1} \text{ m}^{-2} \]
- Look up Pb barrier requirement on graph

Requires 0.28 mm Pb in door

Need 0.36 mm Pb in door, so the more distant $T=1$ office sets the requirement
Fits of the $NT/(Pd^2)$ Graphs

- Similarly, it may be acceptable to fit the joint pri/sec barrier requirements for the Representative Radiographic and R&F rooms in Fig. 4.5–4.8 of the report as well as requirements for Cardiac Angiography units with various sized image receptors to the Archer equation, yielding a new set of $\alpha$, $\beta$, and $\gamma$ fitting parameters.
- Here $\eta_0$ = max value of $NT/(Pd^2)$ requiring no shielding.
- This equation can be inverted, i.e. $NT/(Pd^2)$ written as a function of $x$ (but note $1/\gamma$ exponent).

CT Scanner Shielding: A Teaser

- Estimate unshielded weekly kerma in occupied area near scanner, $K_{un}$
  - I urge you to use the DLP method, since it’s trivial!
- Presume $P/T$
- Barrier requires transmission
- Get barrier thickness
  - Data in NCRP Rept 147 from Simpkin Health Phys 58, 363–7: 1990 (refit)
- More from Donna Stevens & Doug Shearer in a moment…
CT Scanner Floors and Ceilings are often too thin!

ADD Pb to ceiling (~1/32")

“Normal” wall shielding to 7 ft

ADD Pb to floor (~1/32")

-- typ 10 ft -->

CT Scanner

CT Scanner in a Shielding Cave

ADD Pb to wall above 7 ft (~1/32")

“Normal” wall shielding to 7 ft

ADD Pb to ceiling (~1/32")

-- typ 10 ft -->

ADD Pb to floor (~1/32")

Surveys

• After installation of the shielding barriers, NCRP-147 states that a qualified expert should assure that the barriers are
  – Free of voids
  – Of adequate attenuation
• More later from Mark Towsley...

Conclusions I

• Design goals, $P$:
  – Controlled areas = 0.1 mGy/wk
  – Uncontrolled areas = 0.02 mGy/wk
• Reasonable occupancy factors, $T$:
  – for individuals in uncontrolled areas
  – effect is to increase kerma to $P/T$
• Transmission, $B$, is ratio of kerma with and without shielding
  – fit to Archer equation
  – “hard” HVL results from beam hardening

Conclusions II

• Workload, $W$
  – measures tube usage
  – at a given kVp, kerma $\propto W$
  – $W$ distributed over range of kVp; determines
    • unshielded kerma
    • transmission
  – Workload survey of early 1990s is in Report
    • Total workload $\leq 1000$ mA·min/wk
    • May need adjusting with technology changes
  – in radiographic room, chest bucky gets ~all the high kVp exposures

Conclusions III

• Primary radiation
  – Can account for shielding due to image receptor
• Secondary radiation
  – Scatter
  – Leakage (greatly improved model)
• Shielding models in NCRP-147
  – NCRP-49 extensions
  – Unshielded kerma per patient
  – $NT/Pd^2$ for “representative” rad & R&F rooms
Conclusions IV

• 1/16 inch Pb remains as standard wall barrier for radiographic, fluoro, and interventional suites
• If cassette/grid/table attenuation is assumed, typical standard density concrete floors suffice
• Mammography
  – standard construction gypsum wallboard walls suffice
  – solid core wood doors suffice

Conclusions V

• CT
  – estimates of unshielded kerma made from
    • manufacturer’s isoexposure curves
    • Shearer’s scatter fraction applied to CTDI/ DLP
  – workload is high (100-200 patients/wk)
  – transmission data available in report
  – results
    • 1/16 inch Pb remains as standard wall barrier
    • Floors & ceilings may need attention
    • May need to run Pb up walls to ceiling

Conclusions VI

• Consult your regulatory agency!
  – Most state codes require prior blessing of shielding designs
  – To the best of my understanding, there’s only 1 shielding QE (per the NCRP Rep. No. 147 definition) in any of the state radiation protection departments
• Regardless, we need to partner with the regulators to assure the safety of our installations