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NCRP 147 Shielding Calculations

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History - NCRP Report # 49

- 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
History - NCRP Report #147

- Draft completed 2002; 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?
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* 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, \( P \)

- Accepted 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
  - vs NCRP-151 where \( P \) is a dose equivalent

<table>
<thead>
<tr>
<th>Design Goal ( P )</th>
<th>Controlled area</th>
<th>Uncontrolled areas</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>NCRP-49</strong></td>
<td>50 mGy/y =1 mGy/wk</td>
<td>5 mGy/y =0.1 mGy/wk</td>
</tr>
<tr>
<td><strong>NCRP-147</strong></td>
<td>( Fraction \ (=\frac{1}{2}) ) of 10 mGy/yr limit for new operations = 5 mGy/yr (~matches fetal dose limit) = 0.1 mGy/wk</td>
<td>1 mGy/y = 0.02 mGy/wk</td>
</tr>
<tr>
<td><strong>Effect</strong></td>
<td>Factor of 10 decrease</td>
<td>Factor of 5 decrease</td>
</tr>
</tbody>
</table>
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 \( P/T \)

<table>
<thead>
<tr>
<th>Recommended Occupancy Factors</th>
<th>( T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Offices, labs, pharmacies, receptionist areas, attended waiting rooms, kids’ play areas, 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>½</td>
</tr>
<tr>
<td><strong>Corridors</strong>, patient rooms, employee lounges, staff rest rooms</td>
<td>1/5</td>
</tr>
<tr>
<td><strong>Corridor doors</strong></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

\[ B(x) = \frac{K(x)}{K(0)} \]
### 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
  
  $W_{tot} = 3047 \text{ mA} \cdot \text{min/wk}$ for $N = 20 \text{ patients/wk}$

Workload Distribution, $W(kVp)$

- General Radiographic Room; all barriers in room
  
  $W_{tot} = 277 \text{ mA} \cdot \text{min/patient}$ for $N = 112 \text{ patients/wk}$
General Radiographic Room
Workload Distribution, $W(kVp)$

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

Note: high kVp content of workload against chest bucky

• and...

General Radiographic Room
Workload Distribution, $W(kVp)$

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

Note: very little high kVp content of workload against anything but chest bucky
Update on Workload Data

• Since the workload survey was published over a decade ago, the digital revolution has occurred in radiographic imaging
  – 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
  – Greater through-put in number of patients in each room =
    • More patients per week in each room
    • Fewer radiographic rooms (!)

Update on Workload Data

• 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/mA·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!

0.5 m = 1.6 ft

0.3 m = 1 ft

1.7 m = 5.6 ft

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. \( NT/(Pd^2) \)
1\textsuperscript{st} 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 \{\textit{Secondary radiation}\}

Primary, Scatter, and Leakage

Must protect from primary radiation

Must protect from scatter & leakage radiation
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 $x_{\text{pre}}$ gives same transmission as that seen for actual image receptors.

$$x_{\text{tot}} = x + x_{\text{pre}}$$
Primary Transmission Through Patient, Image Receptor, and Supports

Data of Dixon (1994)

No patient & grid & cassette:
B = 4.7E-6 kVp \(2.181\)

No patient & grid & cassette & cassette support structures & radiographic table:
B = 9.36E-13 kVp \(4.917\)

Values of \(x_{\text{pre}}\) (Grid+cassette+support)

(x_pre: Pre-exposure value)

- **Gypsum**
- **Plate Glass**
- **Concrete**
- **Steel**
- **Lead**

Graph shows the relationship between transmission and kVp for different types of radiographic tables.
Scatter Radiation

Scaled Normalized Scatter Fraction
Leakage Radiation

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

How far off is NCRP-49’s leakage model?
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: $K_{sec}^{1} = 2.7$ mGy patient$^{-1}$
- Total unshielded weekly kerma is then
  \[
  K(0) = \frac{2.7 \text{ mGy pat}^{-1} \times 25 \text{ pat wk}^{-1}}{(4m)^2} = 4.22 \text{ mGy wk}^{-1}
  \]

Cath Lab Example: Wall

- 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.
$B = 0.0047$

$x = 1.2 \text{ mm Pb}$

$B = 0.017$

Requires 10 mm wallboard
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
Shielding Model No. 3 for “Representative Rooms”

- 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

Representative Radiographic Room

- Secondary Barrier
- Cross-table Lateral Wall
- Primary Wall
- Bucky Wall
- Chest Wall
- U=2% primary wall
Representative Radiographic Room

Rad Room: Chest Bucky

Cross-table Lateral Position
$U=9\%$

Over-table Position
$U=89\%$ shooting down at floor

(Another primary wall gets $U=2\%$ of the floor/other barrier distribution; assume tube is centered over-table)

Rad Room: floor/other barriers applies to Over-table and Cross-table positions

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Representative Radiographic Room

The world's smallest possible x-ray room!
“Representative R&F Room”

- Also consider a “Representative R&F room”
  - Has same layout as “Standard Radiographic Room except an under-table fluoro x-ray tube and image intensifier are added, centered over table
  - Does fluoro as well as standard radiographic work, with table and chest bucky and cross-table work

- Assume
  - 75% of patients imaged as if in radiographic room
  - 25% of patients imaged by fluoroscopy tube
Equivalency of Shielding Materials

- From “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 = $1.2 \times \text{concrete thickness requirement}$
Example: Radiographic Room

- \( N = 113 \) pat/wk
- Slab on-grade
- Single story

Sample Rad Room
Control Booth

- Assume Control Booth = “\( U = 2\% \) wall”
- Assume \( d = 8 \) ft = 2.44 m, \( P = 0.02 \) mGy wk\(^{-1}\) (to be conservative), \( T = 1 \), with \( N = 113 \) patients/wk
- Then
  \[
  \frac{NT}{Pd^2} = \frac{113 \text{ pat wk}^{-1} \times 1}{0.02 \text{ mGy wk}^{-1} \times (2.44 \text{ m})^2} = 950 \text{ mGy}^{-1} \text{ m}^{-2}
  \]
- Look up Pb barrier requirement on graph
Requires 0.67 mm = 1/38” Pb in wall/window

Example: Radiographic Room

Doorway, $T=1/8$, uncontrolled
CT Scanners: Estimate Unshielded Kerma

- Estimate ambient kerma around scanner
  - Manufacturer’s isoexposure curves
    - extrapolate using $1/r^2$ from isocenter
    - scale by mAs used clinically vs. for isoexposure curve
    - varies with phantom!

CT Scanner in a Shielding Cave

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

ADD Pb to ceiling (~1/32")

ADD Pb to floor (~1/32")
Surveys

• After installation of the shielding barriers, a qualified expert should assure that the barriers are
  – Free of voids
  – Of adequate attenuation

Surveys For Voids

• Are the barriers are free of voids?
  – Visual inspection prior to walls/ceiling being closed up
  – Radiation survey with GM or scintillation survey meter looking at penetration of barrier
    • x rays from installed equipment or portable
    • gamma rays from a nuclear source (licensing?)
Surveys For Voids

- Watch for:
  - Unshielded line-of-site from source to occupied area (e.g. installation ≠ plans)
  - Leaded drywall sheets (4’x8”) installed upside down (so 1’ of Pb doesn’t contact the floor)
  - Improper lapping of Pb between adjacent drywall sheets
  - Improper wrapping of leaded door/window frames, electrical boxes, plumbing, air ducts, etc.
  - Holes

Surveys For Adequacy

- Assure that thickness of barrier material installed will decrease kerma in occupied area to $\leq P/T$
  - Visual inspection (prior to walls being closed) may confirm barrier thickness
  - After installation is complete, can measure transmission through installed barrier using portable x-ray unit
- Can repeat shielding calculation with that transmission/barrier thickness to assure that barrier is adequate for presumed number of patients
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 kermas 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 $\neq 1000$ 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