2007 AAPM Summer School

Overview and Basis of Design for NCRP Report 147

Douglas J. Simpkin, Ph.D.
Aurora St. Luke's Medical Ctr
Milwaukee, WI
dsimpkin@wi.rr.com
http://www.geocities.com/djsimpkin/

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!*

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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"

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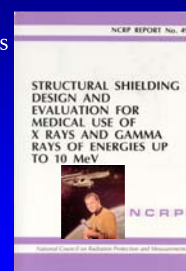
History of Diagnostic X-ray Shielding Design

- 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



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History – NCRP/ AAPM Task Group 1992-2004

- 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

Ben Archer, Linc Hubbard, Bob Dixon & I meet at Bob's beach house (off season... Can you tell the Yankees from the Southerners?)

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NCRP-147 Cochairs

- Joel Gray
  - clinical/ industry medical physicist
- Ben Archer
  - clinical medical physicist

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NCRP-147 Membership

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

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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

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NCRP-147 Consultants

- Marv Rosenstein, NCRP
- Andrew Poznanski, M.D…..(*who*?)
- Ken Kase
  - *Helped shepherd the report through it's 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)

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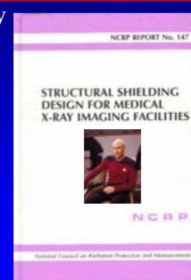
History - NCRP Report #147

- 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)



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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!*

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Exponential Attenuation of X rays

- No barrier will *completely* eliminate the radiation dose outside a diagnostic x-ray room
- *What is safe?*

Typical x-ray tech upon hearing that he's still getting some dose in the control booth

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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.

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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

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Design Goal, *P*

	Controlled Area	Uncontrolled Area
NCRP-49 1976	50 mGy/y = 1 mGy/wk	5 mGy/y = 0.1 mGy/wk
NCRP-147 2004	*Fraction* (=½) of 10 mGy/y limit for new operations = 5 mGy/y (~matches fetal dose limit) = 0.1 mGy/wk	1 mGy/y = 0.02 mGy/wk
Effect	*Factor of 10 decrease*	*Factor of 5 decrease*

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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."

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NCRP Statement 10 (2004)

- In Statement No. 10 *Recent Applications of 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*

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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

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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

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

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

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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

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Recommended Occupancy Factors

Offices, labs, pharmacies, receptionist areas, attended waiting rooms, kids' play areas, x-ray rooms, film reading areas, nursing stations, x-ray control rooms	1
Patient exam & treatment rooms	½
Corridors, patient rooms, employee lounges, staff rest rooms	1/5
Corridor doors	1/8
Public toilets, vending areas, storage rooms, outdoor areas w/ seating, unattended waiting rooms, patient holding	1/20
Outdoors, unattended parking lots, attics, stairways, unattended elevators, janitor's closets	1/40

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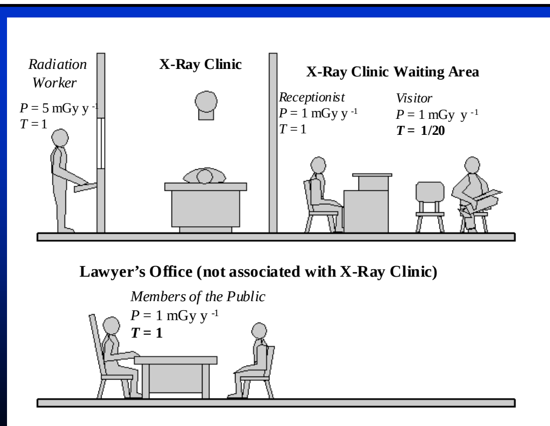
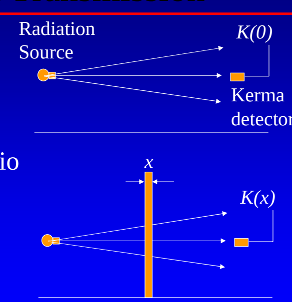


X-ray Beam Transmission

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

$$B(x) = \frac{K(x)}{K(0)}$$



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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)

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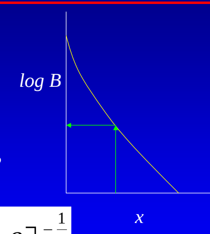
Archer Equation for Transmission Curves

- Archer et al. presented a very useful equation for describing transmission data *B* fit to barrier thickness *x* in 3 parameters (α, β, γ)



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

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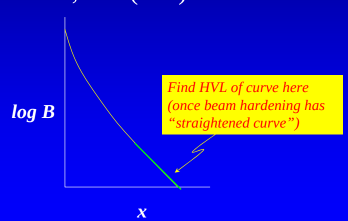
Archer Equation for Transmission Curves

- Note: α is the slope of the transmission curve at large *x*. Therefore, α = (ln 2) / "Hard HVL"



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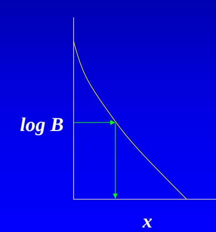
Archer Equation for Transmission Curves

- This can be inverted to solve for *x*

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



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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

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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

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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

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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

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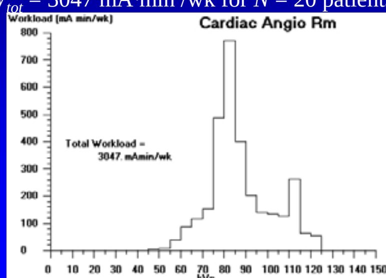
Workload Distribution, *W(kVp)*

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



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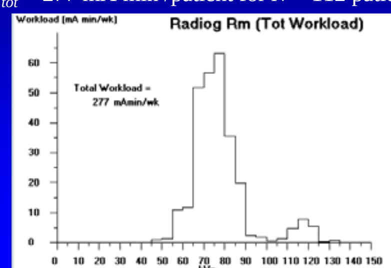
Workload Distribution, *W(kVp)*

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



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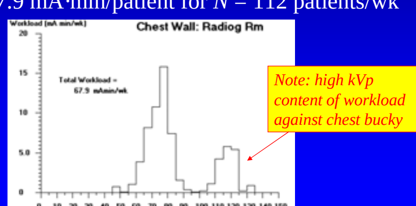
General Radiographic Room Workload Distribution, *W(kVp)*

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



- *and...*

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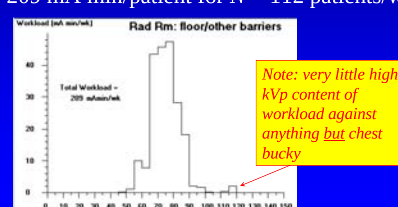
General Radiographic Room Workload Distribution, *W(kVp)*

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



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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 (!)

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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…

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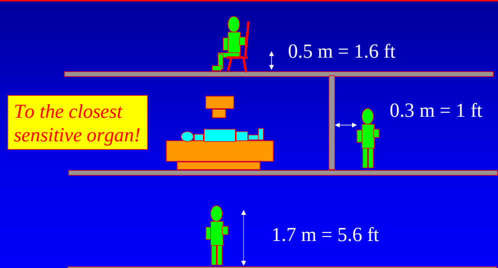
Where in the occupied area do you calculate the kerma?



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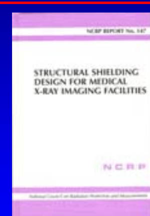
Models for Diagnostic X-Ray Shielding Calculations



Yes

No

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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/(Pd²)*

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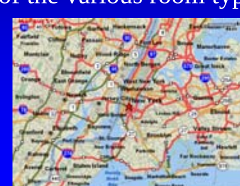
The Three Models In NCRP 147

- 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



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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** } *Secondary radiation*
  - **leakage radiation**

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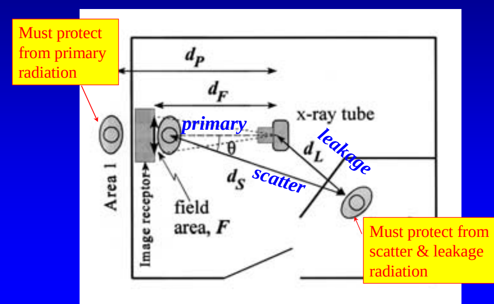
Primary, Scatter, and Leakage



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1st principle extensions to NCRP 49

- The models for primary, scatter, and leakage in NCRP-147 are extensions to what's in NCRP-49
  - x-ray tubes operating over ranges of potentials ("workload distribution")
  - new model for image receptor attenuation
  - new model for leakage

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1st principle extensions to NCRP 49

- 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*,

$$K(x) = \sum_{tubes} \sum_{kVp} \left(K_P(x) + K_S(x) + K_L(x) \right)$$

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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

$$K(x) = \sum_{tubes} \sum_{kVp} \left(K_P(x) + K_S(x) + K_L(x) \right) = \frac{P}{T}$$

- cf. *http://www.geocities.com/djsimpkin/* for shareware *XRAYBARR* to do this
  - *"Dose" in XRAYBARR = "Kerma" in NCRP-147*

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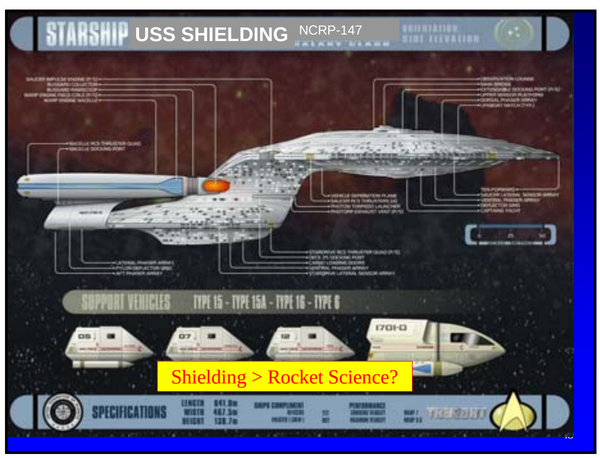
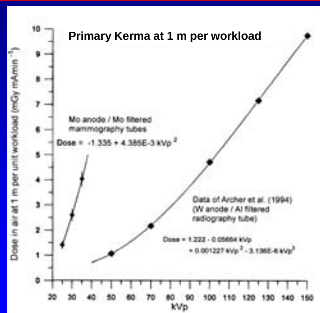


Primary Radiation Model

- 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, $K_P(0) = \dfrac{K_W(kVp)\,W(kVp)}{d_P^2}$
- 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

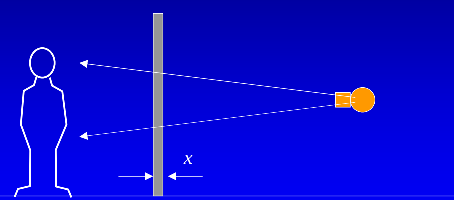
- The kerma behind a primary barrier of transmission *B(x, kVp)* is

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

- For the whole distribution of workloads, total kerma is

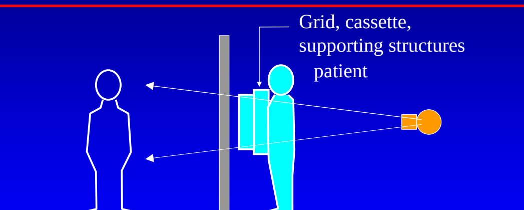
$$K_P(x) = \sum_{kVp} \frac{K_W(kVp)\,U\,W(kVp)}{d_P^2}\,B(x,kVp)$$

Primary Radiation: The NCRP49 Model



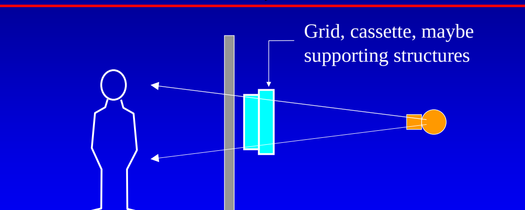
Barrier of thickness *x* decreases raw primary radiation kerma to *P/T*

Primary Radiation: A Realistic Model



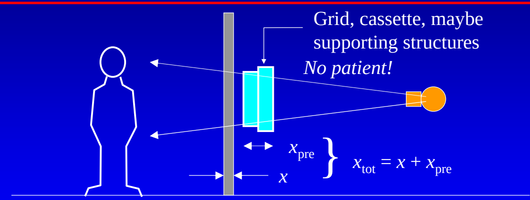
Primary radiation is significantly attenuated before reaching barrier

Primary Radiation: A Conservative, Realistic Model

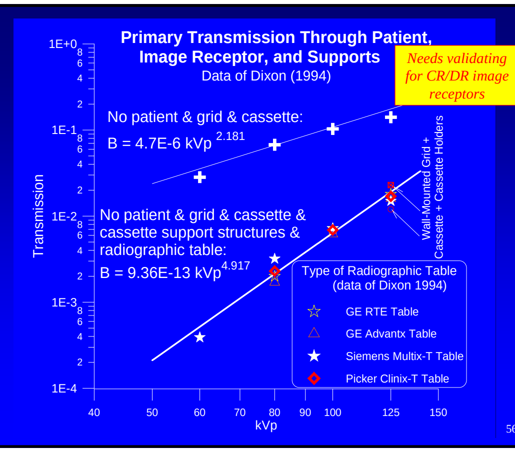


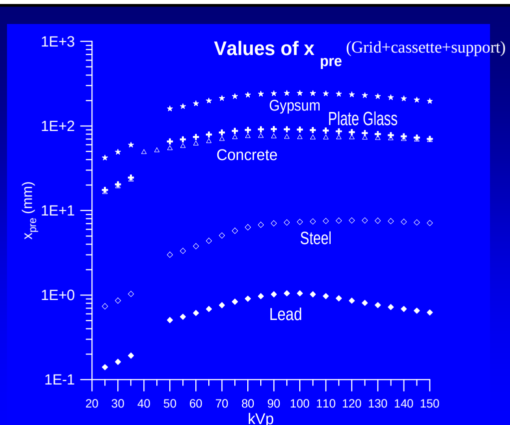
Even without the patient, primary radiation is *still* significantly attenuated before reaching barrier

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.





x_{pre} for Radiographic Room Workload Distributions

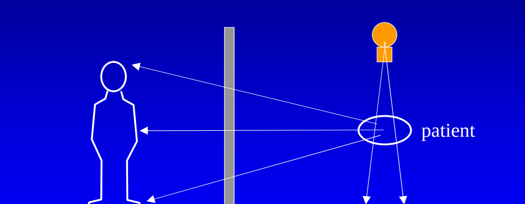
- From Table 4.6:
  - Grid + cassette:
    - 0.3 mm Pb
    - 30 mm concrete
  - Grid + cassette + table/chest bucky supports:
    - 0.85 mm Pb
    - 72 mm concrete

Calculation of Primary Kerma

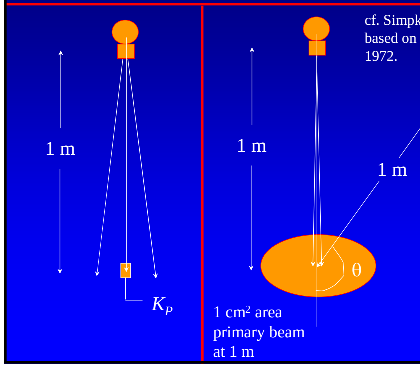
- Same as model in NCRP49 *except*
  - account for workload distribution in kVp
  - QE *may* account for image receptor shielding x_{pre}
- Primary kerma in occupied area is then

$$K_P(x+x_{pre}) = \frac{1}{d_P^2}\sum_{kVp} K_W(kVp)\,U\,W(kVp)\,B(x+x_{pre},kVp)$$

Scatter Radiation



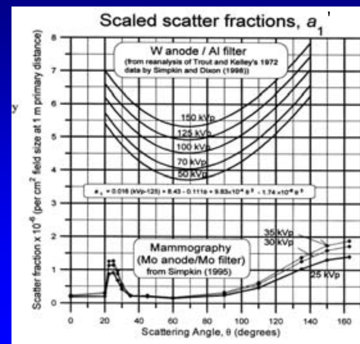
Scaled Normalized Scatter Fraction



cf. Simpkin & Dixon, *HP* 1998, based on data of Kelly & Trout, 1972.

$$a_1' = \frac{K_S}{K_P}$$

Scaled Normalized Scatter Fraction



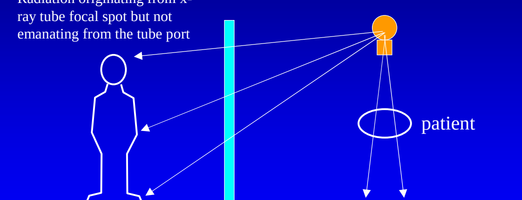
Scatter Radiation

- 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

$$K_S(x,\theta) = \sum_{kVp} \frac{a_1' \times K_W(kVp)\, W(kVp)}{d_S^2} \frac{F}{d_F^2} B(x,kVp)$$

Leakage Radiation

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



Leakage radiation

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

Leakage radiation

- 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

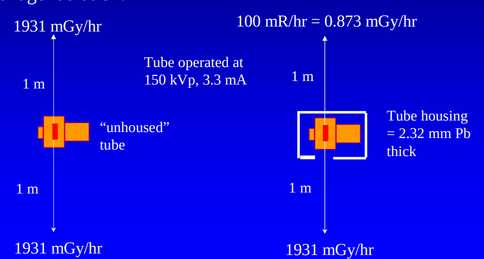
- For tube operating at techniques (*kVp, I)* with transmission through the tube housing B_{housing}, assume leakage kerma rate at 1 m through tube housing is

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

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

New Leakage Model

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



New Leakage Model

- Write ratio of leakage kerma rates at any *kVp* to *L* at kVp_{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 K_L (at 1 m) at that kVp is

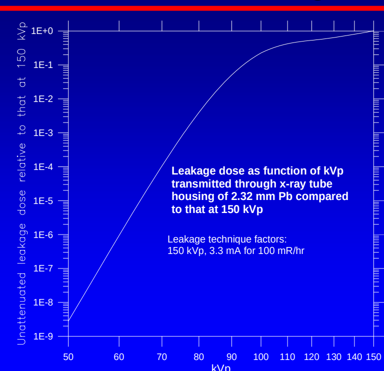
$$K_L(kVp) = \frac{L\ kVp^2\ (1-U)\ W(kVp)\ B_{\text{housing}}(kVp)}{kVp_{\max}{}^2\ I_{\max}\ B_{\text{housing}}(kVp_{\max})}$$

New Leakage Model

- Applying inverse square to distance d_L from tube to shielded area,
- and putting a barrier with transmission exp(–ln(2)*x*/*HVL*) between tube & area yields

$$K_L(kVp) = \frac{L\ kVp^2\ (1-U)\ W(kVp)\ B_{\text{housing}}(kVp)}{kVp_{\max}{}^2\ I_{\max}\ B_{\text{housing}}(kVp_{\max})} \times \frac{1}{d_L^2} \times \exp\left(\frac{-\ln(2)\ x}{HVL(kVp)}\right)$$

How far off is NCRP-49's leakage model?

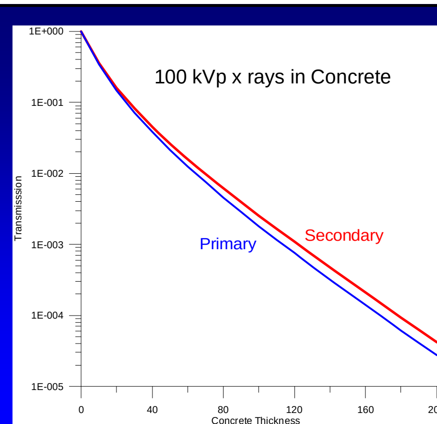


Note:

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***

73



74

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: $1.234 \times 10^1 = 12.34$*

75

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 pat × 2 mA × 2 min/pat = 60 mAmin/wk
  - *P/T* = 0.02 mGy/wk, d = 4 m, 12" II = 730 cm^2 II at 36" = 0.91 m SID

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Single kVp Example

- From Simpkin & Dixon *Health Phys* 1998, unshielded secondary kerma per mAmin at 1 m from a beam of 1000 cm^2 size, 100 kVp, is
  - Forward/back scatter = 3.17×10^{-2} mGy/mAmin
  - Leakage = 9.9×10^{-4} mGy/mAmin
- For our SID and field size, the scatter kerma is

$$K^1_{scatt} = 3.17\times10^{-2}\, mGy \times \left(\frac{730\,cm^2}{1000\,cm^2}\right)\times\left(\frac{1\,m}{0.914\,m}\right)^2 = 2.77\times10^{-2}\,\frac{mGy}{mA\min}$$

- So total secondary kerma at 1 m is =
  - $K^1_{sec} = 2.77\times10^{-2} + 9.9\times10^{-4} = 2.87\times10^{-2}$ mGy/mAmin

77

Single kVp Example

- Total unshielded sec kerma in occupied area is

$$K(0) = \frac{2.87\times10^{-2}\,\frac{mGy}{mA\min}\times 60\,\frac{mA\min}{wk}}{(4m)^2} = 0.107\,\frac{mGy}{wk}$$

- Required transmission is

$$B(x) = \frac{0.02\,mGy/wk}{0.107\,mGy/wk} = 0.186$$

- 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

(for secondary transmission)

78

Shielding Model No. 2

- For each clinical workload distribution, of total workload W_{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 $K_P^{\,1}$ is in Table 4.5
    - Secondary kerma per patient $K_{sec}^{\,1}$ 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)

79

Shielding Model No. 2

- The unshielded kerma, *K(0)*, for
  - N patient procedures (suggested values of N are in Table 4.3) or, equivalently
  - total workload W_{tot} (where workload/pat = W_{norm})
  - can tweak W_{tot} by a QE-specified different workload per patient, W_{site}
- Kerma is then $K(0) = \dfrac{K^1 U N}{d^2} = \dfrac{K^1 U W_{tot}}{d^2 W_{norm}}$
  - (where U is replaced by 1 for secondary barriers)

80

Shielding Model No. 2

- Ratio of *P/T* to *K(0)* is the required transmission

$$B(x) = \frac{P/T}{K(0)} = \frac{P d^2}{N T U D^1} = \frac{P d^2 W_{norm}}{W_{tot} T U D^1}$$

  - *(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**

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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

$$K(0) = \frac{2.7\ mGy\ pat^{-1} \times 25\ pat\ wk^{-1}}{(4m)^2} = 4.22\ mGy\ wk^{-1}$$

82

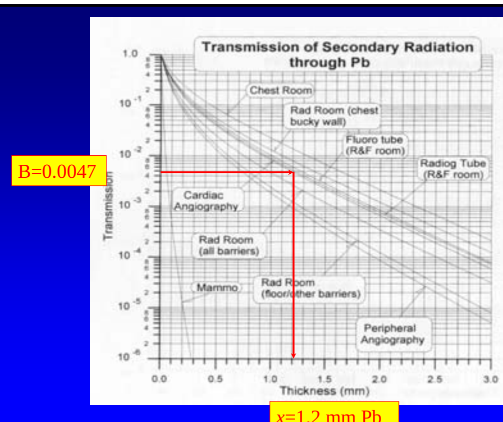
Cath Lab Example: Wall

- Required transmission is

$$B = \frac{P/T}{K(0)} = \frac{0.02\ mGy\ wk^{-1}}{4.22\ mGy\ wk^{-1}} = 0.0047$$

- Look on graph for transmission curve for secondary radiation from Cardiac Angiography Lab (Fig. C.2)→ Requires 1.2 mm Pb.

83

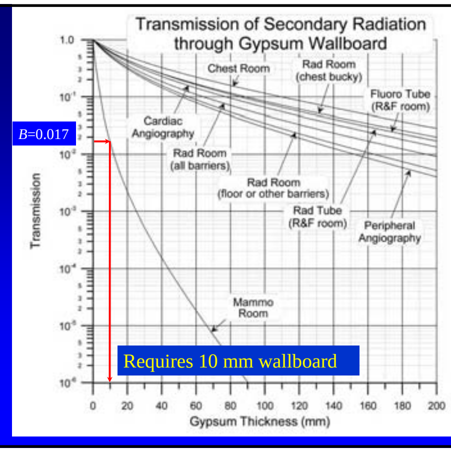


84

Example: Mammography Wall

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

85

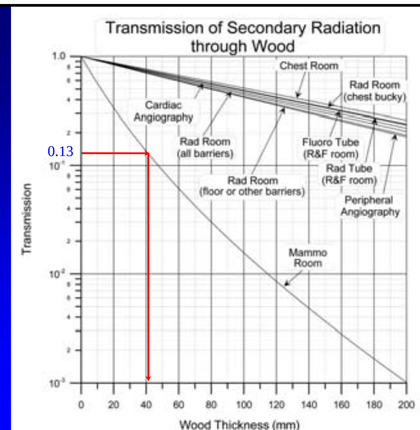


86

Example: Mammography Door

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

87



88

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

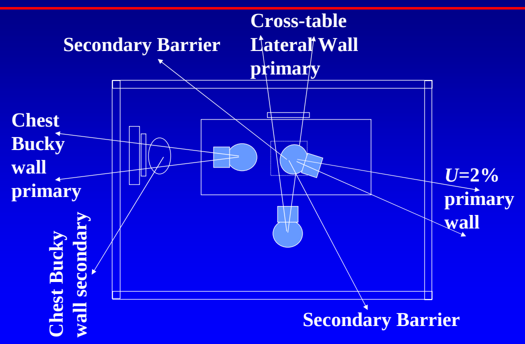
89

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*

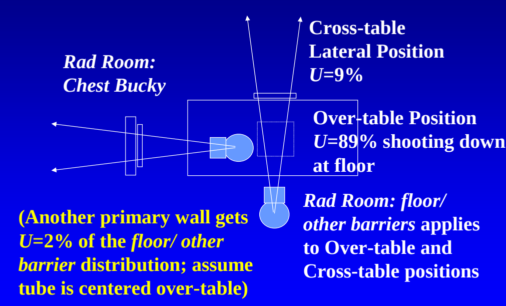
90

Consider *All* X-ray Sources in Room



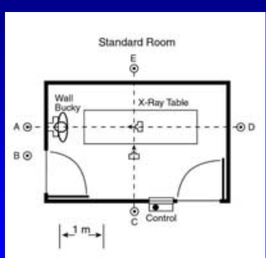
91

Assume workload kVp distributions and use factors seen from 1996 Survey

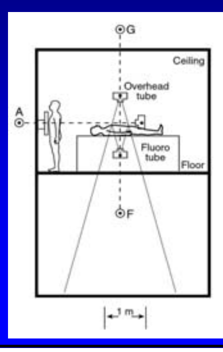


92

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

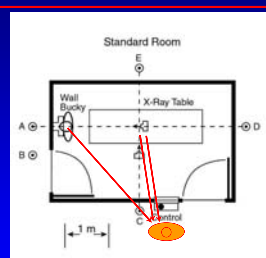


**to conservatively maximize the contributions of the various x-ray beams*



93

Include *all* sources in the calculation



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.)

Vary *N*, and find required control booth barriers as function of *NT/(Pd²)*. Graph results.

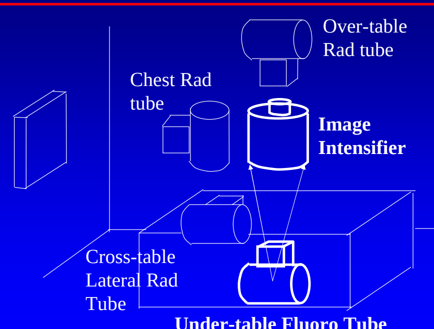
94

"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

95

"Representative R&F Room"



96

“Representative Room” Barrier Requirements

- From Model 2, transmission requirement is

$$B(x) = \frac{P d^2}{N T U K^1}$$

- so the barrier thickness requirement must scale as: $\frac{N T}{P d^2}$

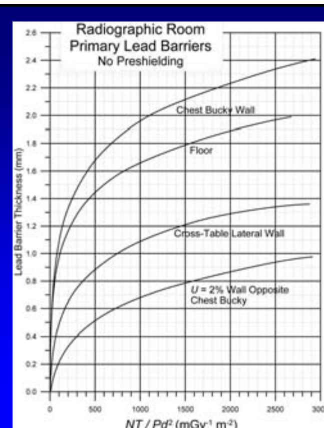
97

98

There are 12 *NT/Pd²* graphs

- For Representative **Radiographic** and **R&F** Rooms:
  - For **Lead** and **Concrete**:
    - Primary barriers with preshielding
    - Primary barriers without preshielding
    - Secondary barriers

99



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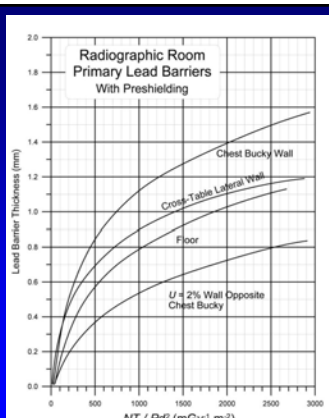

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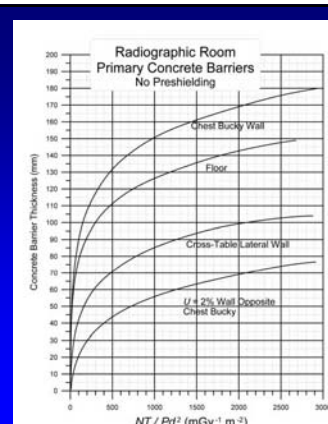

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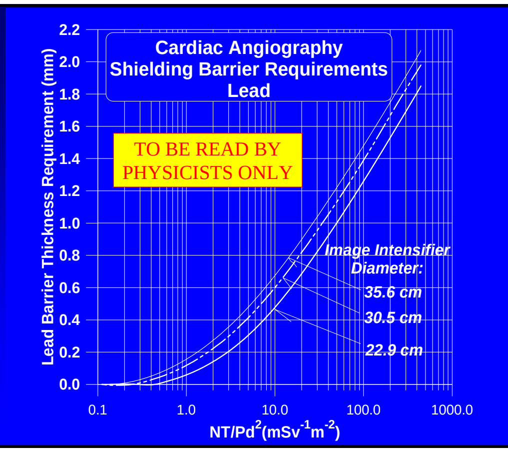


)3

From where is *d* measured?*

Primary Barriers	
Floor	overhead radiographic tube
Chest Bucky wall	chest tube (72" SID)
Crosstable Lateral Wall	cross-table tube (40" SID)
2% U wall	center of table

Secondary Barriers	
Floor	patient on table
Chest Bucky secondary wall	chest tube (72" SID)
Secondary Wall	patient on table
Ceiling	patient on table

** Not in NCRP-147*

104

Equivalency of Shielding Materials

- For "representative room" calculations, conservatively conclude
  - **Steel** thickness requirement = 8 × **Pb thickness** requirement
  - **Gypsum wallboard** thickness requirement = 3.2 × **concrete** thickness requirement
  - **Glass** thickness requirement = 1.2 × **concrete** thickness requirement
- **But ONLY for these representative room calculations!**

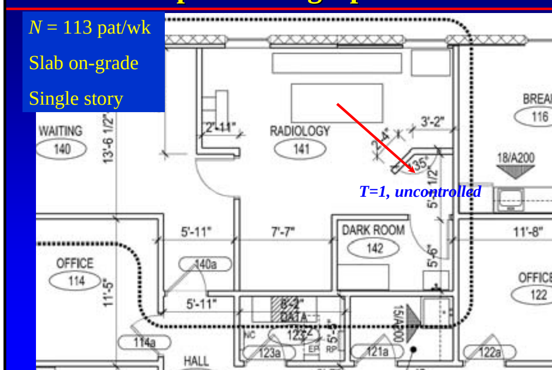
105

Example: Radiographic Room

N = 113 pat/wk

Slab on-grade

Single story



106

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

$$\frac{NT}{Pd^2} = \frac{113\ pat\ wk^{-1} \times 1}{0.02\ mGy\ wk^{-1} \times (2.44\ m)^2} = 950\ mGy^{-1}\ m^{-2}$$

- Look up Pb barrier requirement on graph

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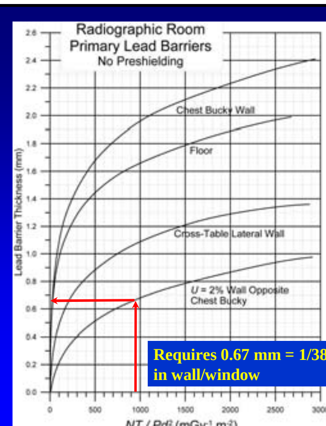
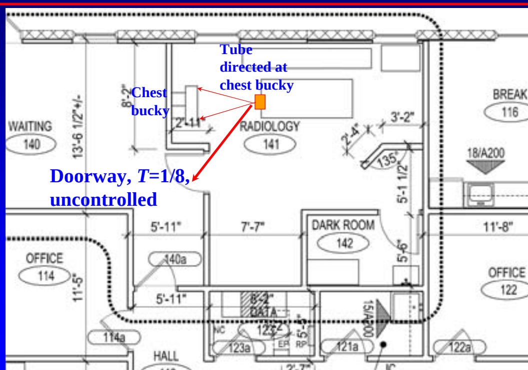


Requires 0.67 mm = 1/38" Pb in wall/window

108

Example: Radiographic Room



109

Sample Rad Room

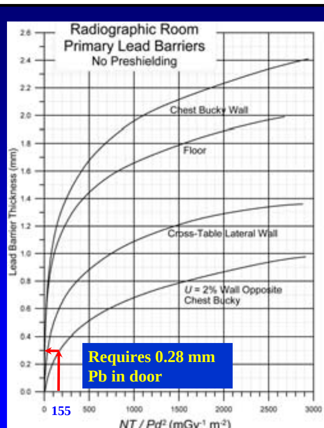
Room Door; Protect Corridor

- 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

$$\frac{NT}{Pd^2} = \frac{113\ pat\ wk^{-1} \times 1/8}{0.02\ mGy\ wk^{-1} \times (2.13m)^2} = 155\ mGy^{-1}\ m^{-2}$$

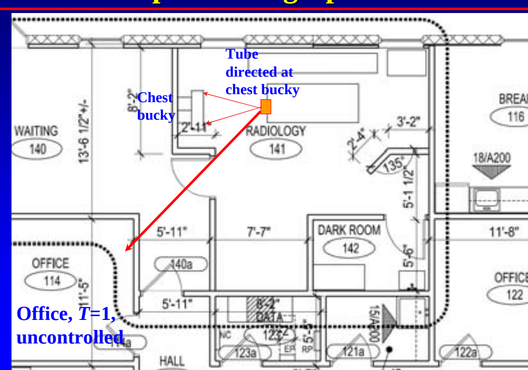
- Look up Pb barrier requirement on graph

110



111

Example: Radiographic Room



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Sample Rad Room

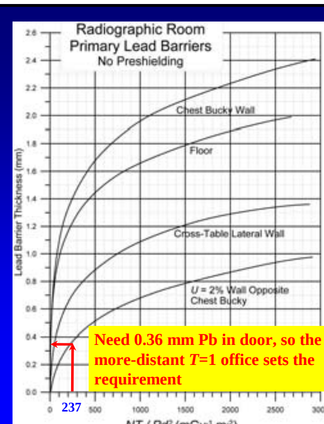
Room Door; Protect Distant Office

- 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

$$\frac{NT}{Pd^2} = \frac{113\ pat\ wk^{-1} \times 1}{0.02\ mGy\ wk^{-1} \times (4.88m)^2} = 237\ mGy^{-1}\ m^{-2}$$

- Look up Pb barrier requirement on graph

113



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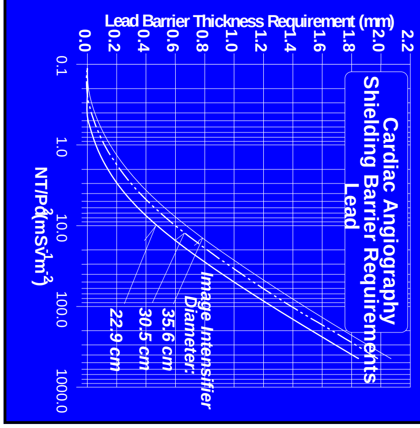

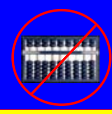

Hate reading graphs?

Like spreadsheets?

The NT/Pd^2 curves should fit the Archer model.

Fits of the $NT/(Pd^2)$ Graphs

- Equation 4.6 in NCRP Rept No 147 gives the required barrier thickness as a function of $NT/(Pd^2)$ for a given type of imaging room. Here K^1 is the kerma per patient at 1 m for this application, and α, β, and γ are fitting parameters of the transmission curve to the Archer equation:

$$x_{barrier} = \frac{1}{\alpha\gamma}\ln\left[\frac{\left(\frac{N\,T\,K^1}{Pd^2}\right)^{\gamma}+\frac{\beta}{\alpha}}{1+\frac{\beta}{\alpha}}\right]. \quad (4.6)$$

- (So if you like this $NT/(Pd^2)$ methodology, you can put utilize it for a number of common secondary shielding problems, including mammography and cath lab barriers, using the fitting parameters in App. C.)

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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 α, β, and γ fitting parameters.
- Here η_0 = max value of $NT/(Pd^2)$ requiring no shielding
- This equation can be inverted, ie. $NT/(Pd^2)$ written as a function of x (but note + 1/γ exponent).

$$x = \frac{1}{\alpha\gamma}\ln\left[\frac{\left[\frac{\left(\frac{NT}{Pd^2}\right)}{\eta_0}\right]^{\gamma}+\frac{\beta}{\alpha}}{1+\frac{\beta}{\alpha}}\right]$$

$$\left(\frac{NT}{Pd^2}\right) = \eta_0\left[\left(1+\frac{\beta}{\alpha}\right)e^{\alpha\gamma x}-\frac{\beta}{\alpha}\right]^{\frac{1}{\gamma}}$$

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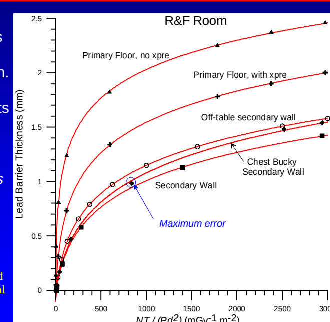
Fits of the $NT/(Pd^2)$ Graphs

Required Pb thickness as a function of *NT/(Pd2)* for barriers around the representative R&F Room from NCRP-147 is shown. The curves are the fits to the Archer equation. The data points are the values used for the fits. *(Note that the solid curves in Figs. 4.5 to 4.8 of NCRP-147 show cubic-spline interpolations to these same data.)*



The maximum deviation between the fitted value and the required thickness x is 0.026 mm Pb (for the "chest bucky secondary wall" in the representative R&F Room) and 1.7 mm concrete (for the "cross-table lateral wall" in the representative Radiographic Room).

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Fits of the $NT/(Pd^2)$ Graphs

Table 1. Source location, η_0, and fitting parameters α, β, and γ to Eq. 1 for shielding barriers in a representative Radiographic Room in NCRP-147 Figs 4.5 and 4.6. η_0 is the maximum value of $NT/(Pd^2)$ for which no shielding is required.

	Barrier	Source location	η_0 (mGy⁻¹ m⁻²)	Lead α (mm⁻¹)	Lead β (mm⁻¹)	Lead γ	Concrete α (mm⁻¹)	Concrete β (mm⁻¹)	Concrete γ
Primary Barriers, No Preshielding (Figs. 4.5a and 4.6a, NCRP Rept No. 147)	Chest Bucky Wall	chest tube	0.4384	2.347	14.02	0.6035	0.03560	0.1195	0.6078
	Floor	overtable tube	0.2176	3.034	20.86	0.5992	0.04165	0.1530	0.4659
	Cross-table Lateral Wall	cross-table tube	1.614	3.311	22.37	0.6904	0.04609	0.1577	0.5478
	2% U wall Opp Chest	center of table	7.791	2.999	21.75	0.6579	0.03913	0.1538	0.4716
Primary Barriers, with Preshielding (Figs. 4.5b and 4.6b, NCRP Rept No. 147)	Chest Bucky Wall	chest tube	21.38	2.466	12.66	1.698	0.03695	0.0934	1.356
	Cross-table Lateral wall	cross-table tube	10.92	3.428	12.15	1.024	0.04796	0.1007	0.8432
	Floor	overtable tube	37.90	2.950	7.837	1.377	0.04229	0.0651	1.159
	2% U wall Opp Chest	center of table	30.76	3.190	18.68	0.8311	0.04126	0.1218	0.6324
Secondary Barriers (Figs. 4.5c and 4.5c, NCRP Rept No. 147)	Floor	patient	26.42	2.802	21.35	0.6991	0.03639	0.1522	0.4992
	Chest Bucky secdry wall	chest tube	10.57	2.604	16.17	0.6961	0.03601	0.1291	0.6082
	Secondary wall	center of table	29.22	2.711	19.76	0.7452	0.03513	0.1441	0.5508
	2% U wall Opp Chest	patient	28.01	2.260	21.47	0.7943	0.03307	0.1514	0.5710

Table 2. Source location, η_0, and fitting parameters α, β, and γ to eq. 1 for shielding barriers in a representative R&F Room in NCRP-147 Figs 4.7 and 4.8.

	Barrier	Source location	η_0 (mGy⁻¹ m⁻²)	Lead α (mm⁻¹)	Lead β (mm⁻¹)	Lead γ	Concrete α (mm⁻¹)	Concrete β (mm⁻¹)	Concrete γ
Primary Barriers, No Preshielding (Figs. 4.7a and 4.8a, NCRP Rept No. 147)	Floor	overhead radiog tube	0.1939	2.484	17.82	0.5903	0.03691	0.1422	0.6124
	Chest Bucky wall	chest tube	0.5515	2.367	14.23	0.6263	0.03568	0.1185	0.6104
	Crosstable Lateral Wall	cross-table tube	1.707	2.482	18.84	0.7005	0.03675	0.1358	0.5364
	2% U wall	center of table	5.296	2.463	17.79	0.7365	0.03622	0.1272	0.5622
Primary Barriers, with Preshielding (Figs. 4.7b and 4.8b, NCRP Rept No. 147)	Floor	overhead radiog tube	3.605	2.345	10.56	0.8309	0.03484	0.07549	0.5746
	Crosstable Lateral Wall	cross-table tube	3.821	2.482	13.48	0.8003	0.03720	0.09758	0.6081
	Chest Bucky wall	chest tube	7.269	2.402	13.15	0.9916	0.03645	0.0953	0.7748
	2% U wall	center of table	8.536	2.474	14.19	0.7994	0.03621	0.1036	0.6462
Secondary Barriers (Figs. 4.7c and 4.8c, NCRP Rept No. 147)	Floor	patient on table	5.951	2.386	14.07	0.8250	0.03599	0.09796	0.5964
	Chest Bucky secdry wall	chest tube (72" SID)	5.766	2.117	23.16	0.8102	0.03670	0.1080	0.6016
	Secondary Wall	patient on table	8.743	2.404	15.95	0.7988	0.03702	0.1066	0.6297
	Ceiling	patient on table	7.104	2.241	14.62	0.7117	0.03422	0.1082	0.5579

Table 3. η_0 and fitting parameters α, β, and γ to eq. 1 for shielding a Cardiac Angiography Lab for various sized image intensifiers.

Image Intensifier Size (diameter)	η_0 (mGy⁻¹ m⁻²)	Lead α (mm⁻¹)	Lead β (mm⁻¹)	Lead γ	Concrete α (mm⁻¹)	Concrete β (mm⁻¹)	Concrete γ
22.9 cm (9")	0.5574	2.446	16.39	0.8860	0.03757	0.1090	0.6354
30.5 cm (12")	0.3199	2.451	16.16	0.7939	0.03727	0.1087	0.5792
35.6 cm (14")	0.2371	2.492	16.21	0.7748	0.03753	0.1096	0.5655

Memorize this for the quiz on Sunday…

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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 $B = \frac{P/T}{K_{un}}$
- 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…*

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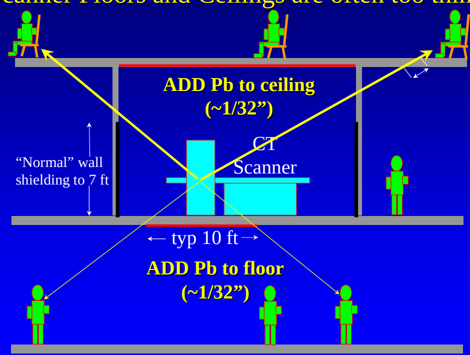
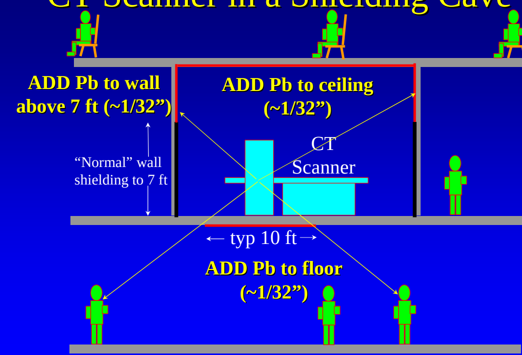
CT Scanner Floors and Ceilings are often too thin!



CT Scanner in a Shielding Cave



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 ≠ 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

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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

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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

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