Diagnostic Shielding Update - *Here At Last!*

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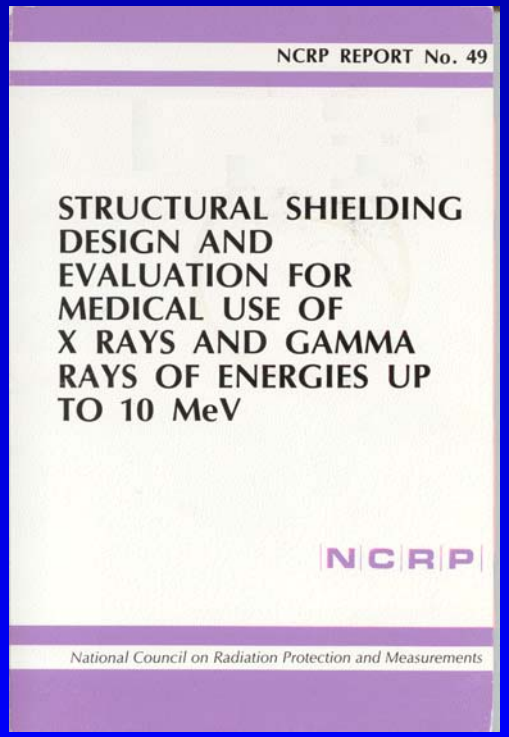
History

- NBS Handbook 60 (1955) & Braestrup & Wykoff Health Physics Text (1958)
- NCRP Reports 34 (1972) & 49 (1976)



History

- AAPM Task Group 9, 1989
  - Interested individuals met at AAPM meetings to discuss on-going concerns with practice of shielding
  - Ted Villafana, chair
- Joint NCRP Scientific Committee SC-9 / AAPM Task Group 13 formed **1992**

Your speaker as an eager young physicist when this project started.

Cochairs

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

Membership

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

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

Consultants

- Andrew Poznanski, M.D…..
- Ken Kase
  - Has helped shepherd the report through it's final reviews
- Wayne Thompson
  - Has kept us honest in the past couple of years, independently redoing sample calculations, checking for self-consistency, & asking "Why?"
- Jack Krohmer (deceased)
  - Jack didn't suffer fools lightly...

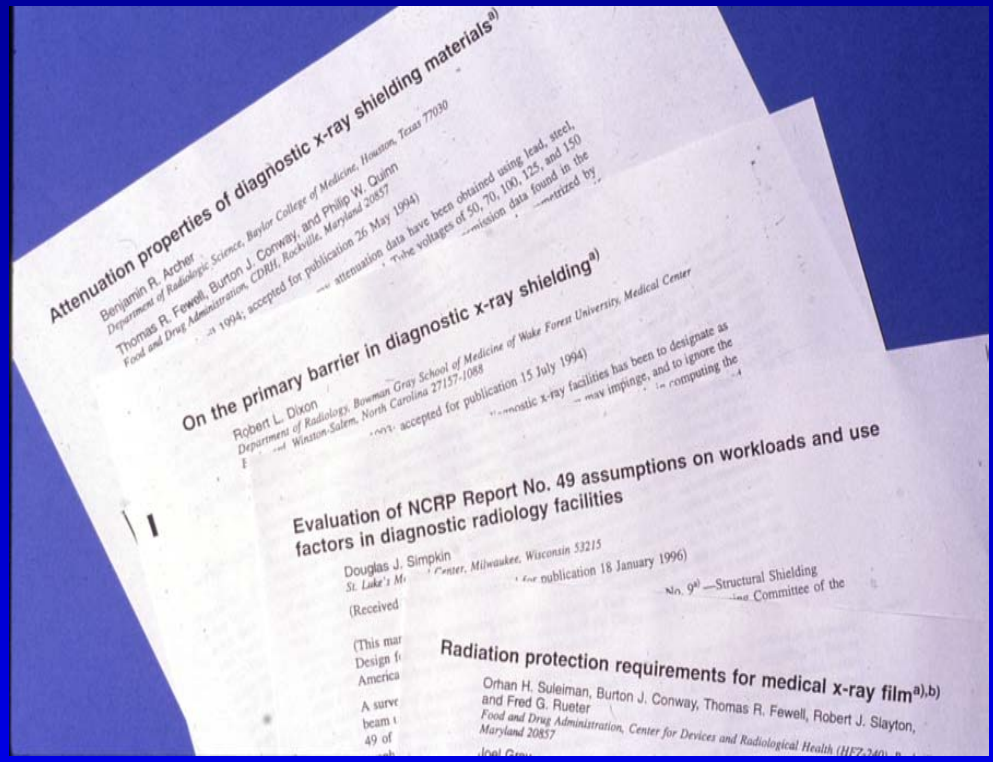
Membership

- Members met ~twice per year (at AAPM & RSNM meetings), and for extended weekends (to actually work)

Ben, Linc, Bob & I

Member Publications

- As new methods were developed, they were peer-reviewed and published by the members
- 16 refereed publications came out of Task Group 9/ SC-9, including
  - 5 in *Medical Physics*
  - 6 in *Health Physics*



Lectures

- Medical / health physics community has been kept informed of our progress throughout
- Per Archer's count, 31 refresher courses / invited lectures have been given by the members at AAPM, HPS, CRCPD, RSNA, AAPM & HPS Chapters, etc

History

- Initial draft prepared for NCRP Council review 2001

- ~2/3 of council members responded, and many positive & minor editorial comments were received
- *BUT* 8 members voted for contingent approval and one member voted for disapproval

NCRP Scientists Assigned to SC-9

- James Spahn (1992-1998)
- Eric Kearsley (1998-2001)
- **Marvin Rosenstein** (2001-2004)
  - Implemented the steps necessary to get report accepted, including
    - hammering out permitted dose in uncontrolled areas
    - rewriting for technical accuracy

History

- Final approvals from NCRP 7/9/04 & AAPM 7/7/04
- NCRP Report No. 147 "*Structural Shielding Design for Medical X-ray Imaging Facilities*" goes to the printer shortly.
- Price?

What's in the New Report?

- New report addresses shielding for diagnostic x-ray imaging devices only
- *No dental units*
  - (cf. NCRP Report No. 145; x-ray shielding section written by Marc Edwards)
- *No therapy simulators or therapy machines*
  - (separate task group; cf. Ray Wu & Jim Deye)
- *No radionuclides*.

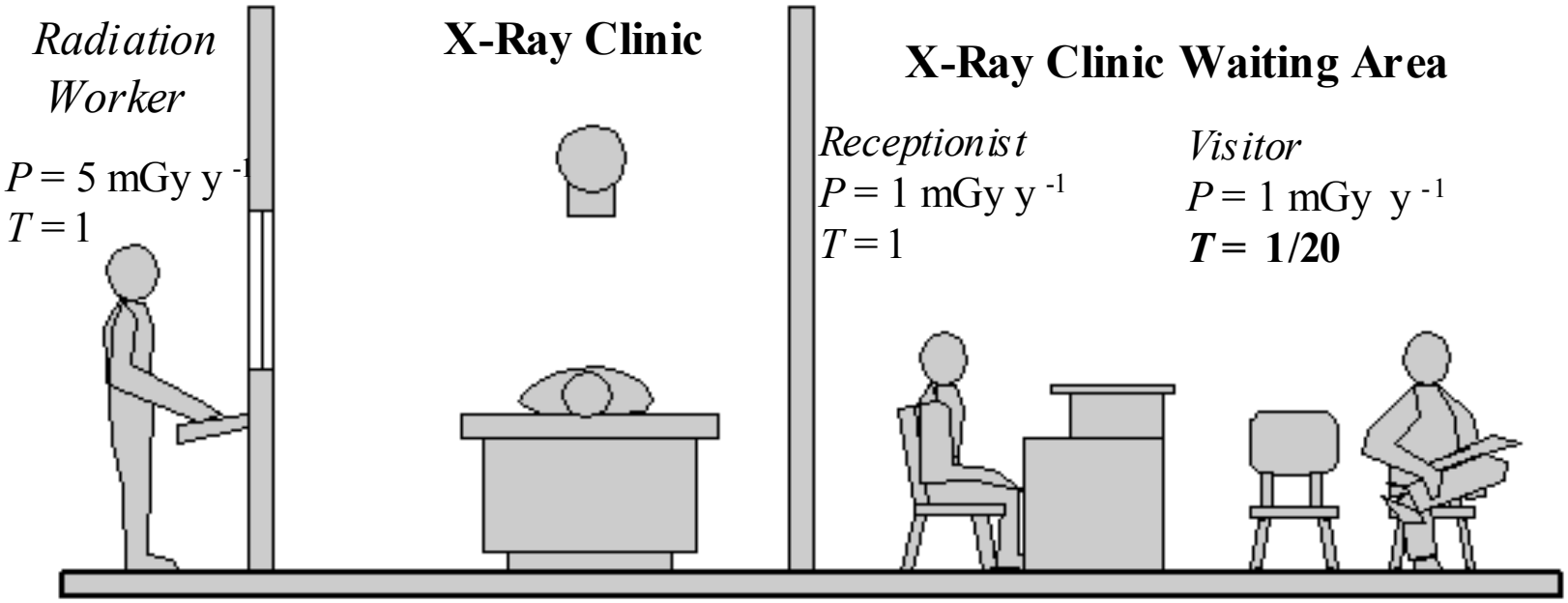
The Qualified Expert

- "A medical (or medical health) physicist who is competent to design radiation shielding for medical x-ray imaging facilities. The *QE is a person who is Board Certified by ABR, ABMP, ABHP, or CCPM."*

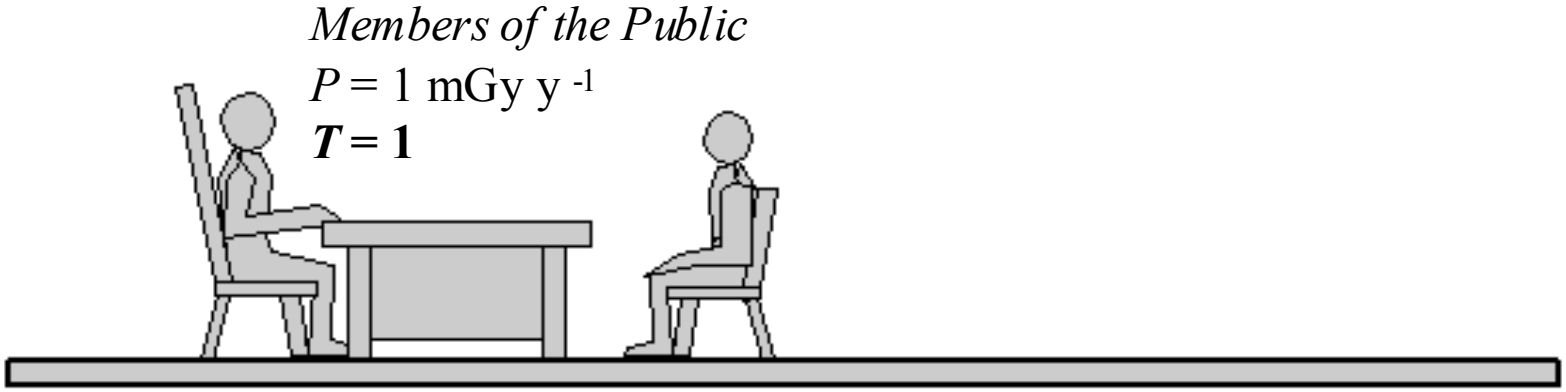
Design Goal, *P*

- Design Goal *P* = accepted radiation level to the occupied area
  - *P* is now a kerma value
  - *P* must be consistent with NRCP Report No 116 (but these are effective dose equivalents, which can't be measured)

Design Goal *P*	***Controlled area***	***Uncontrolled areas***
NCRP-49	50 mGy/y =1 mGy/wk	5 mGy/y =0.1 mGy/wk
New report (based on NCRP-116)	*Fraction* (=½) of 10 mGy/yr limit for new operations = 5 mGy/yr (~matches fetal dose limit) = 0.1 mGy/wk	1 mGy/y = 0.02 mGy/wk
Effect	*Factor of 10 decrease*	*Factor of 5 decrease*



Lawyer's Office (not associated with X-Ray Clinic)



What happened to 0.25 mSv/y?

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."

What happened to 0.25 mSv/y?

- NCRP had a change in leadership in 2003
- Thomas Tenforde 8/03: "The 0.25 mSv/y recommendation in Report 116 dates back to NCRP Statement No. 6 on "*Control of Air Emissions of Radionuclides*" published in 1984. Its original intent was to limit public exposure to airborne emissions of radionuclides, and did not specifically refer to other sources of external radiation exposure."
- NCRP is reviewing Report No. 116

Uncontrolled P=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=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

Uncontrolled P=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)

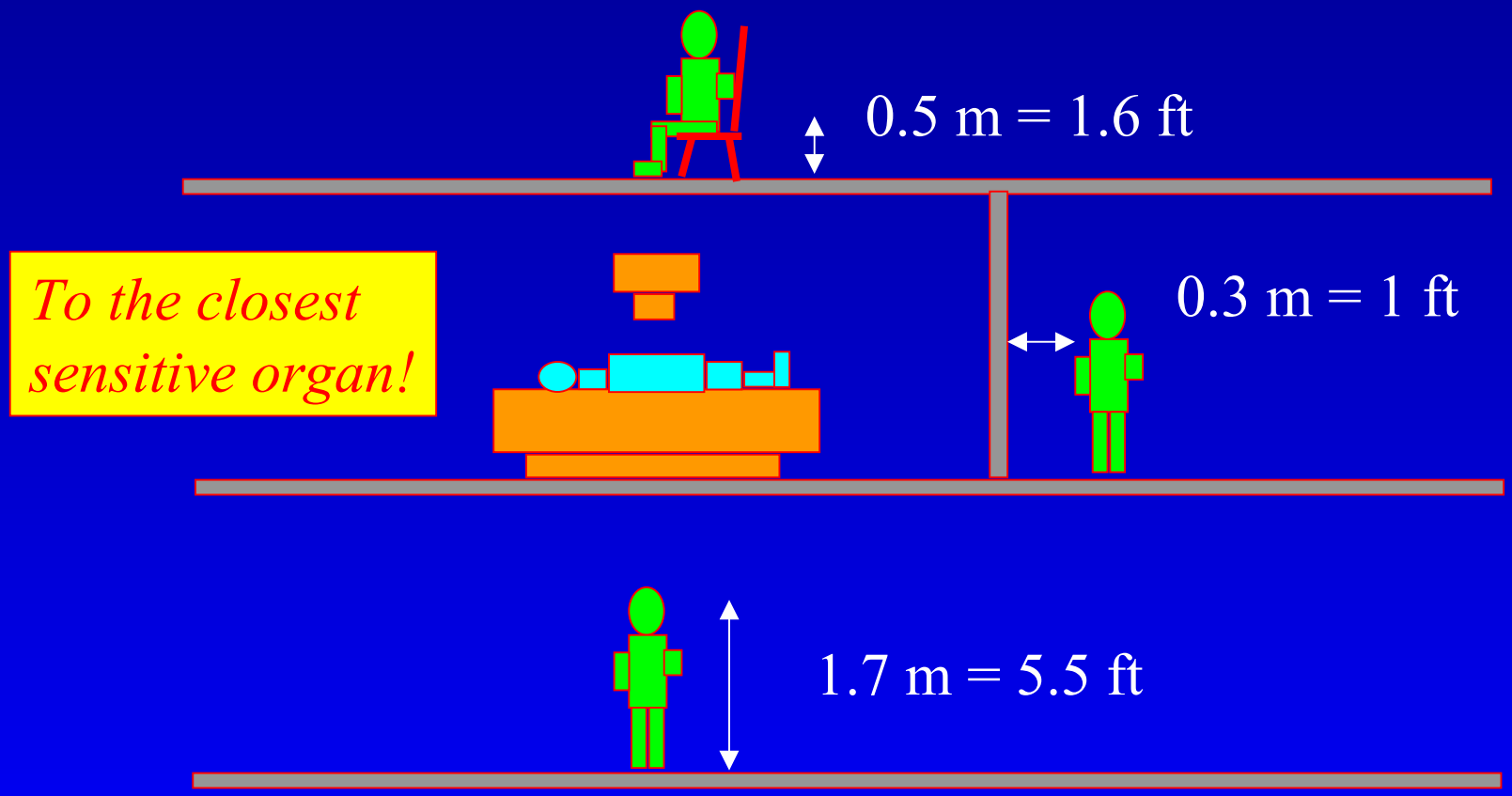
Occupancy Factor, *T*

- 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*
- Compromise on some *T* values for acceptance

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

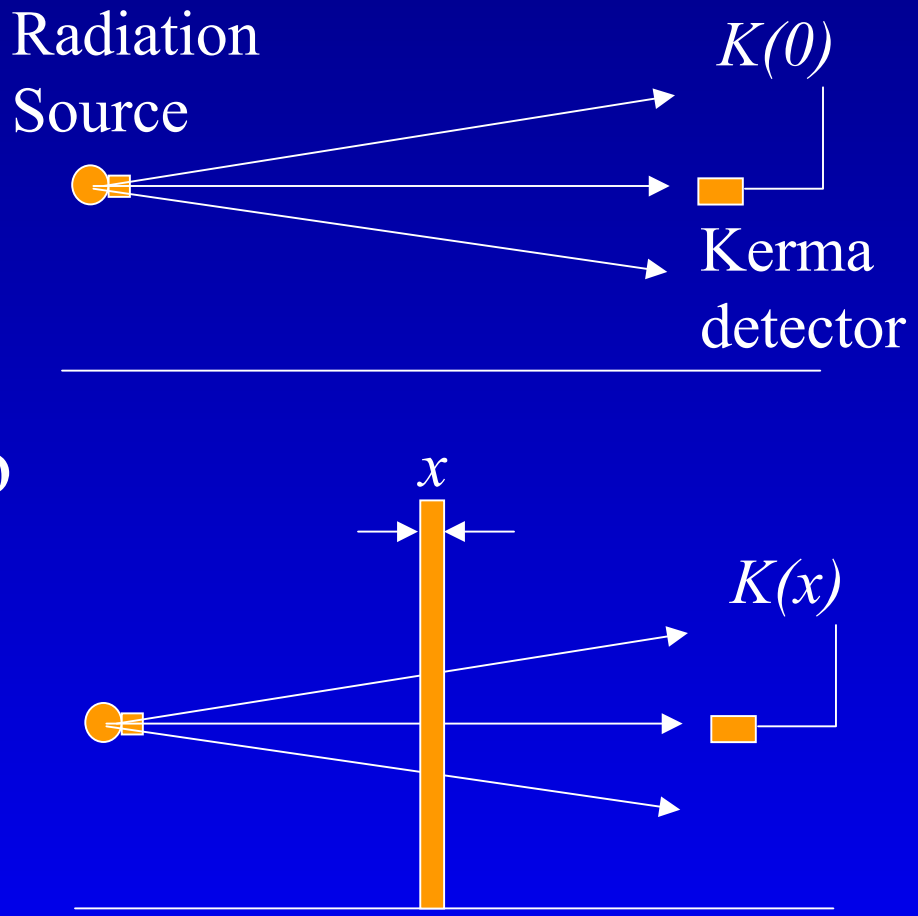
Where in the occupied area do you calculate the kerma?



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

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

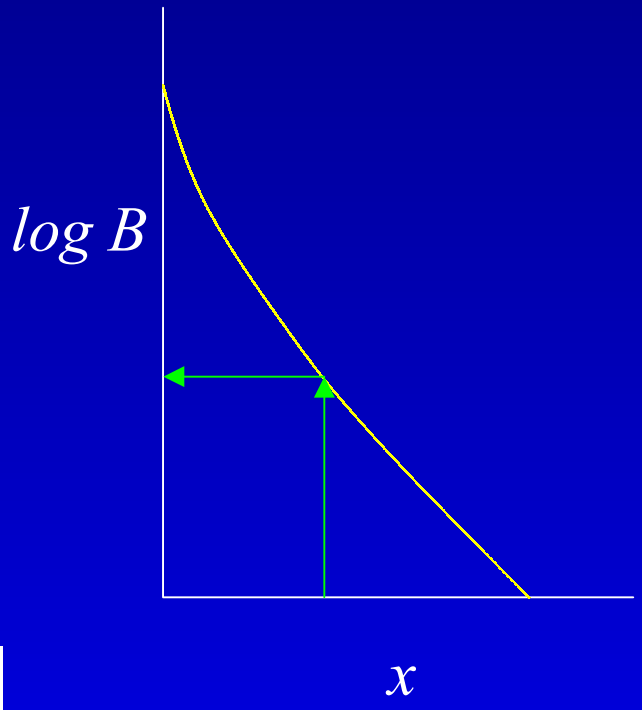


Sources of Transmission Data

- Measured or calculated *B(x)* data of modern three phase /constant potential 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

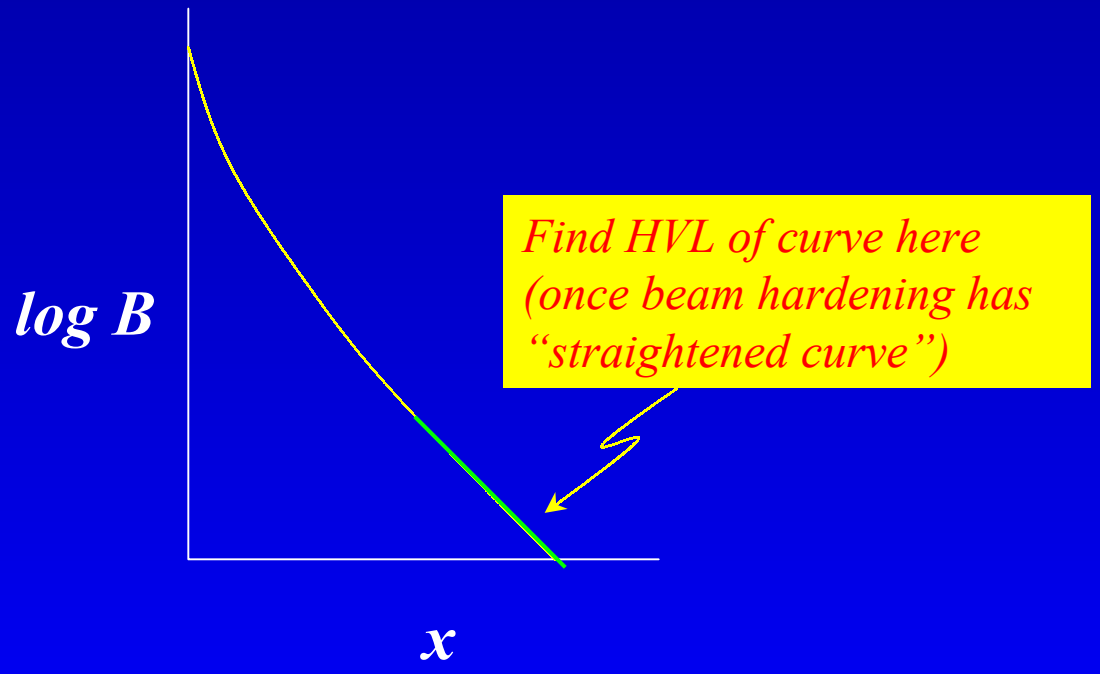
- Archer et al. presented a very useful equation for describing transmission data B fit to barrier thickness x in 3 parameters (α, β, γ)



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

Archer Equation for Transmission Curves

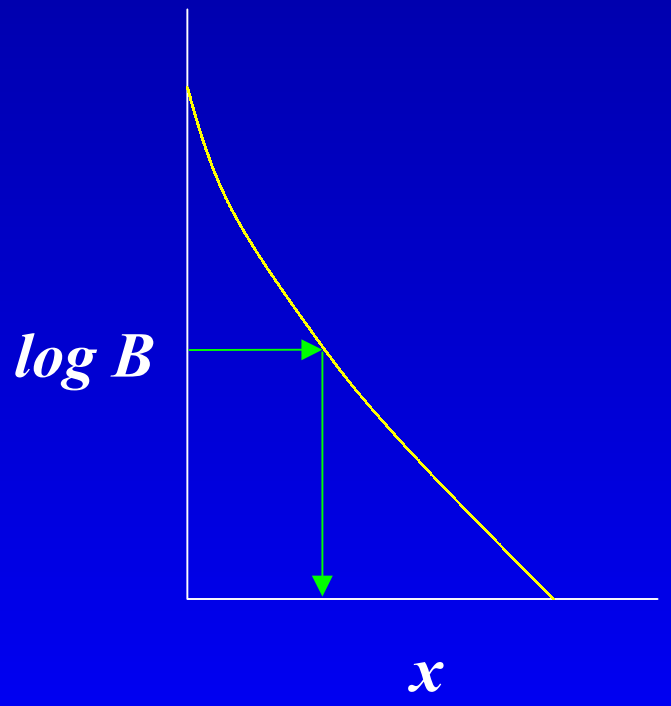
- Note: α is the slope of the transmission curve at large x. Therefore, α = (ln 2) / "Hard HVL"



Archer Equation for Transmission Curves

- This can be inverted to solve for x

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



Workload, *W(kVp)*

- *W* is a measure of the x-ray tube's use = the time integral of the tube current
- 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*

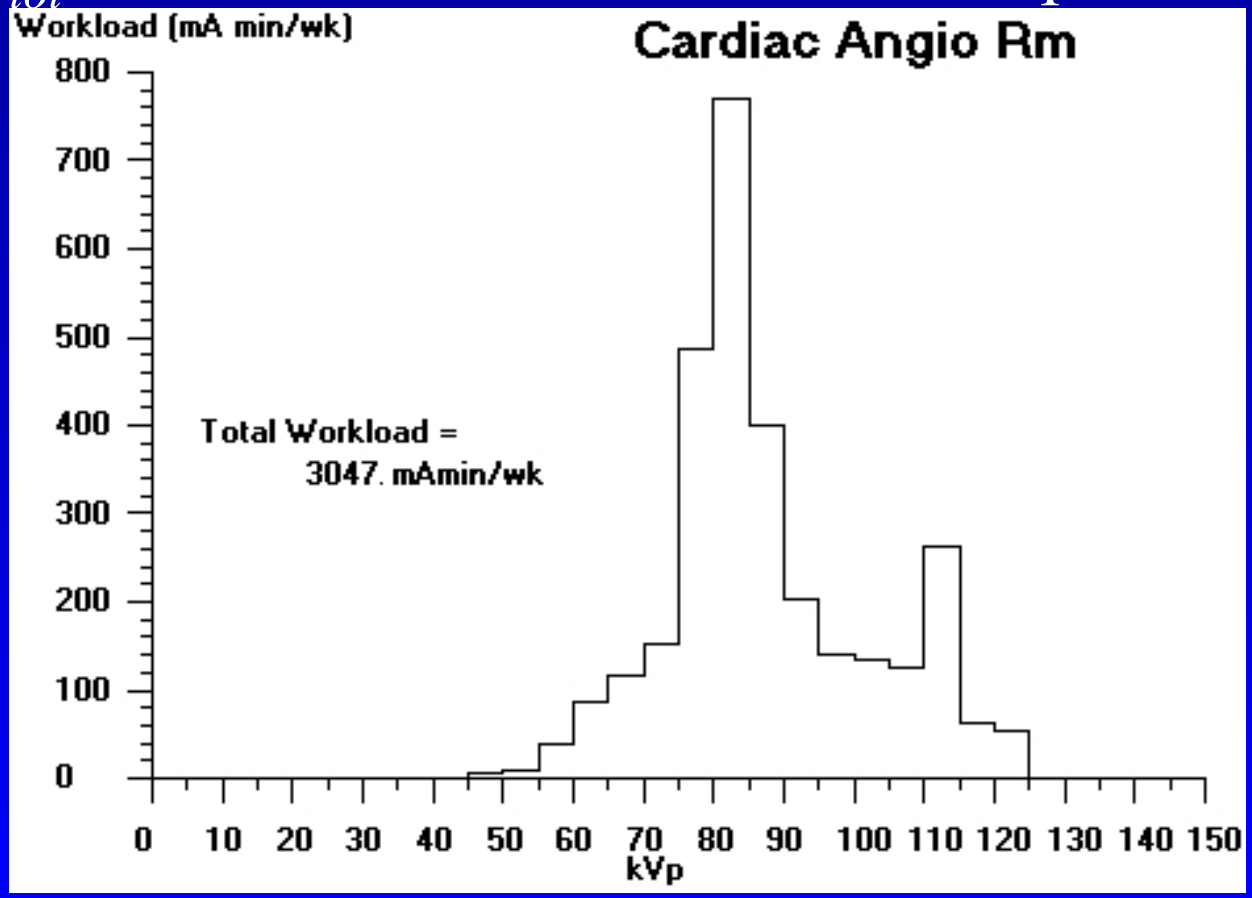
- To determine *W* used clinically, a survey of modern medical facilities was undertaken by AAPM TG 9 in the early 1990s and published in 1996 (Simpkin).
- Objectives of survey:
  - *W* per patient in various types of diagnostic settings (general radiography, cath lab, etc.)
  - the weekly average number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

Workload Survey

- Found total *W* to be far different from the 1000 mA·min/wk blindly assumed
  - Radiographic Rooms: 277 mA·min/wk
  - Chest Rooms: 45 mA·min/wk
  - Cardiac Angio Rooms: 3050 mA·min/wk
- *The NCRP Report accepts the shapes of these workload distributions as reasonable, and allows for modification of the total W as needed.*

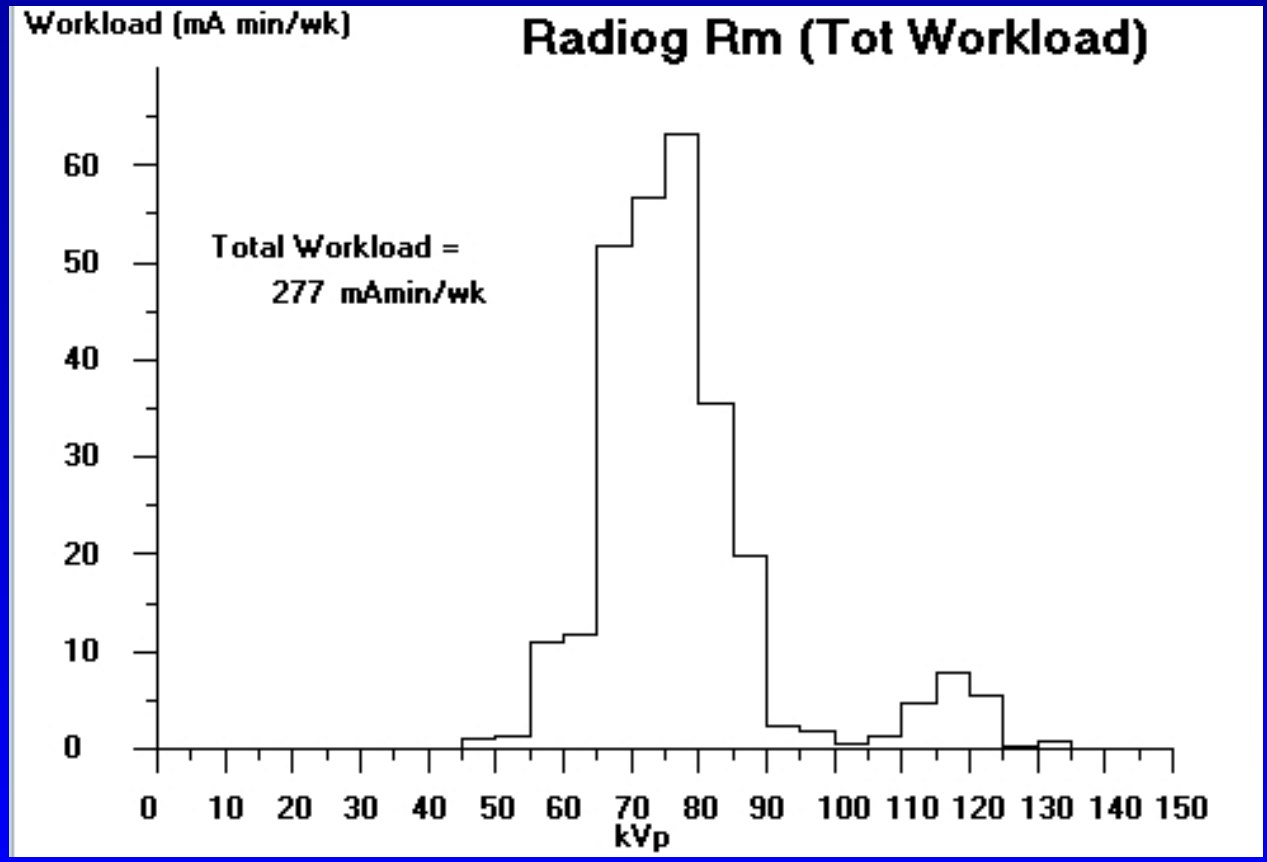
Workload Distribution, *W(kVp)*

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



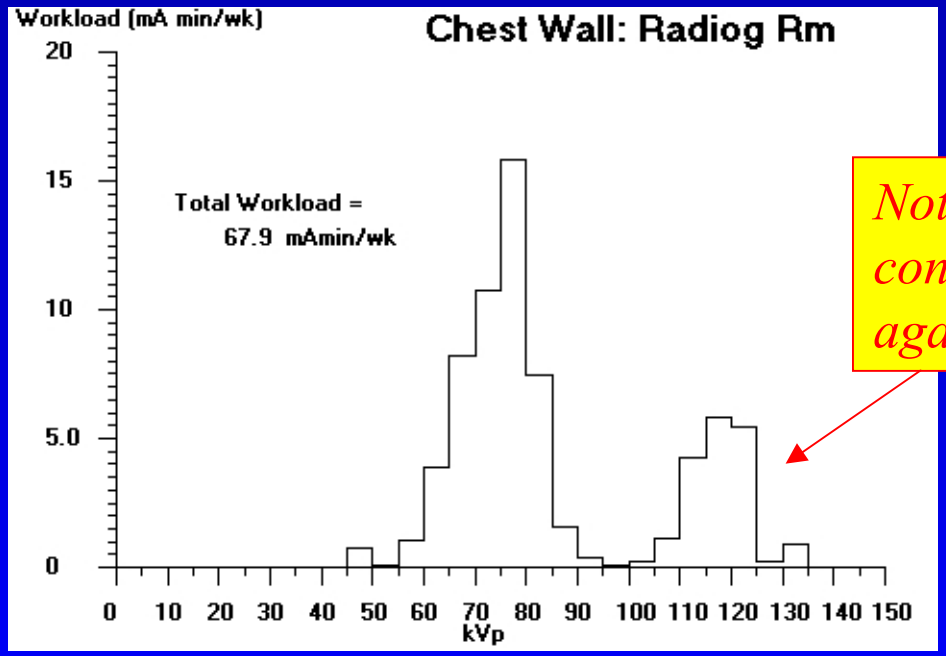
Workload Distribution, *W(kVp)*

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

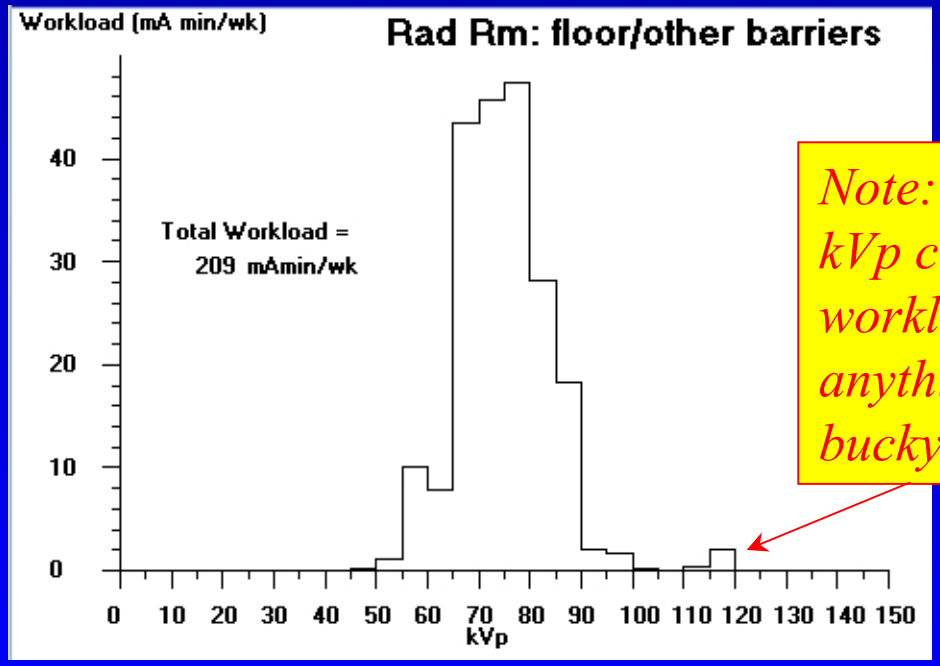


Note: high kVp content of workload against chest bucky

- *and...*

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

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



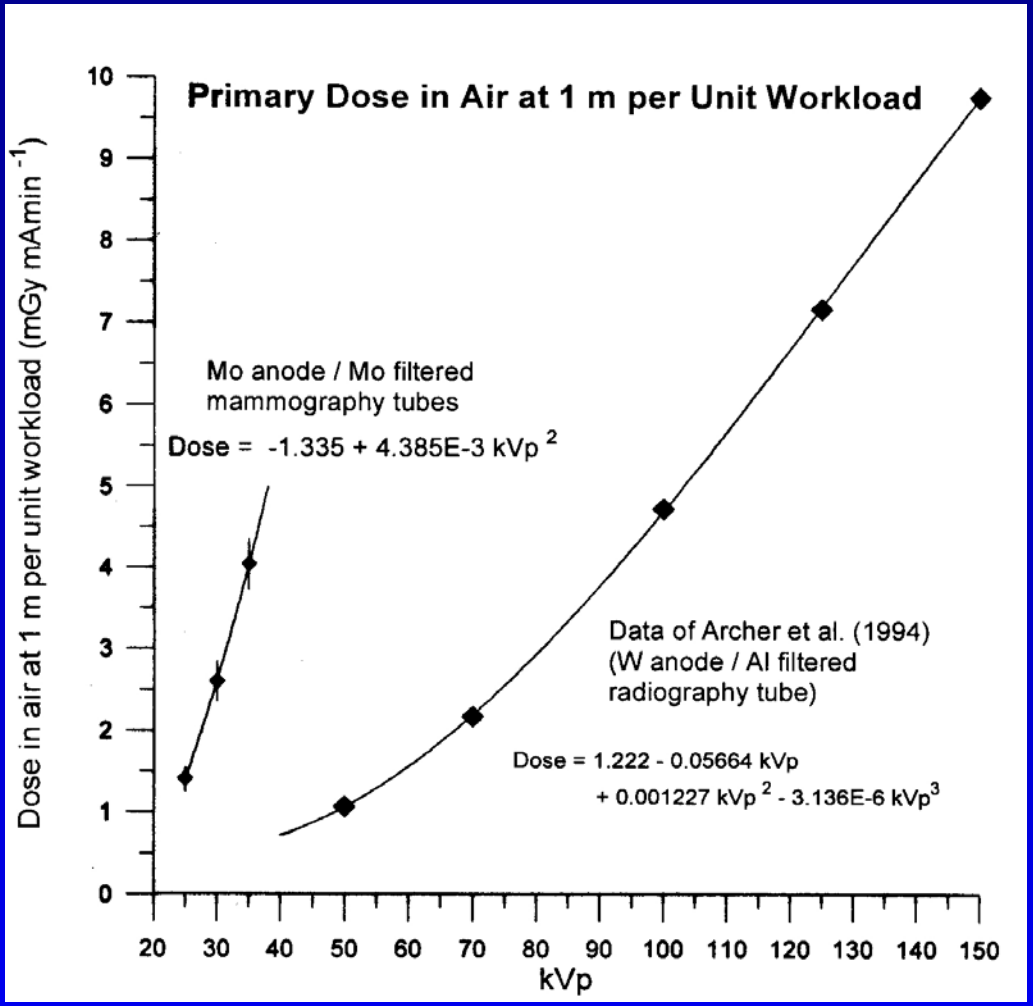
Note: very little high kVp content of workload against anything <u>but</u> chest bucky

Theory *(the stuff buried in the Appendices)*

- The kerma in the occupied area may have contributions from
  - **primary radiation**
  - **scatter radiation** } *Secondary radiation*
  - **leakage radiation** }
- from multiple x-ray sources (or tube positions) operating over ranges of kVp ("workload distribution")

Primary Radiation Output

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



Unshielded Primary Beam Kerma

- At a given *kVp*, for a fraction *U* of the tube's workload directed at a barrier, then the unshielded primary kerma is

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

- *U* is the ***use factor*** for this barrier

Use Factors from TG 9 Survey

(Simpkin 1996)

- Of total workload in radiographic room
  - 22% at chest bucky wall
  - 7% at cross-table lateral wall
  - 2% at another, unspecified wall
  - remainder (~70%) at floor
- Of the workload not directed at chest bucky
  - 89% at floor
  - 9% at cross-table lateral wall
  - few % at another, unspecified wall

Use Factors from TG 9 Survey

- $U = 0$ for modalities where primary beam is stopped by image receptor
  - image intensified fluoro (e.g. special procedures, cath lab)
  - mammography

Kerma Behind a Primary Barrier

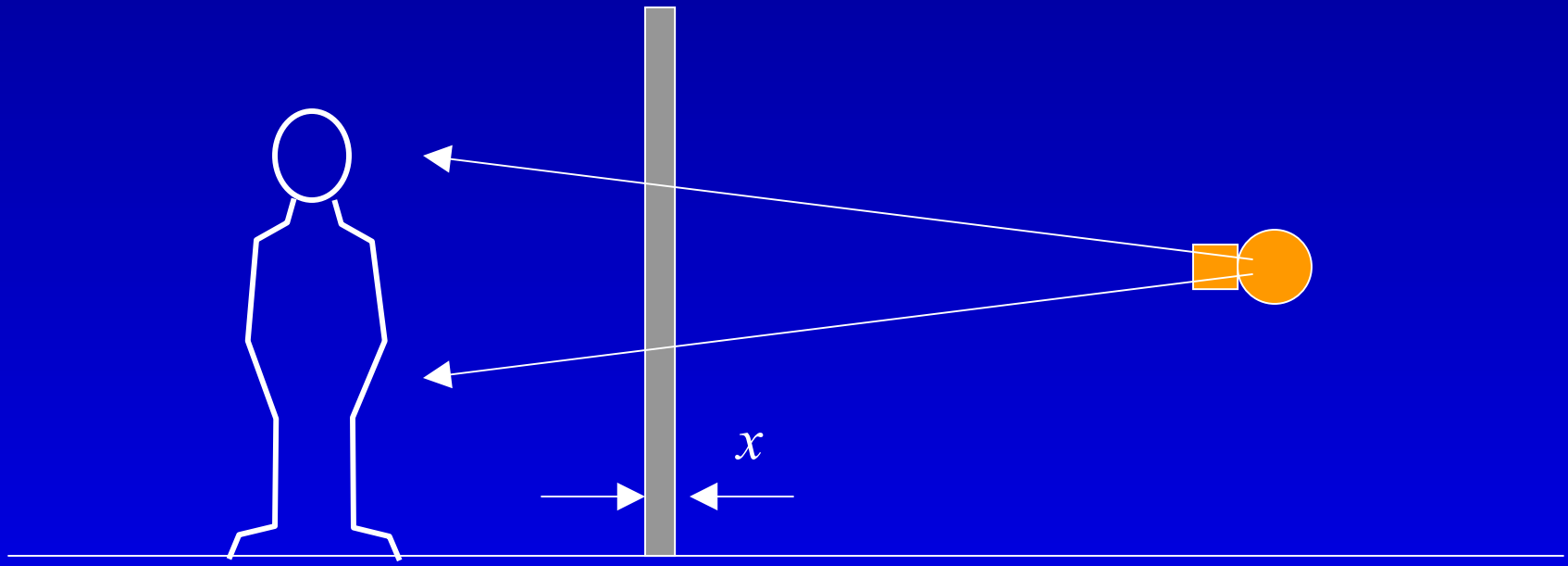
- Kerma behind a primary barrier of transmission *B(x, kVp)*

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

- For the whole distribution of workloads, total kerma is

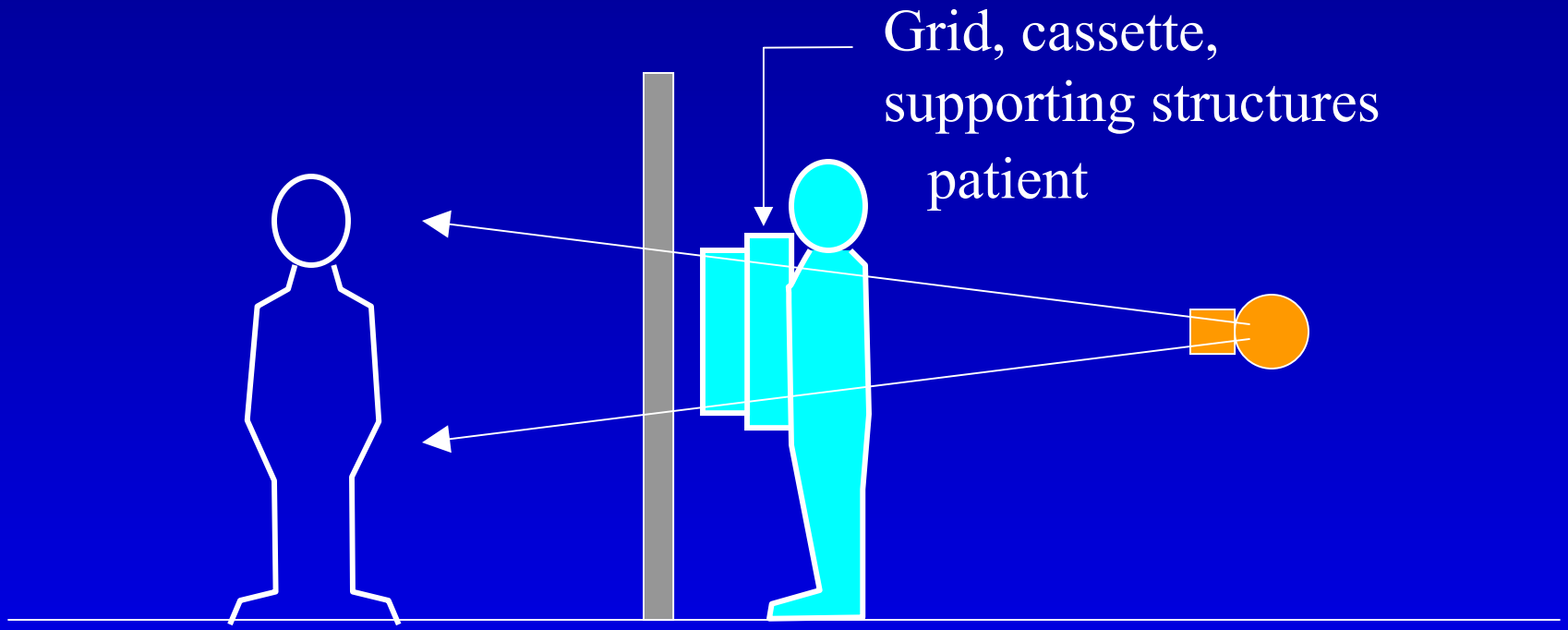
$$K_P(x) = \sum_{kVp} \frac{K_W(kVp)\,U\,W(kVp)}{d_P^2}\,B(x,kVp)$$

Primary Radiation: The NCRP49 Model



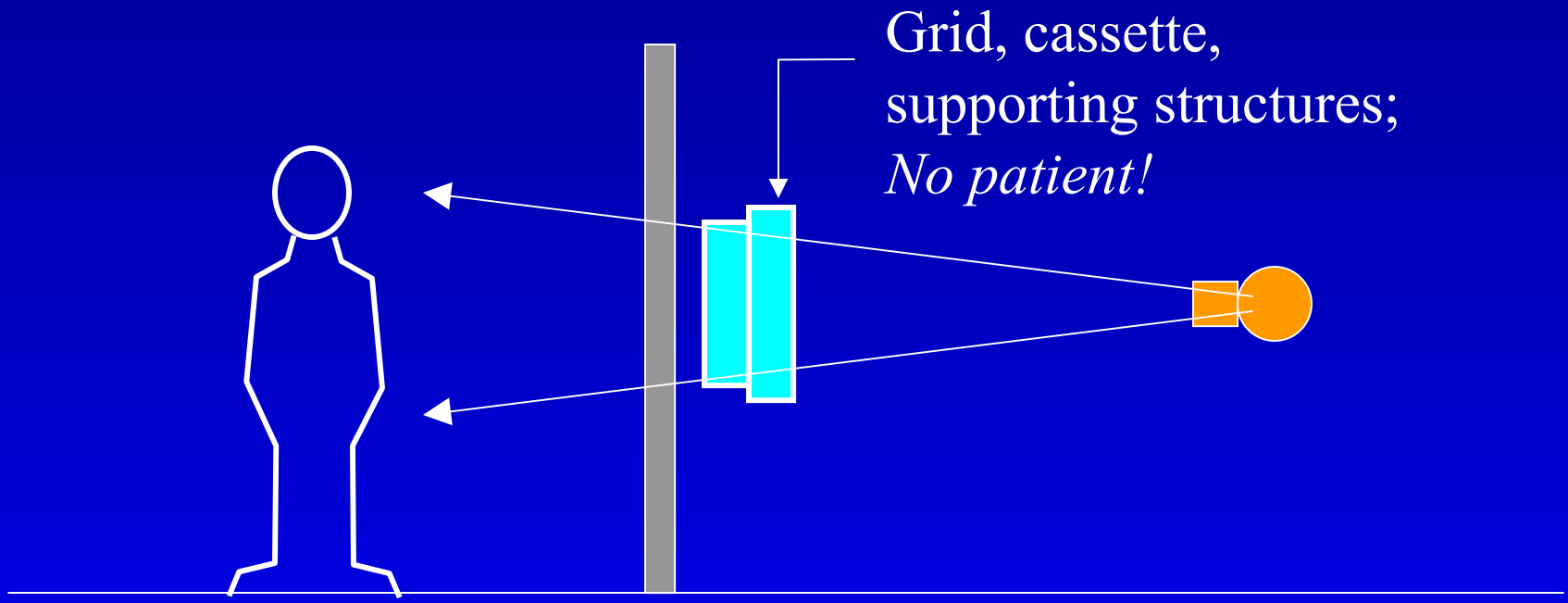
Barrier of thickness *x* decreases raw primary radiation to *P/T*

Primary Radiation: The Reality



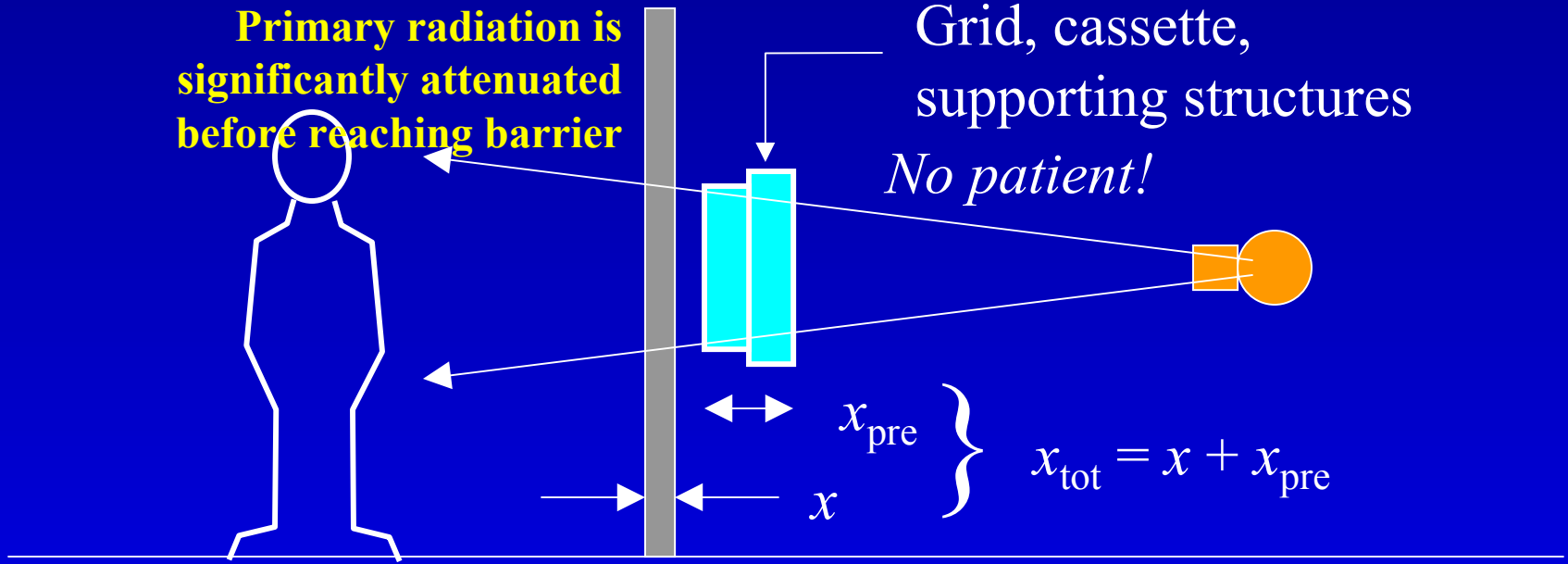
Primary radiation is significantly attenuated before reaching barrier

Primary Radiation: The NCRP Rep No. 147 Model

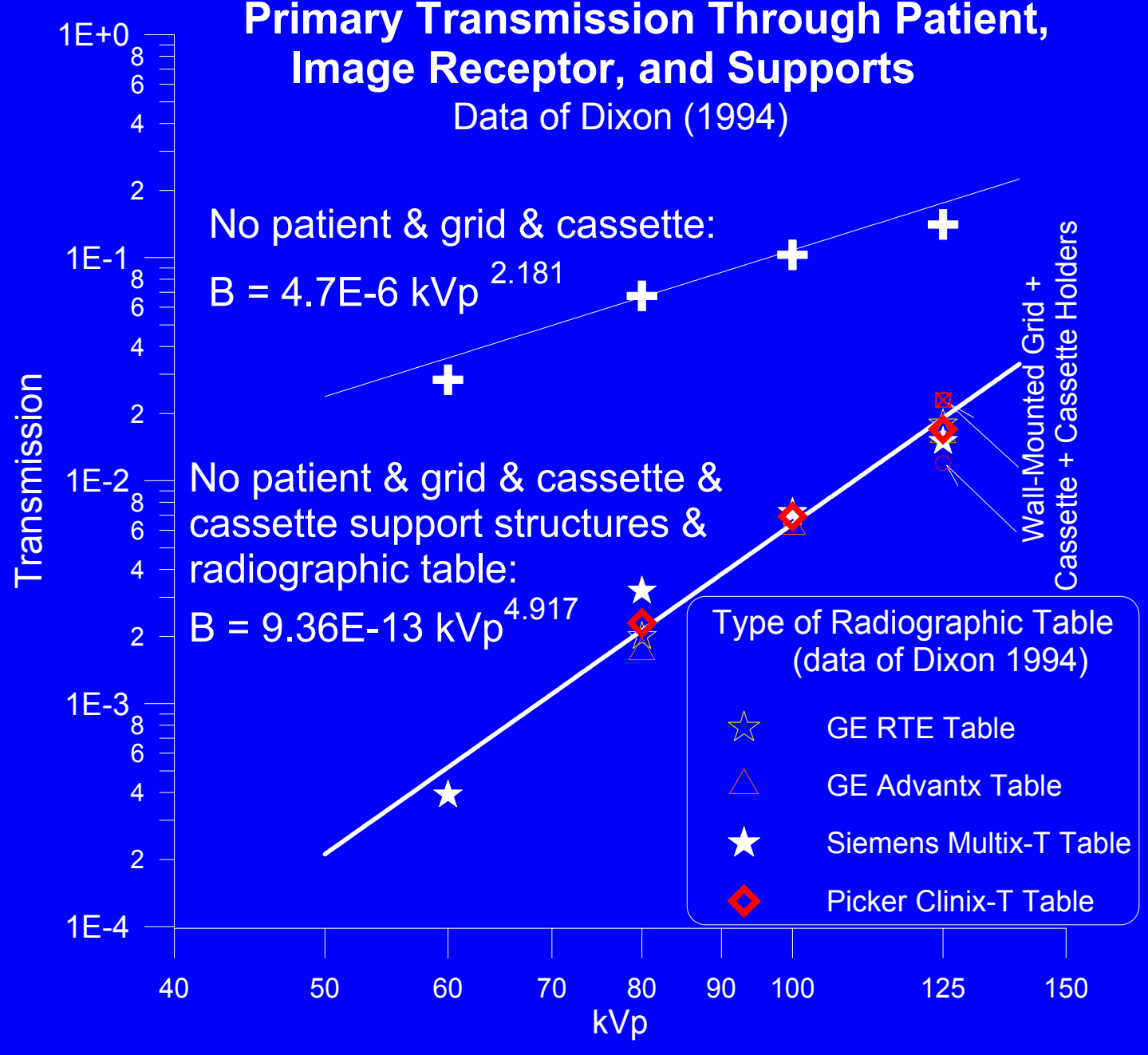


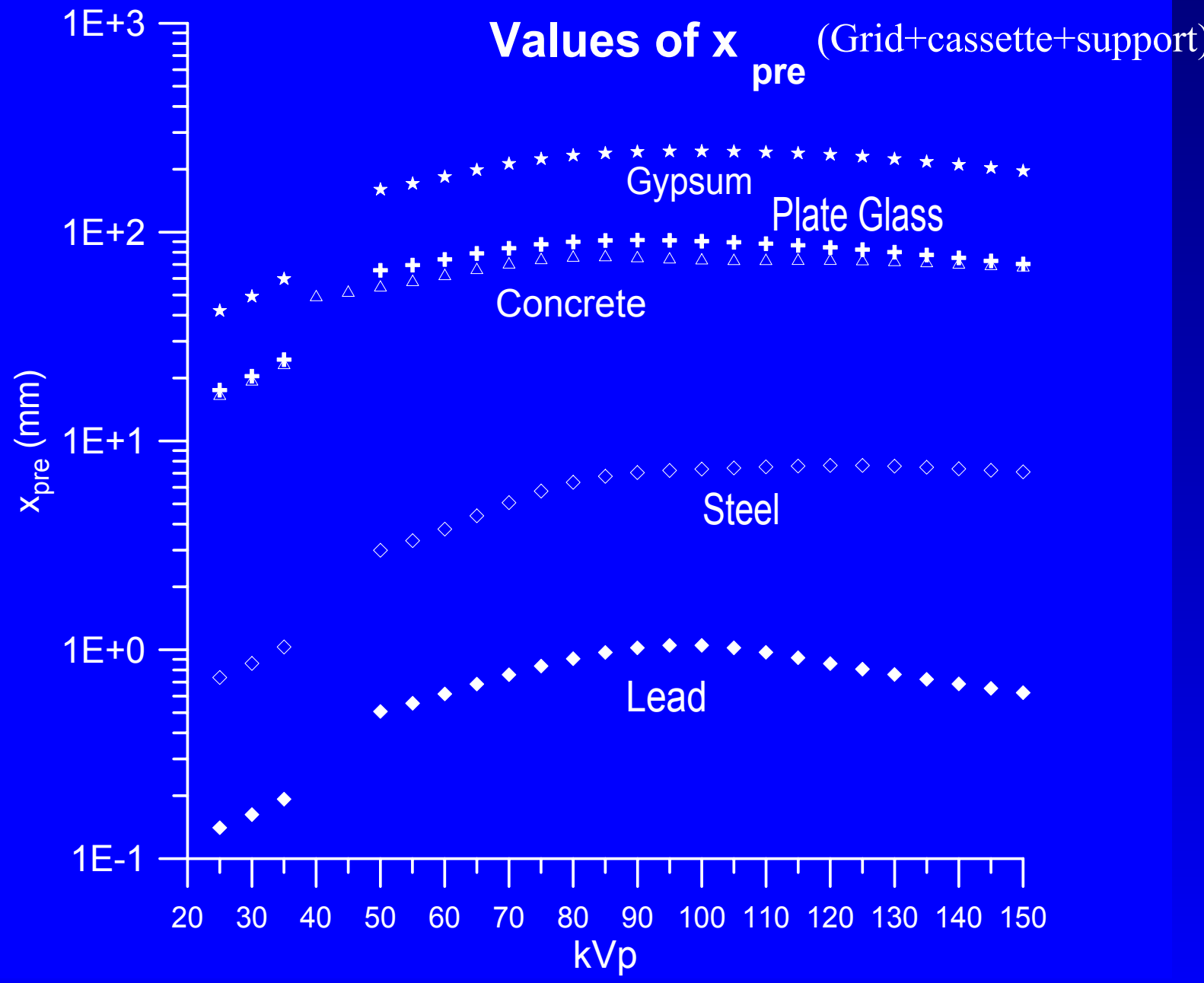
Primary radiation is *still* significantly attenuated before reaching barrier

Primary Radiation: The NCRP Rep No. 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.


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 kVp4.917
Wall-Mounted Grid + Cassette + Cassette Holders
Transmission
1E+0
8
6
4
2
1E-1
8
6
4
2
1E-2
8
6
4
2
1E-3
8
6
4
2
1E-4
40
50
60
70
80
90
100
125
150
kVp
Type of Radiographic Table (data of Dixon 1994)
GE RTE Table
GE Advantx Table
Siemens Multix-T Table
Picker Clinix-T Table


Values of x pre (Grid+cassette+support)
1E+3
1E+2
1E+1
1E+0
1E-1
x pre (mm)
Gypsum
Plate Glass
Concrete
Steel
Lead
20 30 40 50 60 70 80 90 100 110 120 130 140 150
kVp

x_{pre} for Radiographic Room Workload Distributions

- Grid + cassette:
  - 0.3 mm Pb
  - 3 cm concrete
  - 9 cm gypsum wallboard
- Grid + cassette + table/chest bucky supports:
  - 0.85 mm Pb
  - 7.2 cm concrete
  - 23 cm gypsum wallboard

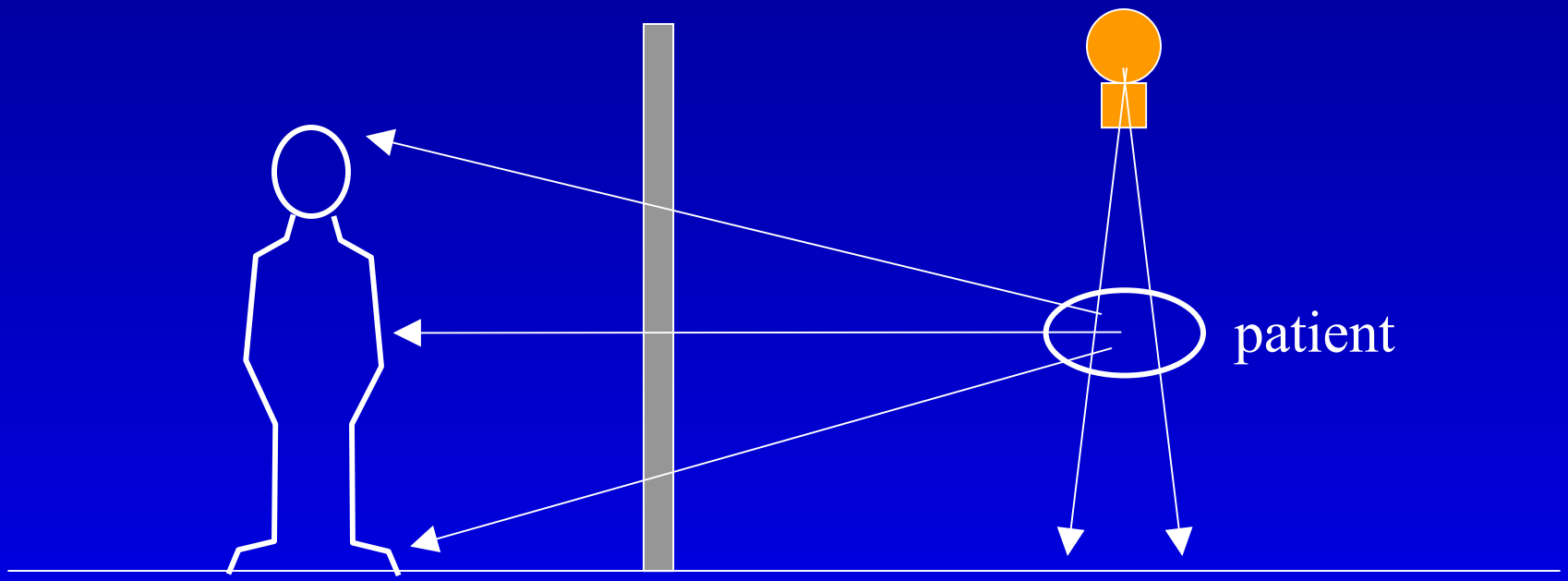
Calculation of Primary Kerma

- Same as model in NCRP49 *except*
  - account for workload distribution in kVp
  - account for image receptor attenuation x_{pre}
- Transmitted primary kerma is then

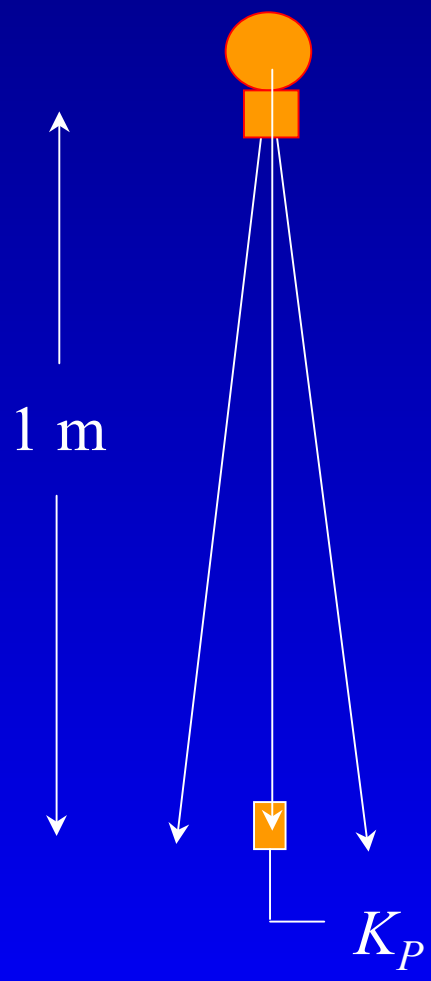
$$K_P(x + x_{pre}) =$$

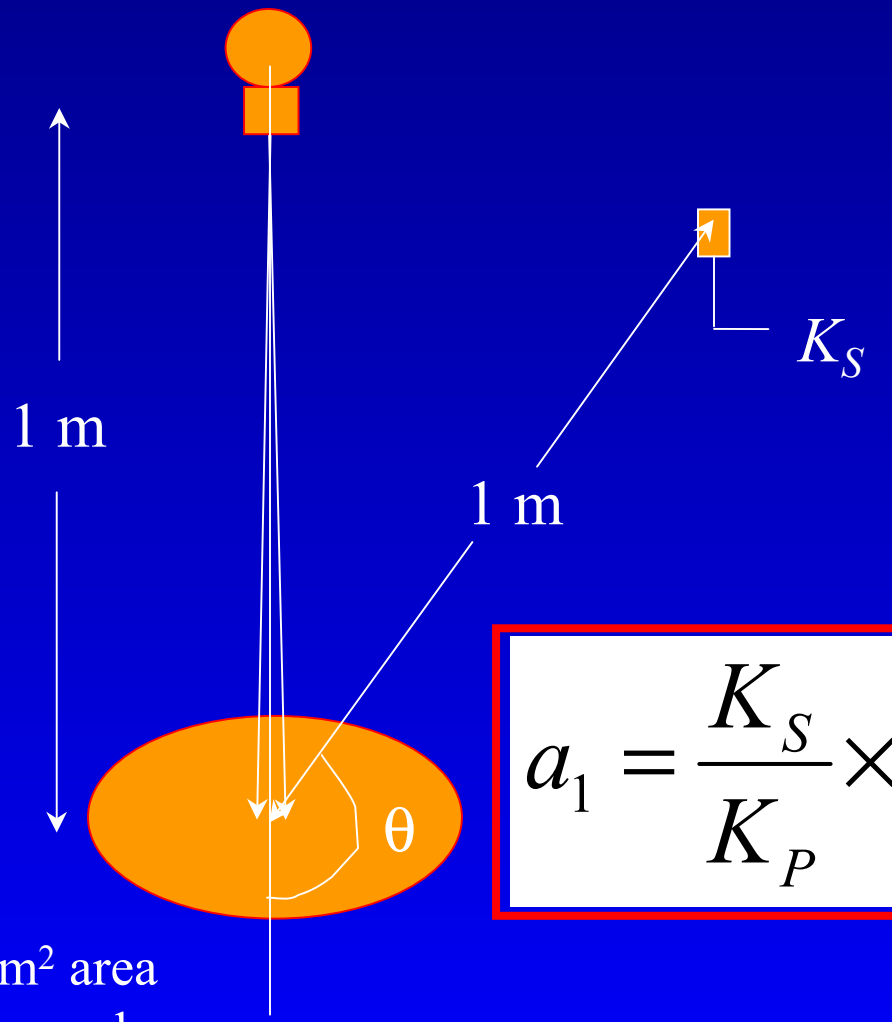
$$\frac{1}{d_P^2} \sum_{kVp} K_W(kVp)\, U\ \ W(kVp)\, B(x + x_{pre}, kVp)$$

Scatter Radiation



Scaled Normalized Scatter Fraction

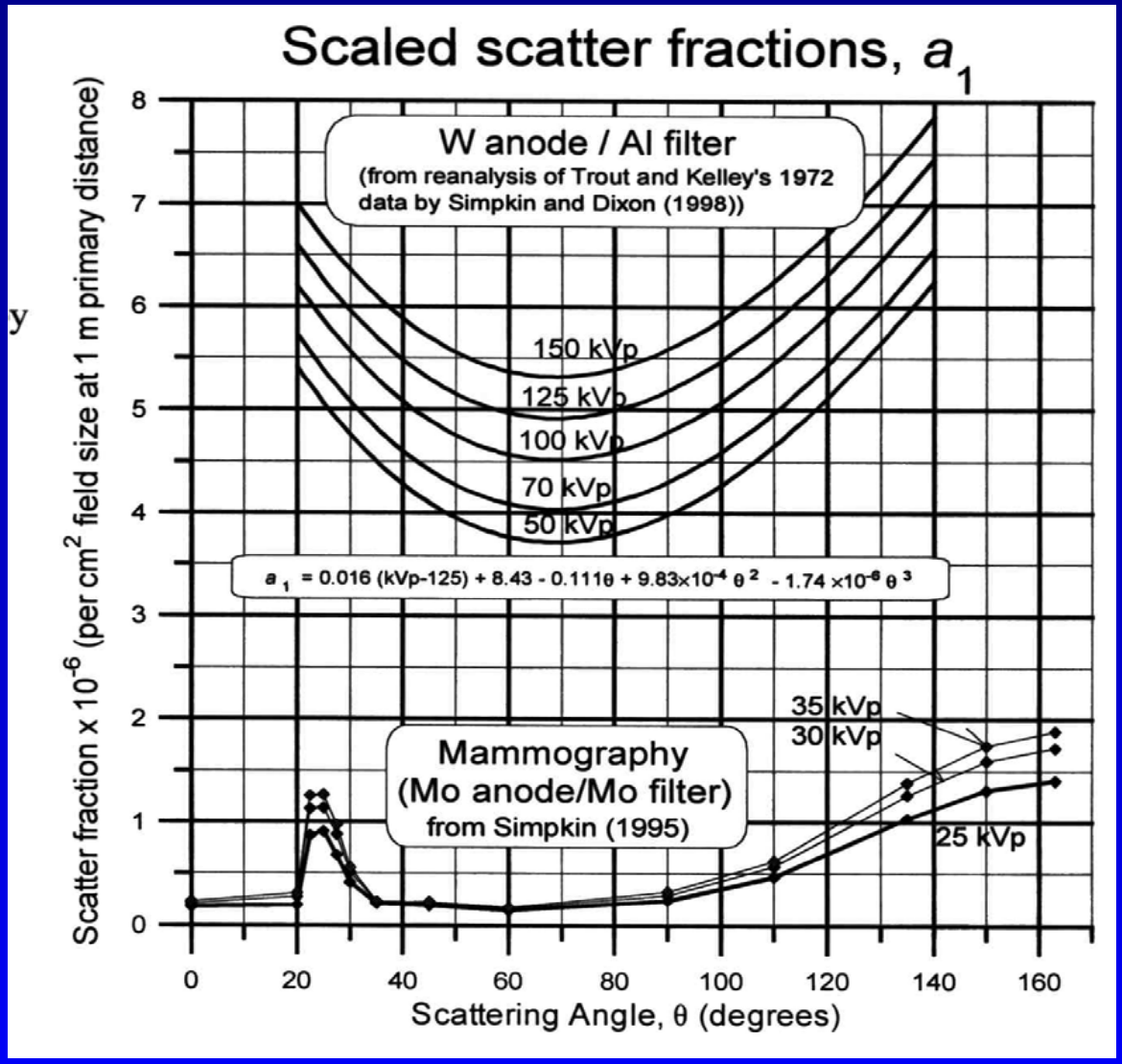




1 cm^2 area primary beam at 1 m

$$a_1 = \frac{K_S}{K_P} \times 10^{+6}$$

Scaled Normalized Scatter Fraction



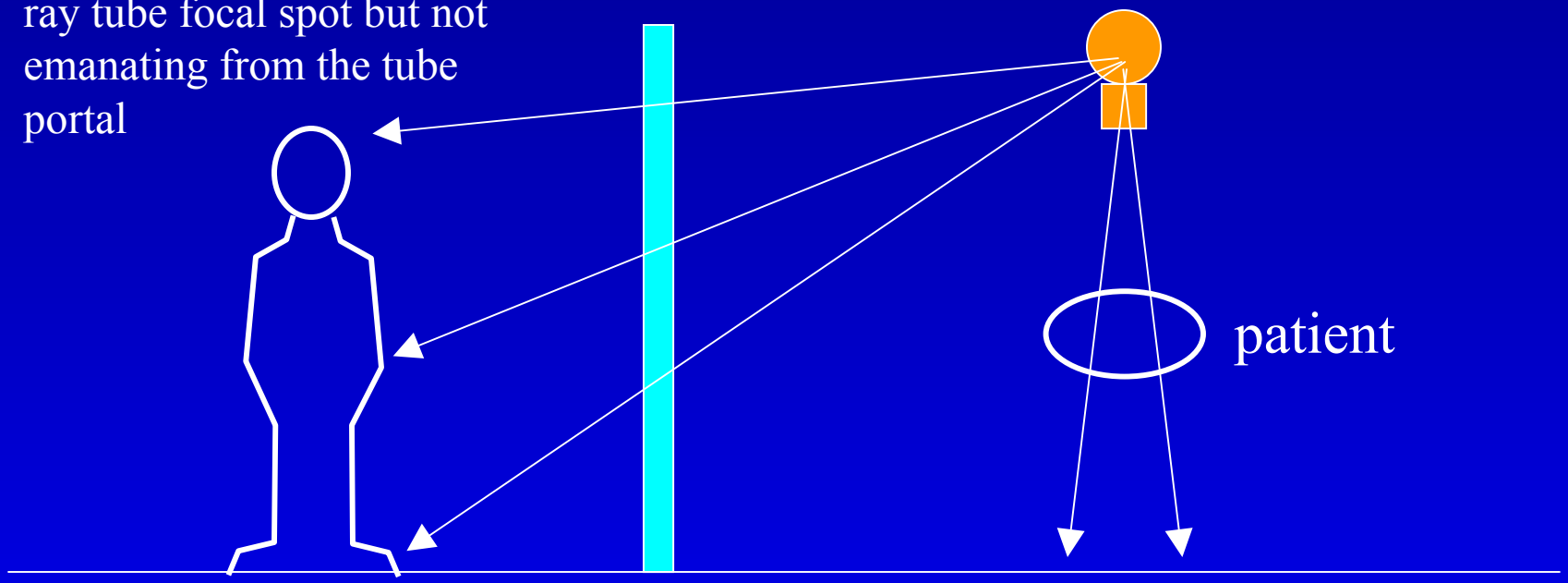
Scatter Radiation

- Same theory as NCRP-49
  - with reevaluated scatter fraction
  - 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

$$K_S(x,\theta) = \sum_{kVp} \frac{a_1 \times 10^{-6}\ K_W(kVp)\,(1-U)\,W(kVp)}{d_S^2} \frac{F}{d_F^2} B(x,kVp)$$

Leakage Radiation

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



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} (NCRP49 suggests 3.3 mA at 150 kVp, 4 mA at 125 kVp, 5 mA at 100 kVp; these remain fairly typical today)

Leakage radiation

- Because of heavy filtering by the tube housing, only the highest energy photons exist in the leakage beam
- Leakage intensity is inversely proportional to the square of the distance from the tube, d_L
- Transmission of leakage radiation is exponential, with the "hard" HVL at that kVp for the barrier material

New Leakage Model

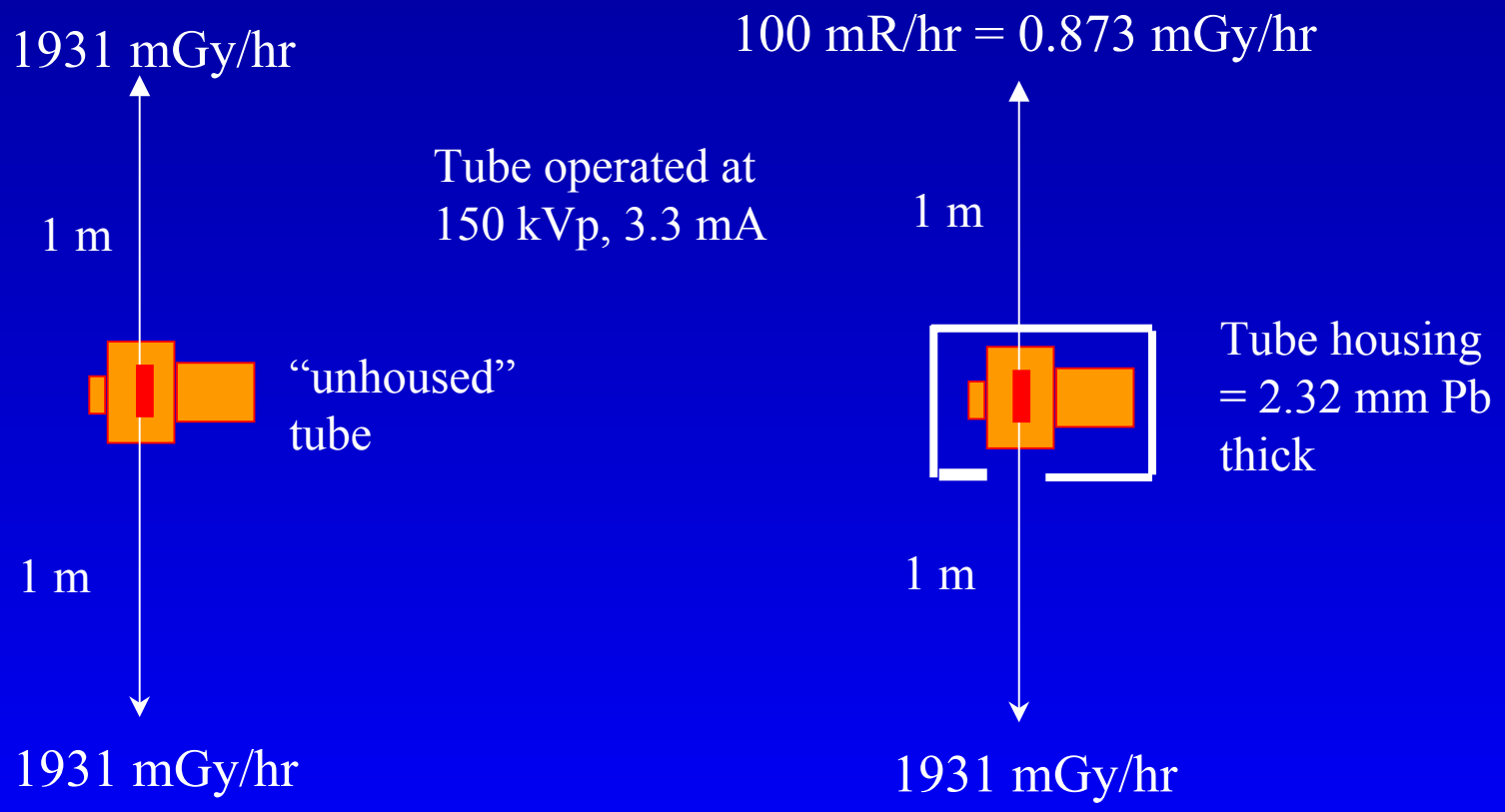
- For tube operating at techniques (*kVp*, *I)* with transmission through the tube housing B_{housing}, assume leakage kerma rate at 1 m through tube housing is

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

- Assume worst case scenario: leakage kerma rate = limit $\dot{K}_{\text{lim}}$ (was= *L)* for tube operation at leakage technique factors (conservative by factors of 3 to ~100s)

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 $\dot{K}_{\text{lim}}$ at kVp_{max}
- 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

$$K_L(kVp) = \frac{\dot{K}_{\text{lim}} \; kVp^2 \; (1-U) \, W(kVp) \, B_{\text{housing}}(kVp)}{kVp_{\text{max}}{}^2 \; I_{\text{max}} \; B_{\text{housing}}(kVp_{\text{max}})}$$

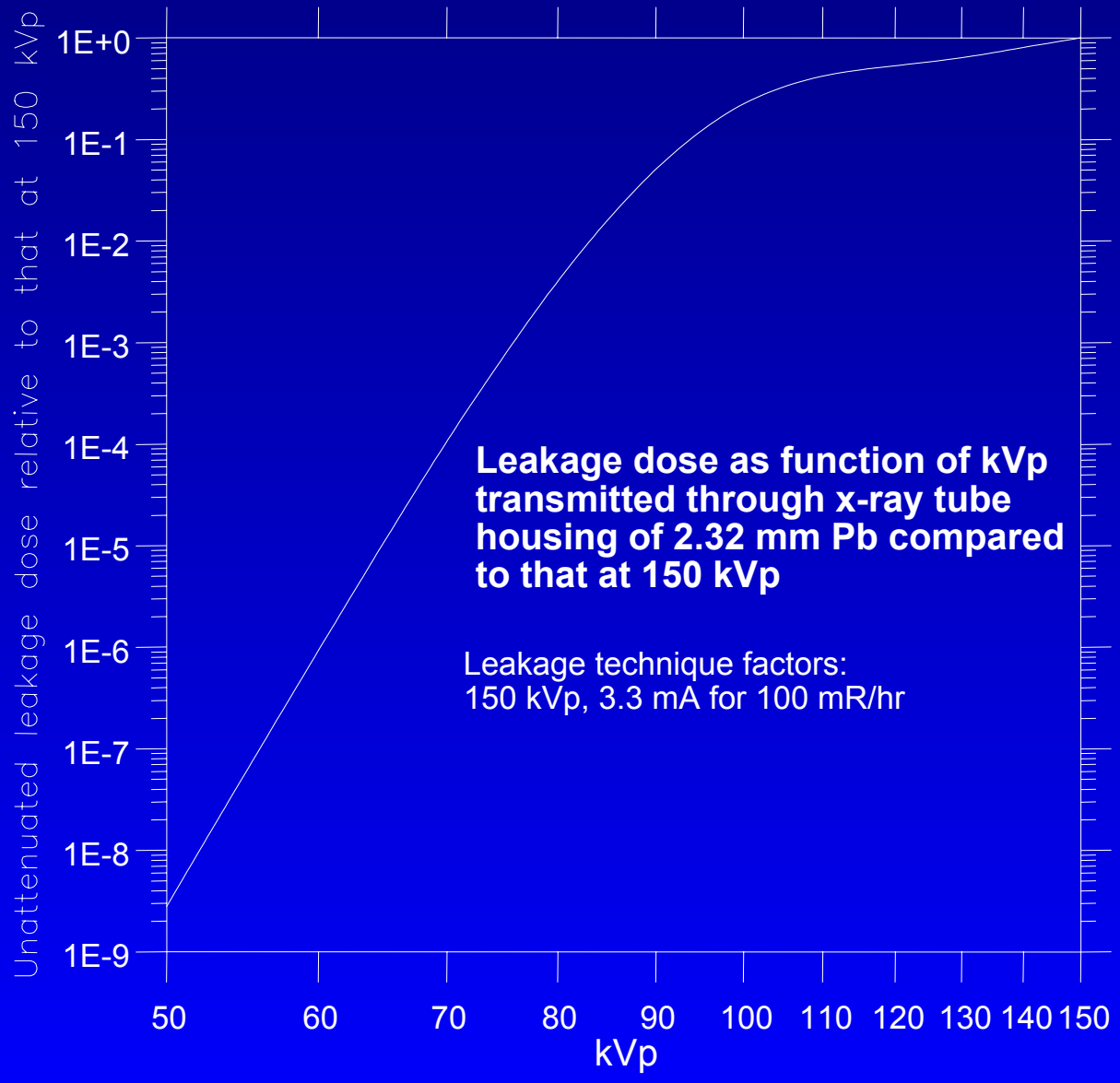
New Leakage Model

- 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

$$K_L(kVp) = \frac{\dot{K}_L \; kVp^2 \; (1-U)\, W(kVp)\, B_{\text{housing}}(kVp)}{kVp_{\max}{}^2 \; I_{\max} \; B_{\text{housing}}(kVp_{\max})} \times$$

$$\frac{1}{d_L^2} \times \exp\left(\frac{-\ln(2)\, x}{HVL(kVp)} \right)$$

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



Shielding Solution 1.

- Using the models of primary, scatter, and leakage radiation, calculate all kerma contributions from all tubes in the room

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

- Iteratively find the thickness x that causes $K(x) = P/T$
- cf. http://www.execpc.com/~dsimpkin/ for shareware

Solution 2. *Keep it Simple, Stupid*

- For each clinical workload distribution, of total workload W_{norm} per patient, for both primary and secondary barriers, can calculate:
  - **K^1 , the kerma per patient at 1 m distance**
  - ***B*, the transmission of the radiation generated by this workload distribution** for primary or secondary barriers

The Shielding Chore Simplifies

- The unshielded kerma for
  - N patients imaged per week, or, equivalently
  - total workload W_{tot} (where workload/pat = W_{norm})
- is then

$$K_{un} = \frac{K^1 U N}{d^2} = \frac{K^1 U W_{tot}}{d^2 W_{norm}}$$

  - (where U is replaced by 1 for secondary barriers)

Required Transmission

- Ratio of P/T to K_{un} is the required transmission

$$B(x) = \frac{P/T}{K_{un}} = \frac{P\,d^2}{N\,T\,UK^1} = \frac{P\,d^2\,W_{norm}}{W_{tot}\,T\,UK^1}$$

  - (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

Cath Lab Example: Wall

- Assume d=4 m, P = 0.02 mGy wk^{-1}, T=1, 12" =30.5 cm diameter image intensifier, 90° scatter, N=25 patients wk^{-1}
- Look up secondary kerma at 1 m per patient for cath lab distribution: K^1 = 2.7 mSv patient^{-1}
- Total unshielded kerma is then

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

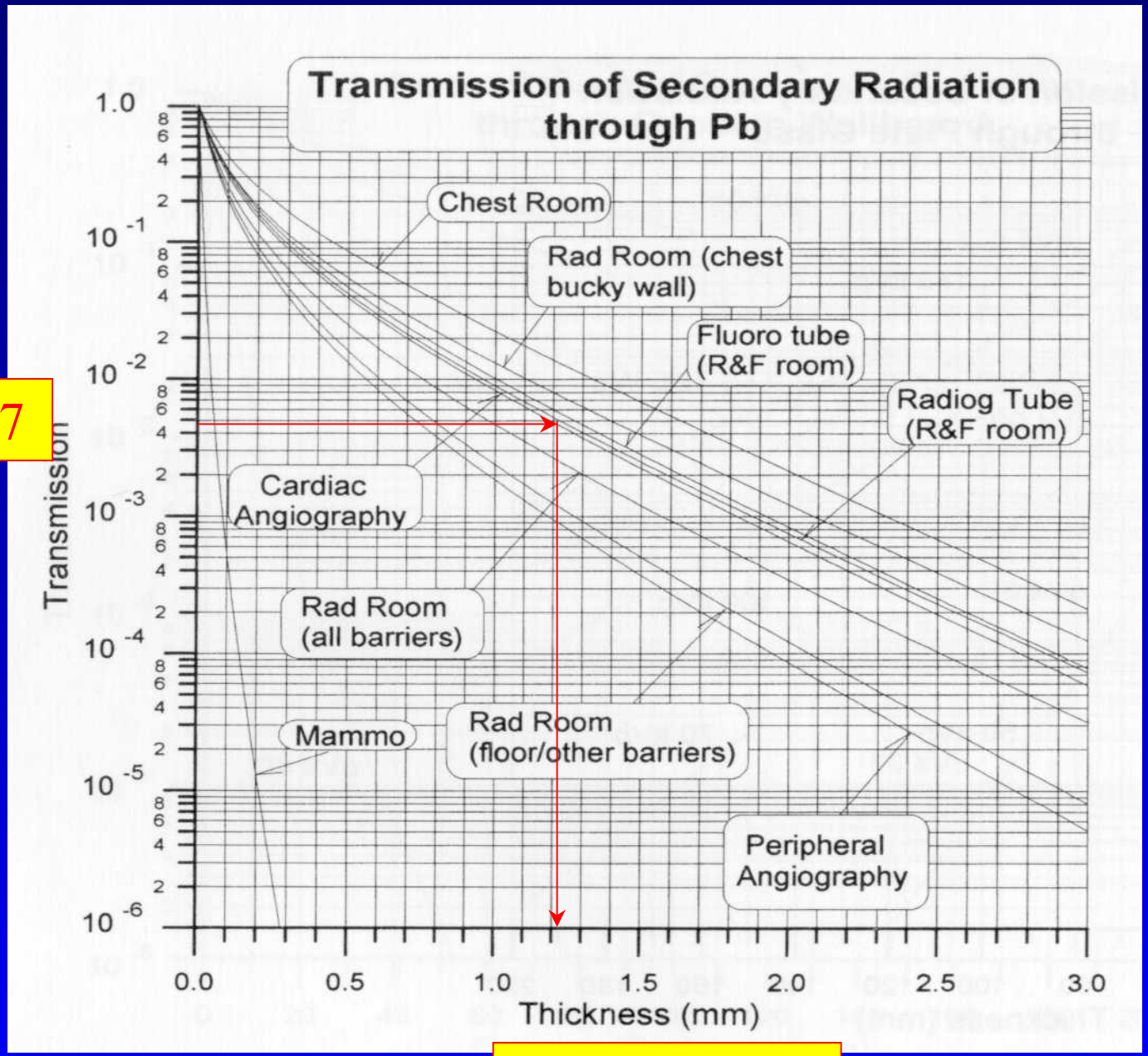
Cath Lab Example: Wall

- Required transmission is

$$B = \frac{P/T}{K_{un}} = \frac{0.02\ mGy\ wk^{-1}}{4.22\ mGy\ wk^{-1}} = 0.0047$$

- Look on graph for transmission curve for secondary radiation from Cardiac Angiography Lab → Requires 1.2 mm Pb (which is satisfied by standard 1/16" sheet)
- *(vs. 1.88 mm Pb requirement of NCRP-49)*

B=0.0047

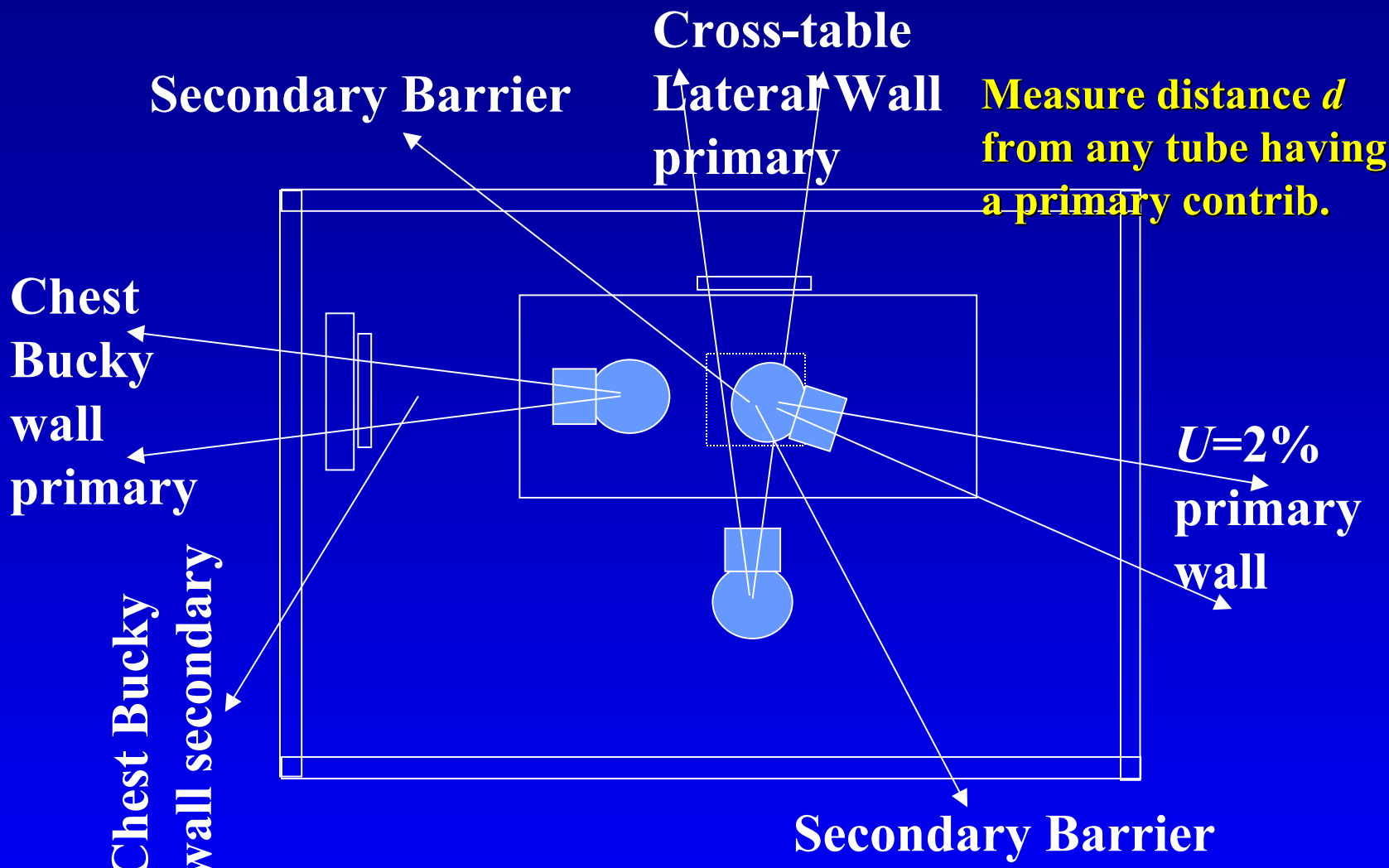


x=1.2 mm Pb

Solution 3. A "Representative Room"

- Even the simplest, most common radiographic room is a complicated assemblage of x-ray tube positions/ workload distributions,
- Calculate the barrier thickness requirements for an *assumed*:
  - conservatively small room layout
    - assures contribution from all sources is maximal
  - distribution of the kinds of exposures made amongst the tubes/positions

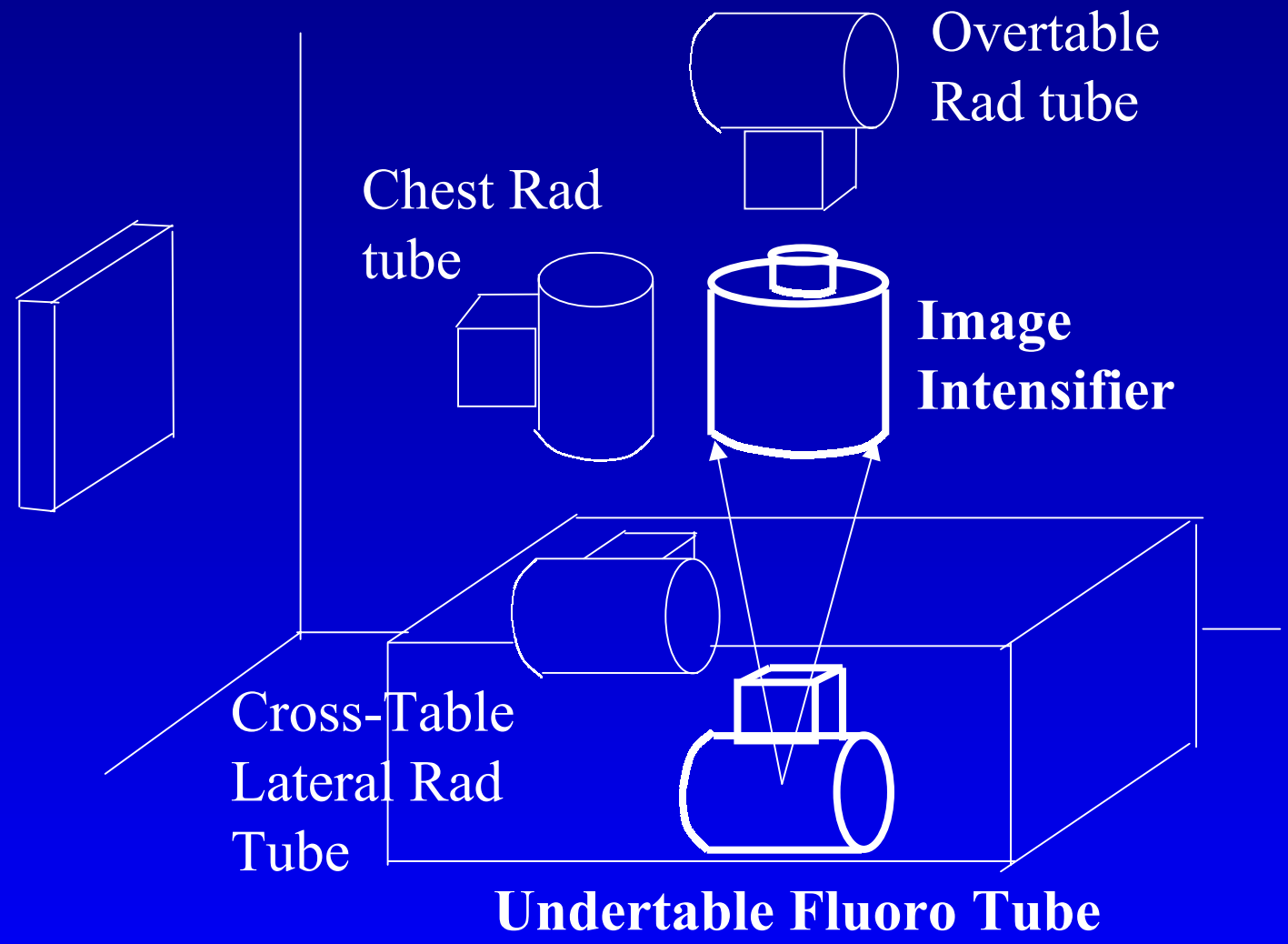
Representative Radiographic Room



"Representative R&F Room"

- Also assume a "Representative R&F room"
  - Has same layout as "Representative Radiographic Room" except an undertable fluoro x-ray tube and image intensifier are added, centered over table
  - Does fluoro as well as standard radiographic work, with table and chest buckies and crosstable work
- Assume
  - 75% of patients imaged as if in radiographic room
  - 25% of patients imaged by fluoroscopy tube

"Representative R&F Room"



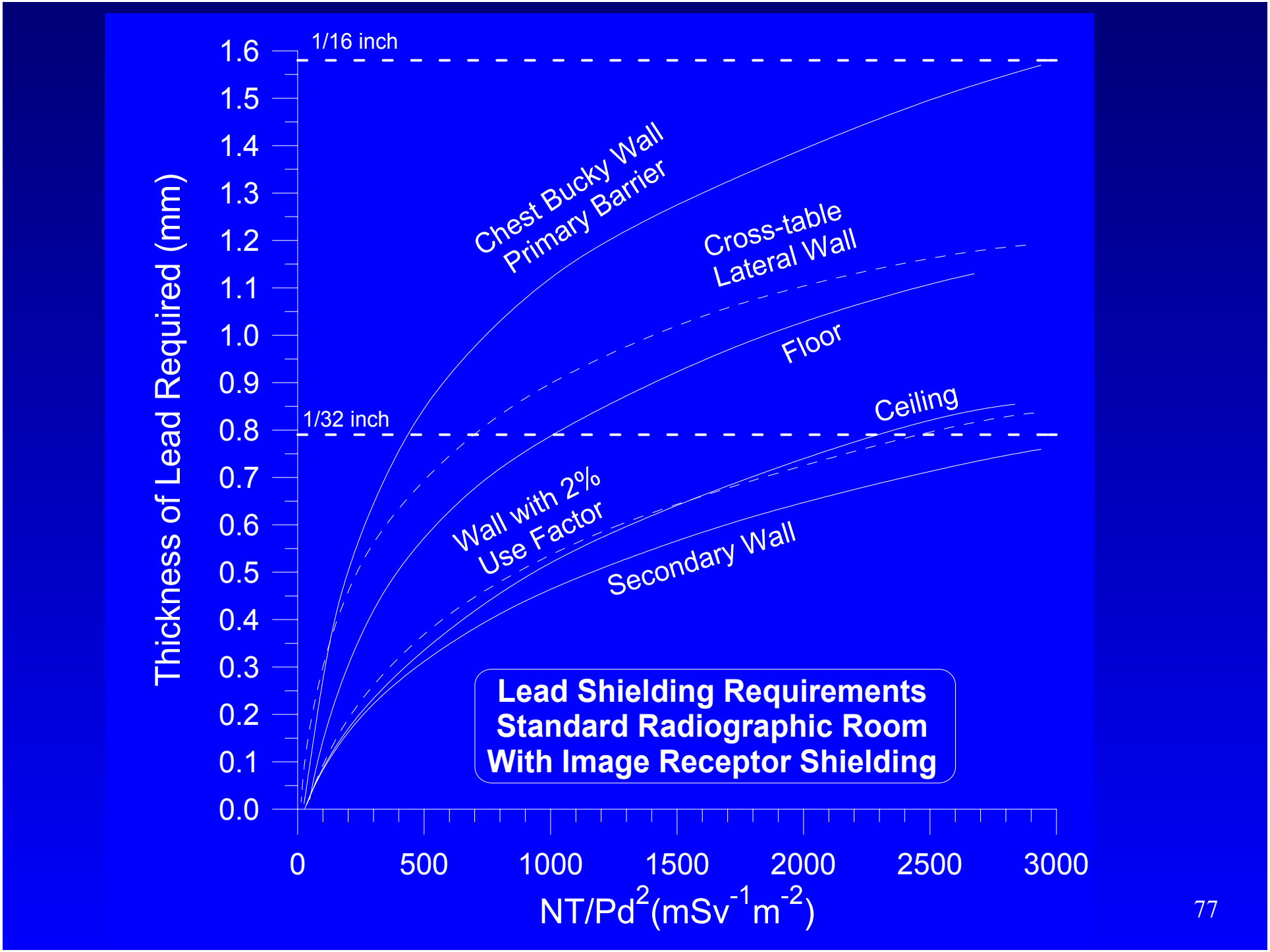
"Representative Room" Barrier Requirements

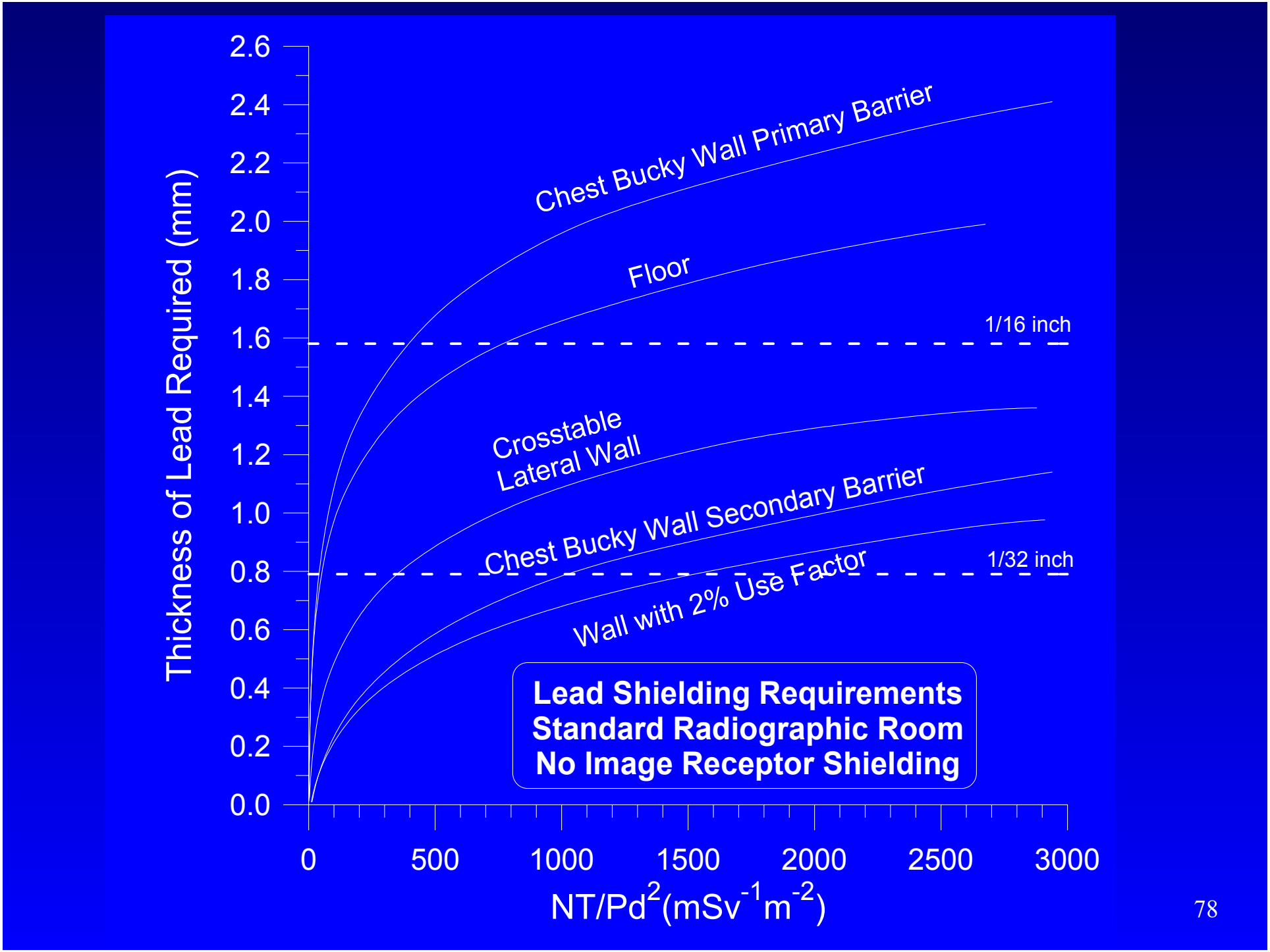
- Given barrier transmission requirement

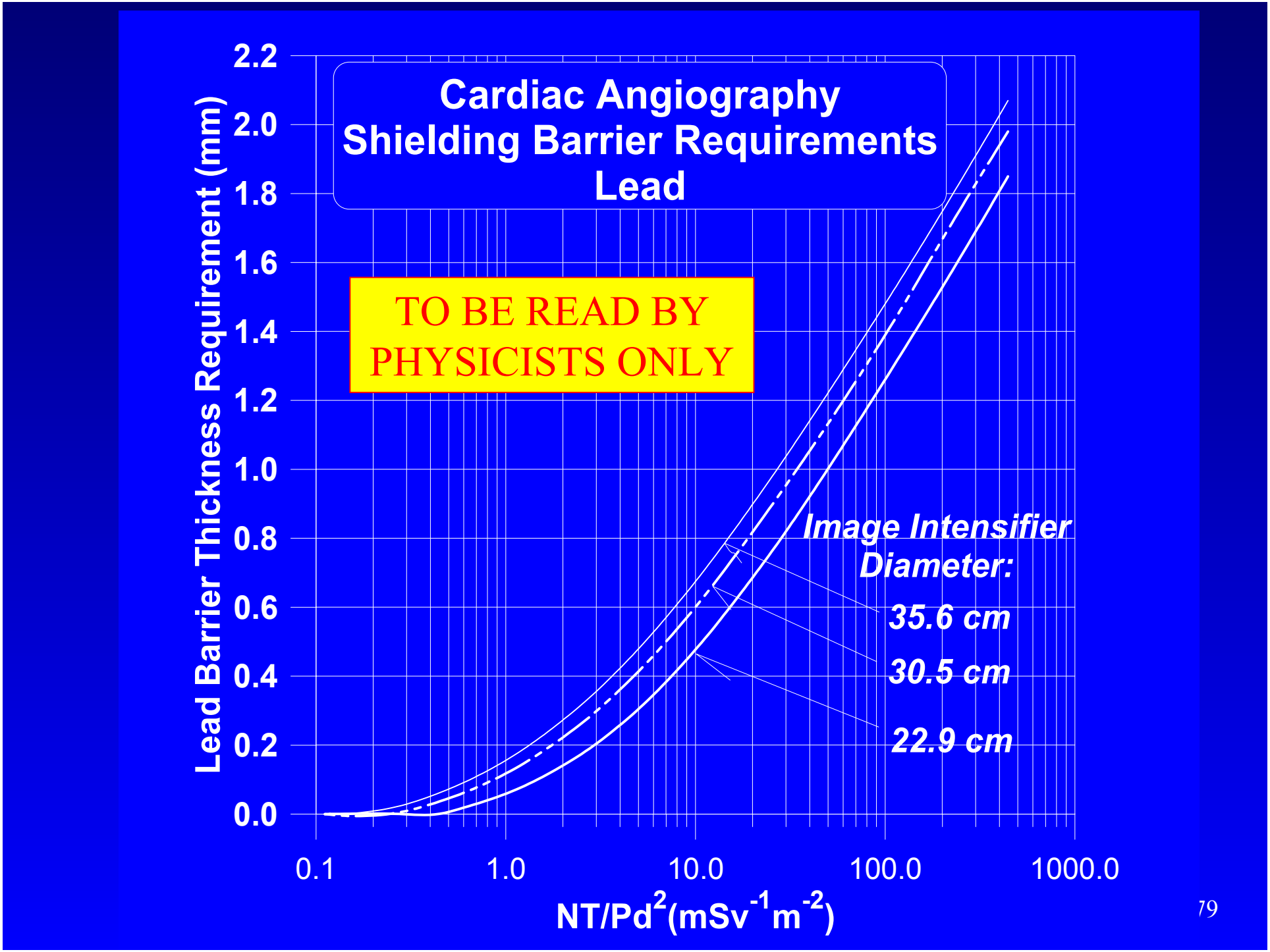
$$B(x) = \frac{P\,d^2}{N\,T\,UK^1} = \frac{P\,d^2\,W_{norm}}{W_{tot}\,T\,UK^1}$$

- then the barrier thickness requirement must scale as:

$$\frac{N\,T}{P\,d^2} = \frac{W_{tot}\,T}{W_{norm}\,P\,d^2}$$


1/16 inch
1/32 inch
Chest Bucky Wall
Primary Barrier
Cross-table
Lateral Wall
Floor
Ceiling
Wall with 2%
Use Factor
Secondary Wall
Lead Shielding Requirements
Standard Radiographic Room
With Image Receptor Shielding
Thickness of Lead Required (mm)
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0
500
1000
1500
2000
2500
3000
NT/Pd2(mSv-1m-2)


Thickness of Lead Required (mm)
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
500
1000
1500
2000
2500
3000
NT/Pd2(mSv-1m-2)
Chest Bucky Wall Primary Barrier
Floor
1/16 inch
Crosstable
Lateral Wall
Chest Bucky Wall Secondary Barrier
Wall with 2% Use Factor
1/32 inch
Lead Shielding Requirements
Standard Radiographic Room
No Image Receptor Shielding


Cardiac Angiography
Shielding Barrier Requirements
Lead
TO BE READ BY
PHYSICISTS ONLY
Lead Barrier Thickness Requirement (mm)
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0.1
1.0
10.0
100.0
1000.0
NT/Pd2(mSv-1m-2)
Image Intensifier
Diameter:
35.6 cm
30.5 cm
22.9 cm

Equivalency of Shielding Materials

- From "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**

CT Scanner Shielding: Overview

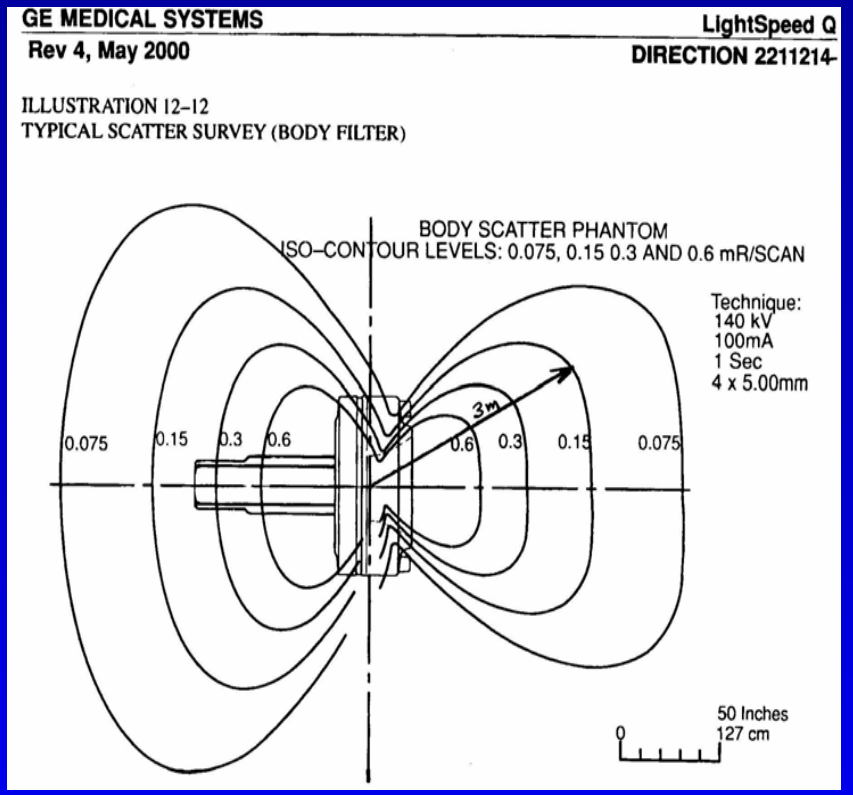
- Estimate unshielded weekly kerma in occupied area near scanner, K_{un}
- Presume P/T
- Barrier requires transmission $B = \frac{P/T}{K_{un}}$
- Get barrier thickness
  - Simpkin *Health Phys* **58**, 363-7: 1990 (refit)

CT Scanners: Estimate Unshielded Kerma

- Estimate Workload
  - 100 - 200 patient/wk typically
  - Helical/multislice scanners: probably
    - 20 cm total thickness imaged for head patients
    - 40-60 cm total thickness imaged for body patients

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 Scanners: Estimate Unshielded Kerma

- Doug Shearer looked at ratio of ambient kerma at 1 m per 10 mm slice scanned to the peripheral (1 cm deep) CTDI
- Shearer's "CT scatter fraction," κ:
  - **Head scans:** $\kappa_{head} = 9 \times 10^{-5}$
  - **Body scans:** $\kappa_{body} = 3 \times 10^{-4}$

Unshielded Kerma from CTDI

- Estimate, for either head or body scans, the ambient kerma per patient around scanner for a slice T_b (mm) thick generated by N_R rotations each at technique $mAs_{Clinical}$

$$K_{CT}^{1}(mGy) = \frac{CTDI(mGy)}{mAs_{CTDI}} \times \kappa \times mAs_{clinical} \times \frac{T_b(mm)}{10\ mm} \times N_R$$

Unshielded Kerma from CTDI

- Can recast this in terms of the thickness of each patient imaged, $L = N_R \times T_b \times pitch$, with each rotation acquired at technique $mAs_{Clinical}$

$$K_{CT}^{1}(mGy) = \frac{CTDI(mGy)}{mAs_{CTDI}} \times \kappa \times mAs_{clinical} \times \frac{L(mm)}{10\ mm} \times \frac{1}{pitch}$$

Unshielded Kerma from DLP

- Since the product of the CTDI used for each patient and the thickness of the patient imaged is the Dose Length Product, *DLP*,

$$K_{CT}^{1}(mGy) = \kappa \times DLP$$

- The *DLP* values can be read off of the scanner, or from European Commission Guidelines:
  - *DLP* = 1,200 mGy cm for heads
  - *DLP* = 1,000 mGy cm for bodies

CT Scanner Example

- Wall near CT scanner: $P/T = 0.02$ mGy wk^{-1}, d=3 m
- 150 patients wk^{-1} (50 bodies, 100 heads)
- Assume
  - 600 mm thickness imaged for each body patient
  - 200 mm for head patients
- CTDI(head)= 40 mGy, CTDI(body)= 2.5 mGy, at 140 kVp & mAs typical of clinical use.
- Pitch=1, 140 kVp

CT Scanner Example

- Then, the unshielded kerma per head patient:

$$K_{CT}^{1} = 40\ mGy \times (9 \times 10^{-5}) \times \frac{200\ mm}{10\ mm} = 0.072\ mGy$$

- and kerma per body patient is

$$K_{CT}^{1} = 25\ mGy \times (3 \times 10^{-4}) \times \frac{600\ mm}{10\ mm} = 0.45\ mGy$$

- so total unshielded weekly kerma at 1 m is

$K_{un}{}^{1}$ = (100×0.072 mGy) + (50 ×0.45 mGy)
= 29.7 mGy

CT Scanner Example

- The unshielded weekly kerma at 3 m is

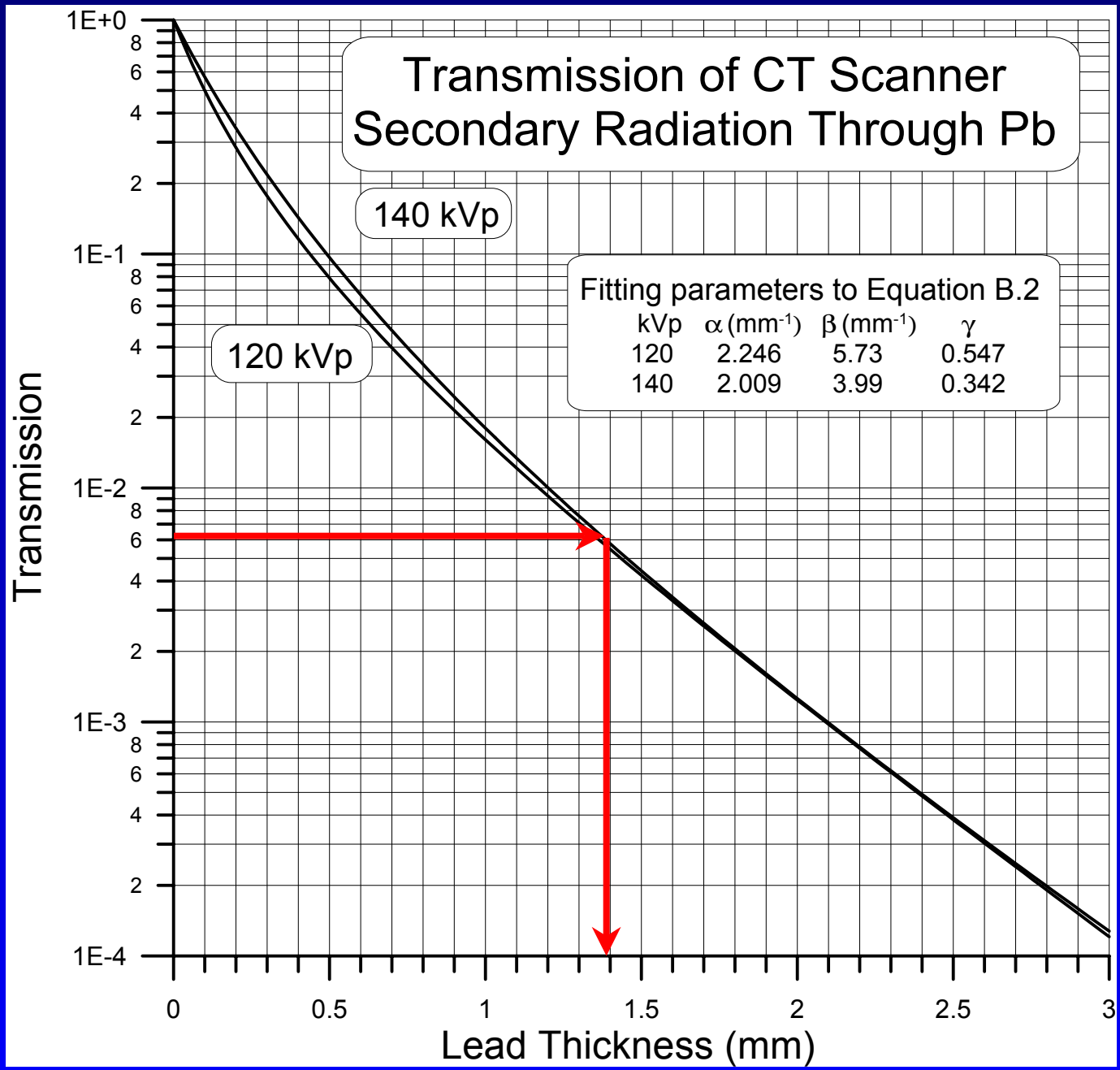
$$K_{un} = \frac{29.7\ mGy}{(3\ m)^2} = 3.3\ mGy$$

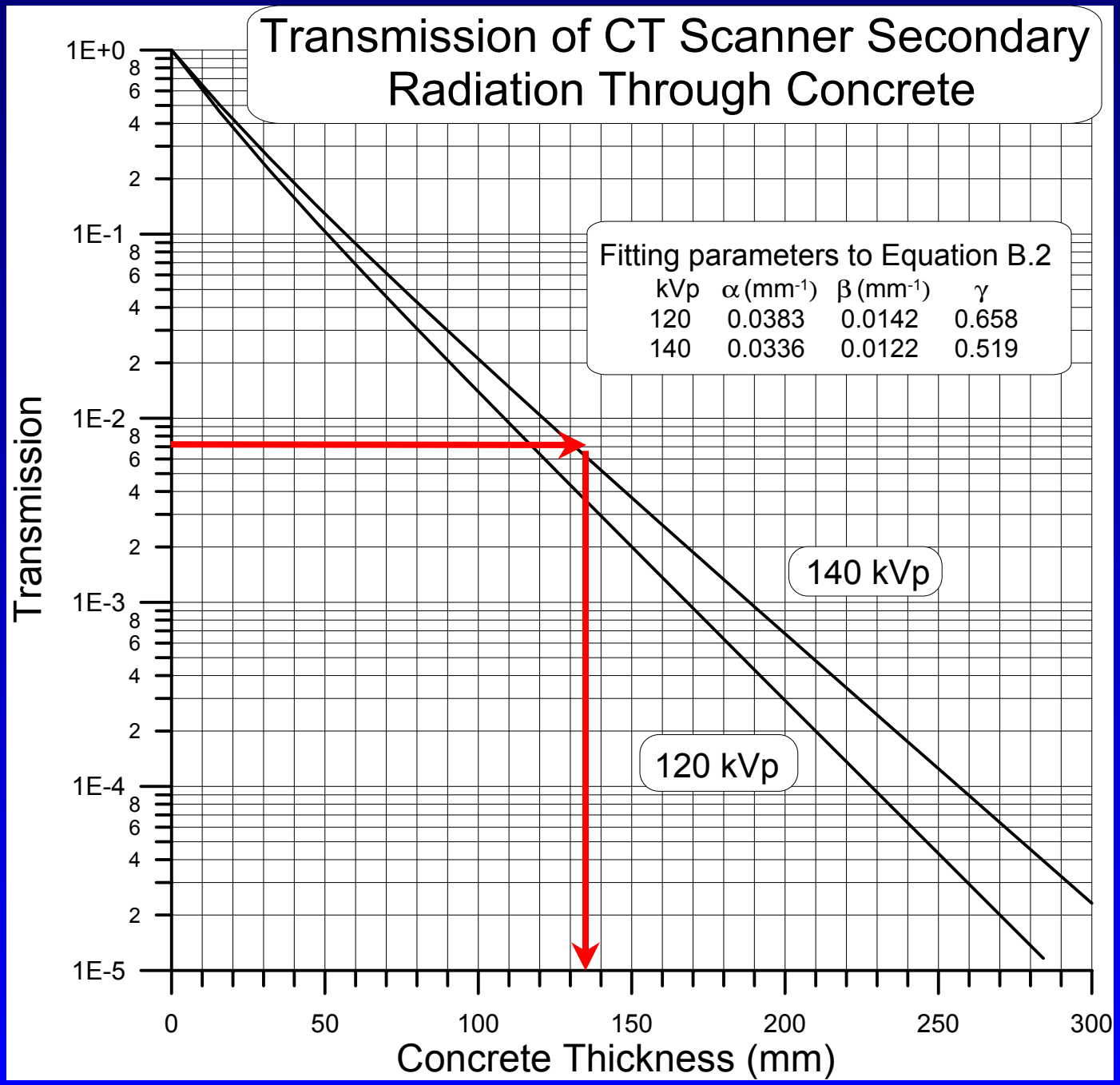
- The transmission required in this wall is therefore

$$B = \frac{0.02\ mGy}{3.3\ mGy} = 6.1 \times 10^{-3}$$

- which, at 140 kVp, is achieved by
  - 1.4 mm Pb, or
  - 136 mm = ***5.4 inches standard density concrete***

WATCH OUT ABOVE & BELOW!


Transmission of CT Scanner
Secondary Radiation Through Pb
140 kVp
120 kVp
Fitting parameters to Equation B.2
kVp α (mm-1) β (mm-1) γ
120 2.246 5.73 0.547
140 2.009 3.99 0.342
Transmission
1E+0
8
6
4
2
1E-1
8
6
4
2
1E-2
8
6
4
2
1E-3
8
6
4
2
1E-4
0
0.5
1
1.5
2
2.5
3
Lead Thickness (mm)


Transmission of CT Scanner Secondary Radiation Through Concrete
Fitting parameters to Equation B.2
kVp α (mm-1) β (mm-1) γ
120 0.0383 0.0142 0.658
140 0.0336 0.0122 0.519
140 kVp
120 kVp
Transmission
1E+0
1E-1
1E-2
1E-3
1E-4
1E-5
0
50
100
150
200
250
300
Concrete Thickness (mm)

Chapter 6: Surveys

- Inspect for proper shielding barrier placement and/or voids
  - visual inspection during construction
  - radiation survey with GM or scintillation survey meter looking at penetration of x- or gamma rays

Chapter 6: Surveys

- Evaluate adequacy of barrier thickness for the occupied area
  - Determine thickness of barrier
    - visually
    - radiation survey
  - Do “inverse shielding calculation” to determine how many patients may be imaged per week so as not to exceed design goal

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, kermas are $\propto W$
  - *W* distributed over range of *kVp*; determines
    - unshielded kerma
    - transmission
  - surveyed workload
    - total workload ≠ 1000 mA·min/wk
    - radiographic rooms: ~300 mA·min/wk
    - cardiac angiography: ~3000 mA·min/wk
  - in radiographic room, chest bucky gets ~all the high kVp exposures

Conclusions III

- Models for shielding developed
  - primary, scatter, and leakage radiation
- Solutions for determining barrier thickness
  - Full theory requires numerical/graphical solution
  - Manual calcs assuming TG-9 workload survey
    - unshielded kerma per patient
    - NT/Pd^2 formalism for "standard" rad & R&F room

Conclusions IV

- 1/16 inch Pb remains as standard wall barrier
- 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
  - unshielded kerma
    - manufacturer's isoexposure curves
    - Shearer's scatter fraction applied to CTDI, DLP
  - workload is high
    - 100-200 patients/wk
    - typically 200 mm heads, 600 mm bodies imaged
  - transmission from Simpkin (1990) or hard HVL
  - results
    - 1/16 inch Pb remains as standard wall barrier
    - floors/ceilings may need attention

Conclusions VI

- NCRP Report No. 147 will be out shortly
- Paraphrasing M.L. King on the steps of the Lincoln Monument, 1963: *"Here at last, here at last. Thank God almighty it's here at last."*