CRSO Meeting, Portland, OR 7/10/07

NCRP 147 Shielding Calculations

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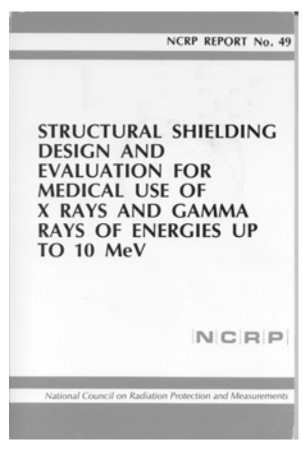
History - NCRP Report # 49

- 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



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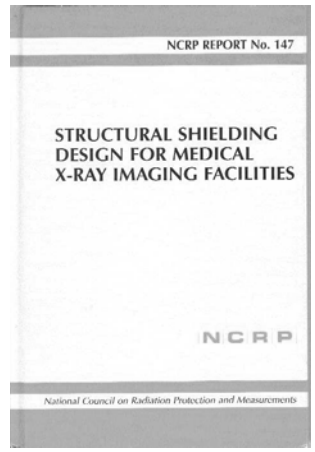
History - NCRP Report #147

- 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)



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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?

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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/she'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*

- 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*

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Design Goal, *P*

Design Goal *P*	***Controlled area***	***Uncontrolled areas***
NCRP-49	50 mGy/y =1 mGy/wk	5 mGy/y =0.1 mGy/wk
NCRP-147	*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*

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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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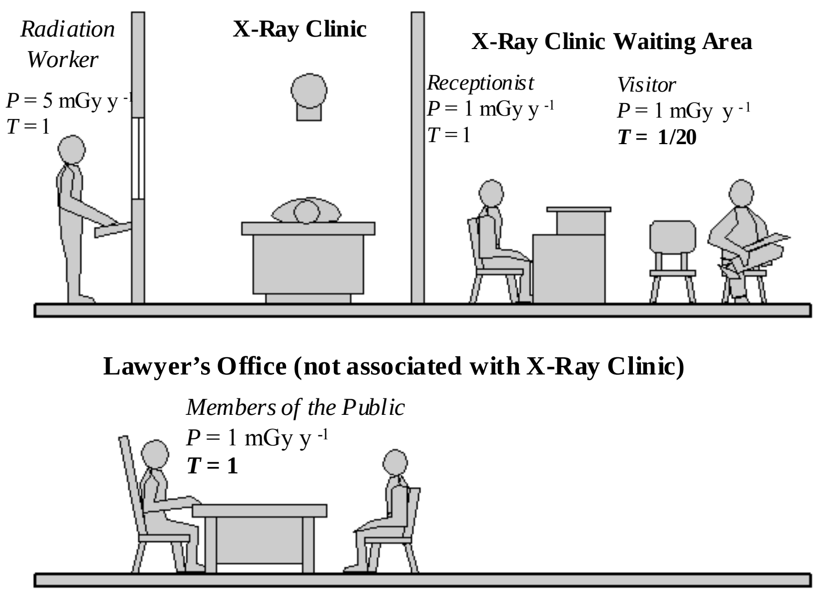
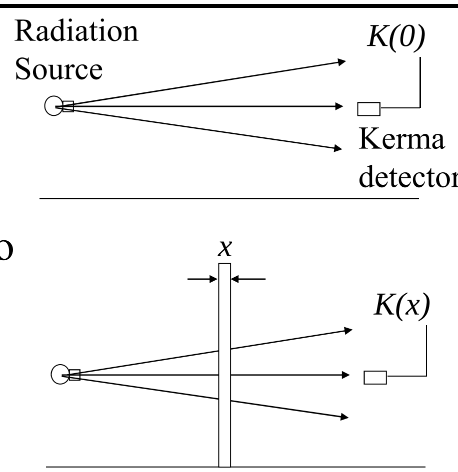


X-ray Beam Transmission

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

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



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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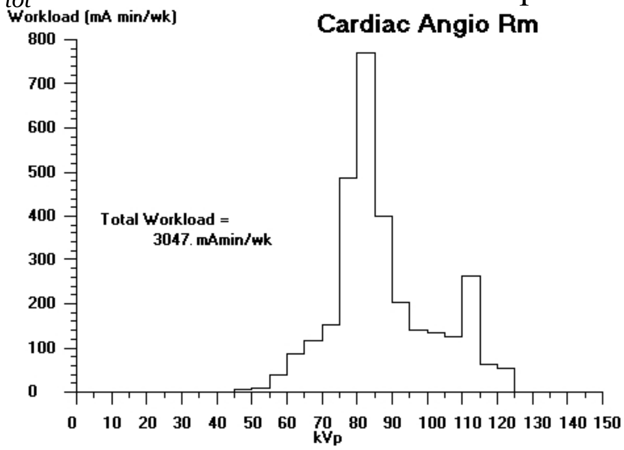
Workload Distribution, *W(kVp)*

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



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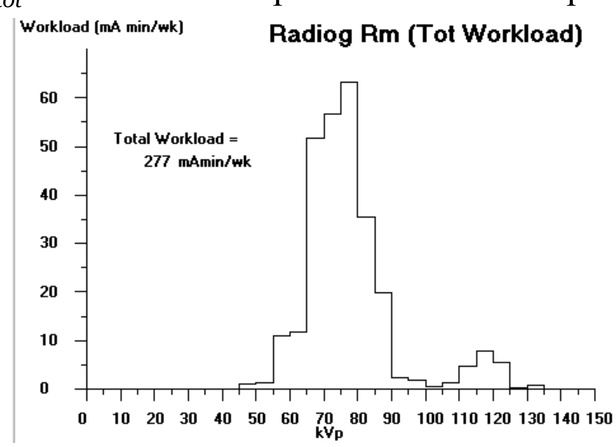
Workload Distribution, *W(kVp)*

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



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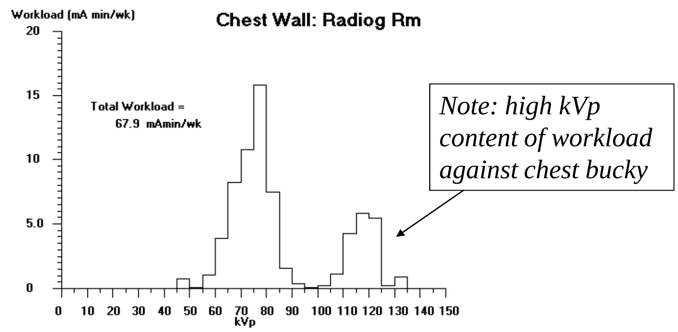
General Radiographic Room Workload Distribution, *W(kVp)*

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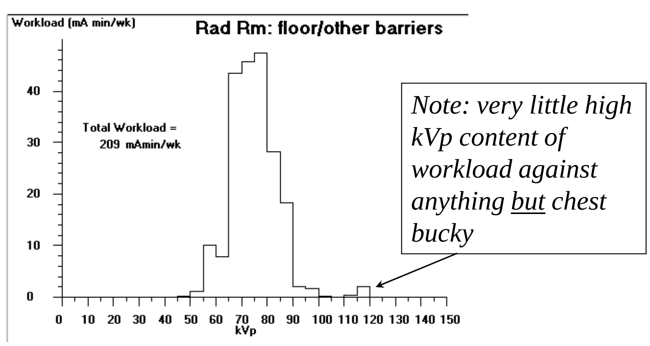
General Radiographic Room Workload Distribution, *W(kVp)*

- 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
  - 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 (!)

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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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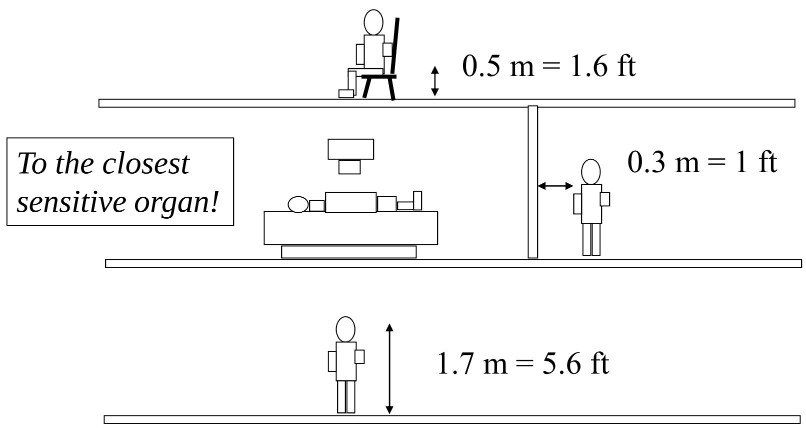
Where in the occupied area do you calculate the kerma?



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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. *$NT/(Pd^2)$*

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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**
  - **leakage radiation**

} *Secondary radiation*

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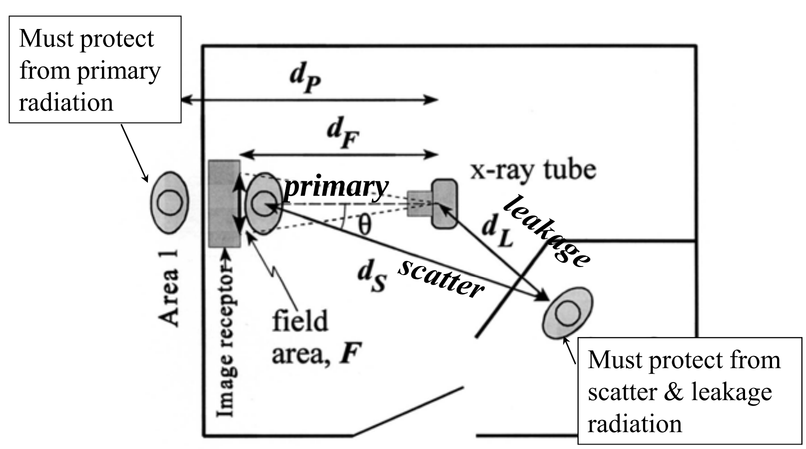
Primary, Scatter, and Leakage



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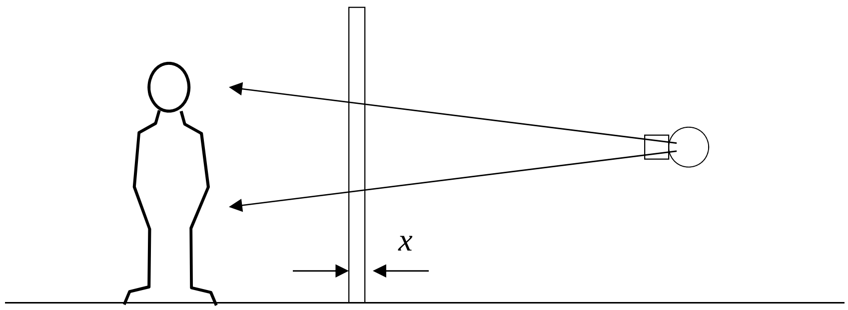
Primary Radiation:
The NCRP49 Model



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

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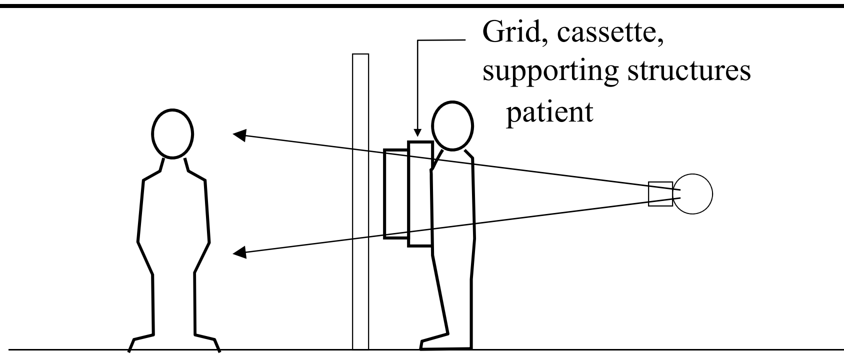
Primary Radiation:
A Realistic Model



Primary radiation is significantly attenuated before reaching barrier

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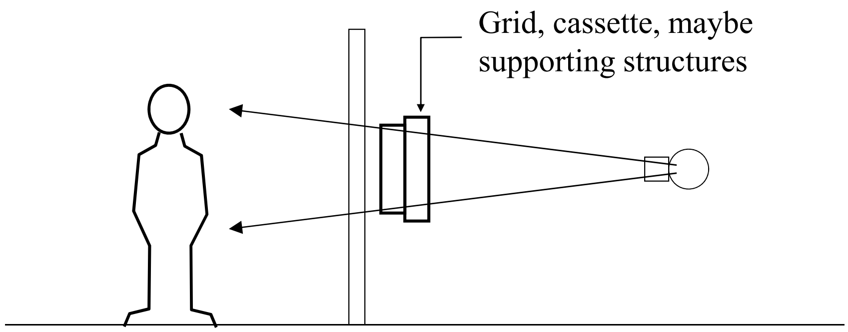
Primary Radiation: A Conservative, Realistic Model



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

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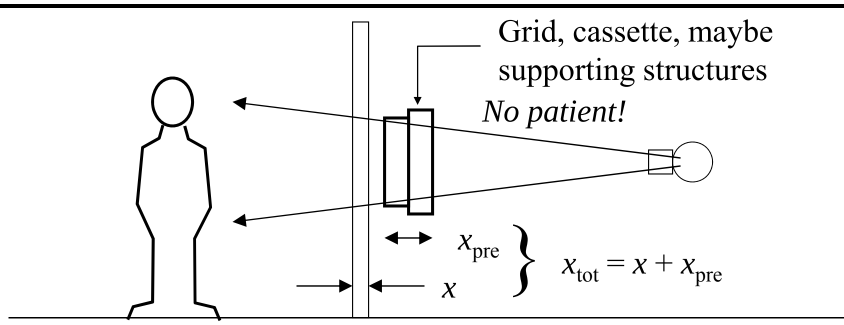
Primary Radiation: NCRP-147 Model



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.

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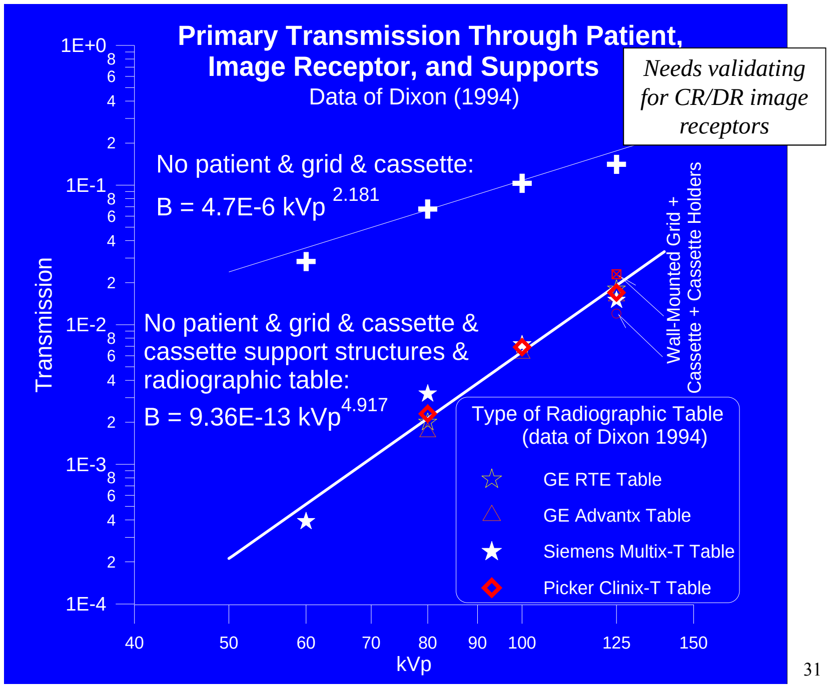
Primary Transmission Through Patient, Image Receptor, and Supports
Data of Dixon (1994)
Needs validating for CR/DR image receptors
No patient & grid & cassette:
B = 4.7E-6 kVp 2.181
No patient & grid & cassette & cassette support structures & radiographic table:
B = 9.36E-13 kVp 4.917
Wall-Mounted Grid + Cassette + Cassette Holders
Type of Radiographic Table (data of Dixon 1994)
GE RTE Table
GE Advantx Table
Siemens Multix-T Table
Picker Clinix-T Table
Transmission
kVp

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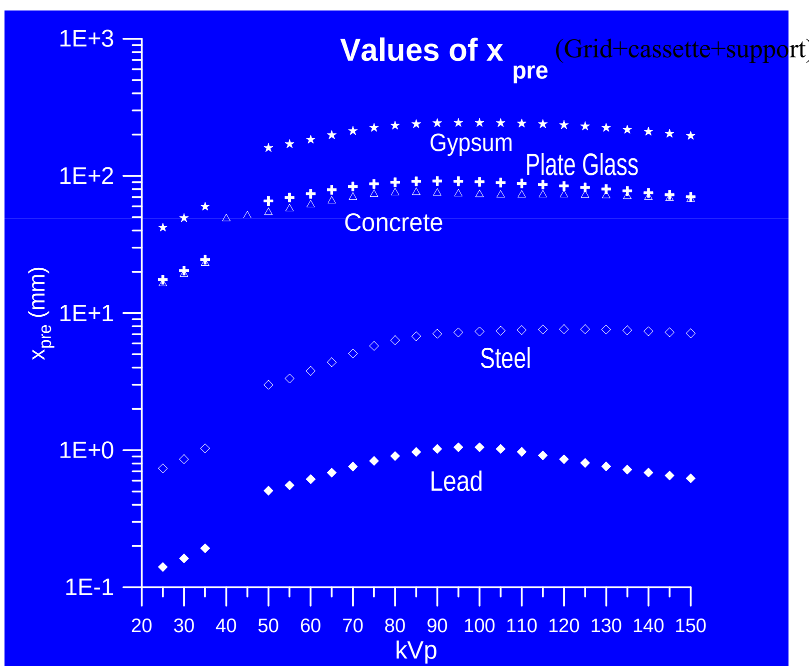
Values of x pre (Grid+cassette+support)
Gypsum
Plate Glass
Concrete
Steel
Lead
x pre (mm)
kVp

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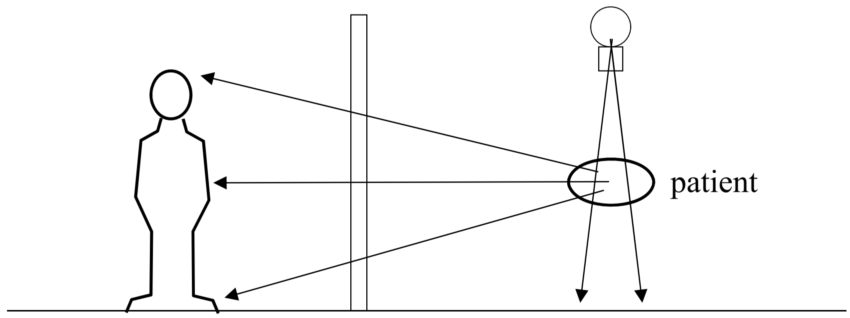
Scatter Radiation



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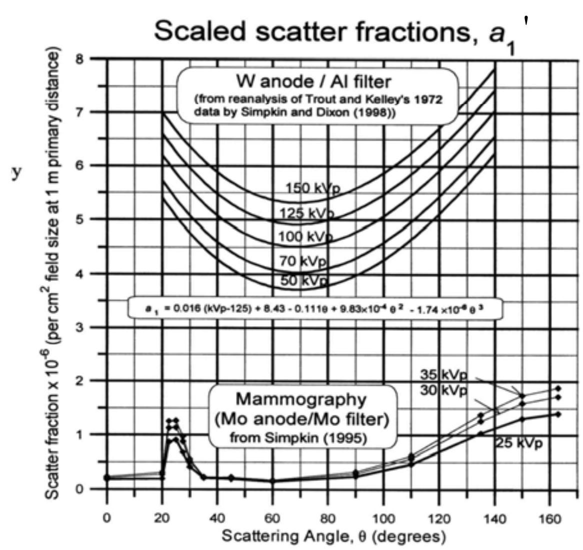
Scaled Normalized Scatter Fraction



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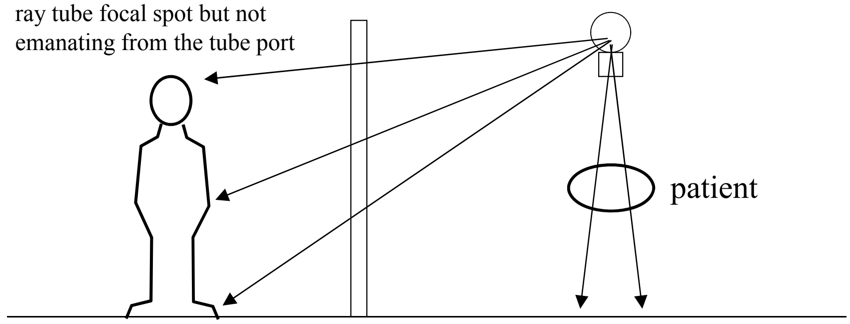
Leakage Radiation

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



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

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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

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

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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.

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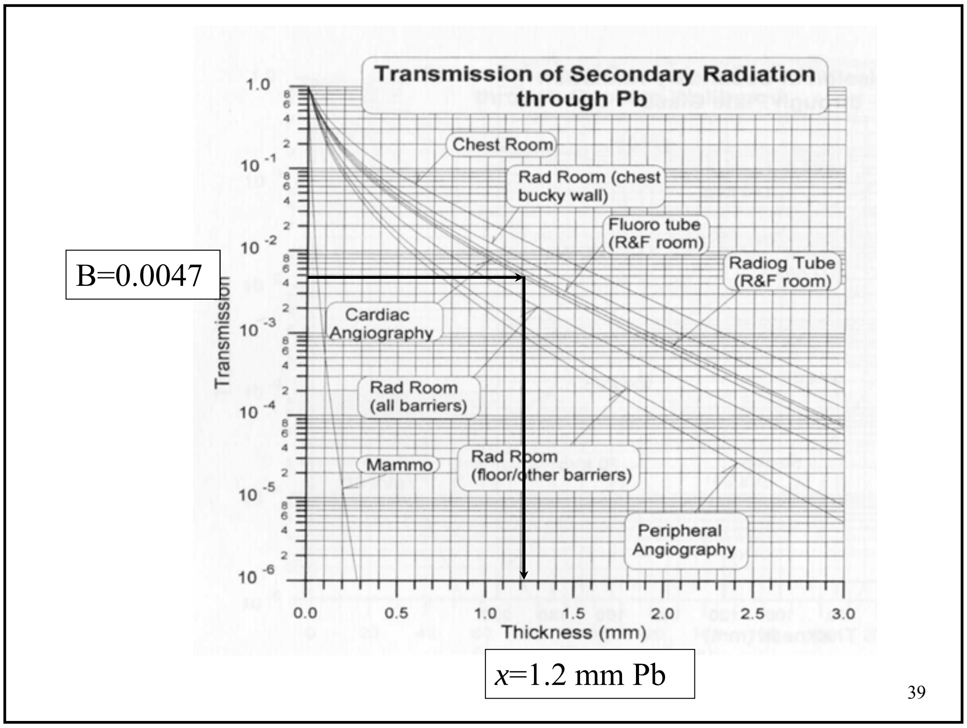
Transmission of Secondary Radiation through Pb
B=0.0047
Chest Room
Rad Room (chest bucky wall)
Fluoro tube (R&F room)
Radiog Tube (R&F room)
Cardiac Angiography
Rad Room (all barriers)
Mammo
Rad Room (floor/other barriers)
Peripheral Angiography
Transmission
Thickness (mm)
x=1.2 mm Pb
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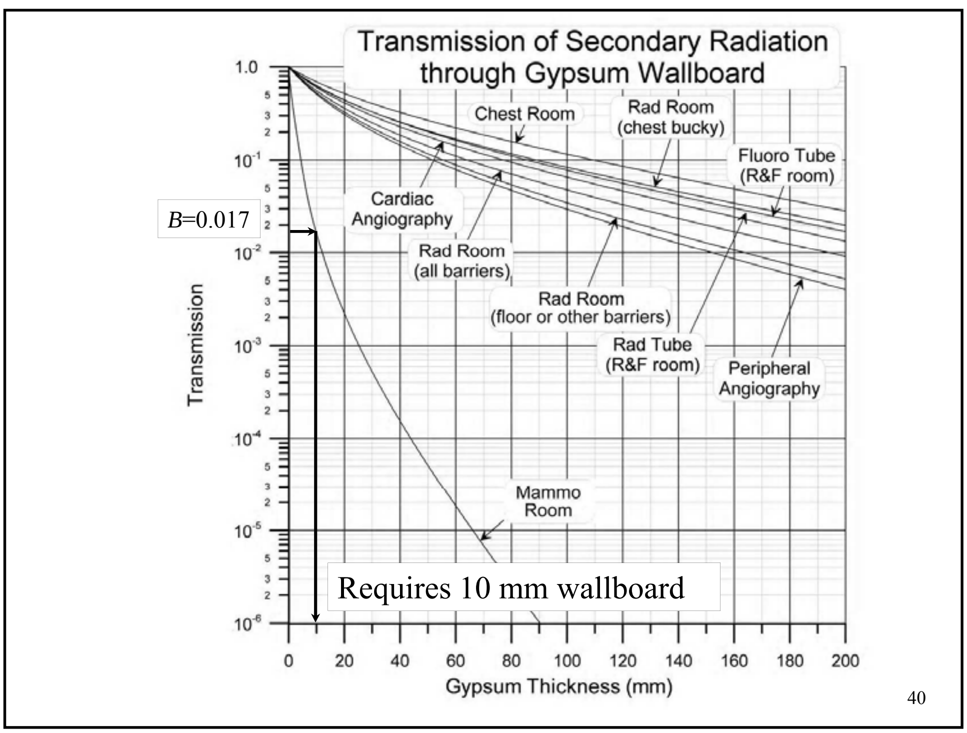
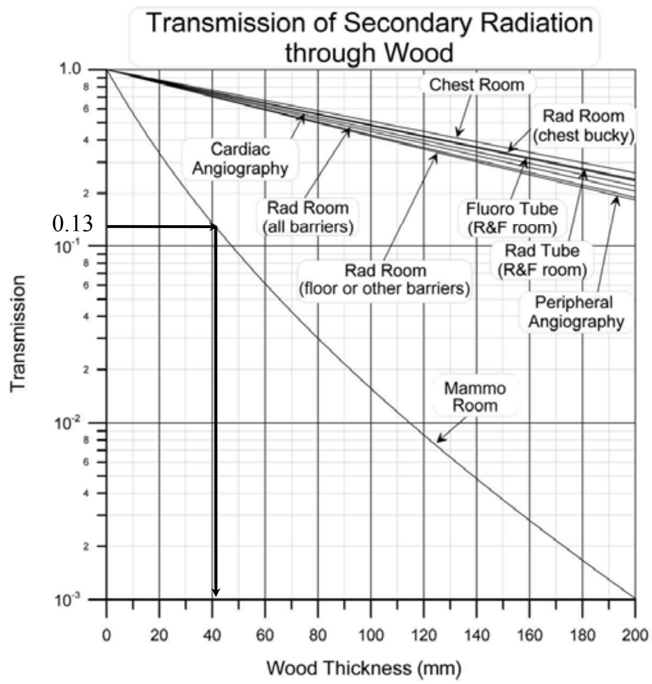

Transmission of Secondary Radiation through Gypsum Wallboard
B=0.017
Chest Room
Rad Room (chest bucky)
Fluoro Tube (R&F room)
Cardiac Angiography
Rad Room (all barriers)
Rad Room (floor or other barriers)
Rad Tube (R&F room)
Peripheral Angiography
Mammo Room
Requires 10 mm wallboard
Transmission
Gypsum Thickness (mm)
40



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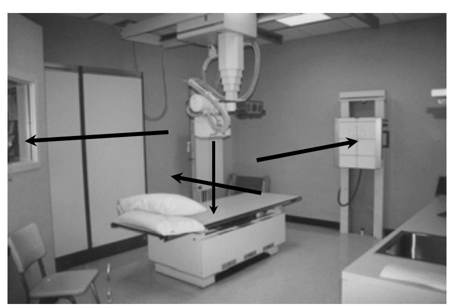
Shielding Model No. 3 for "Representative Rooms"

- Scheme No. 2 can't handle complicated assemblages of x-ray tubes/ positions/ workload distributions, such as in a radiographic or radiographic/ fluoroscopic room



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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*

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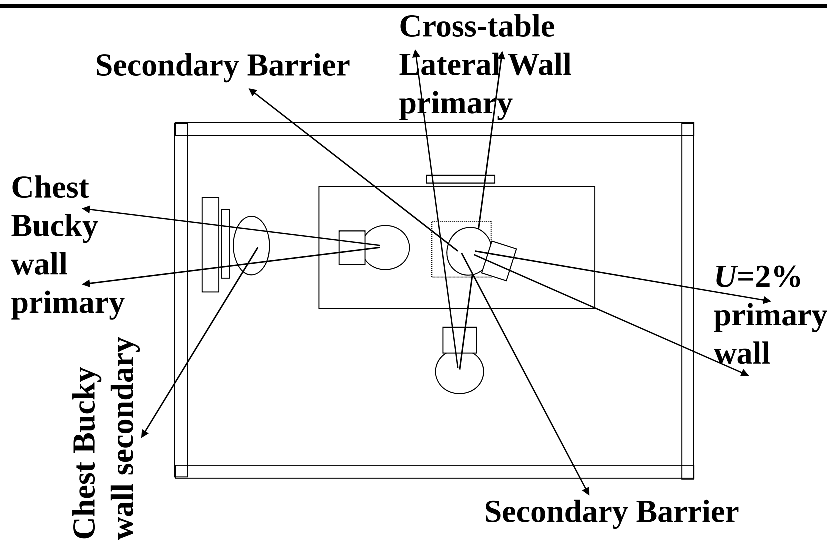
Representative Radiographic Room



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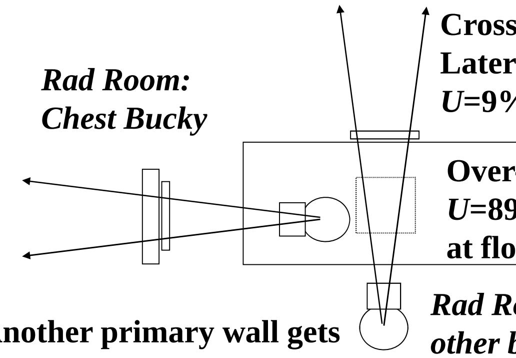
Representative Radiographic Room

Cross-table Lateral Position *U*=9%

Rad Room: Chest Bucky



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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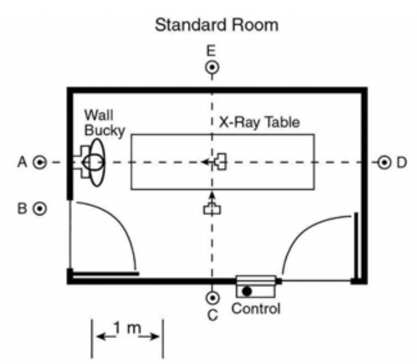
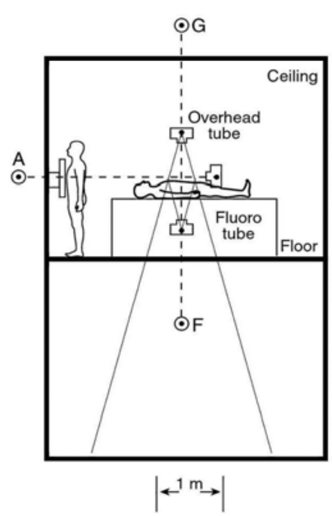
Representative Radiographic Room

The world's smallest possible x-ray room!





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"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

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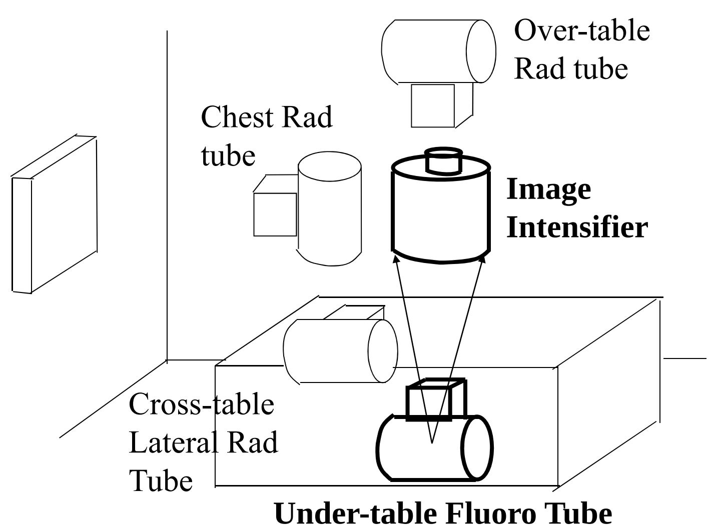
"Representative R&F Room"



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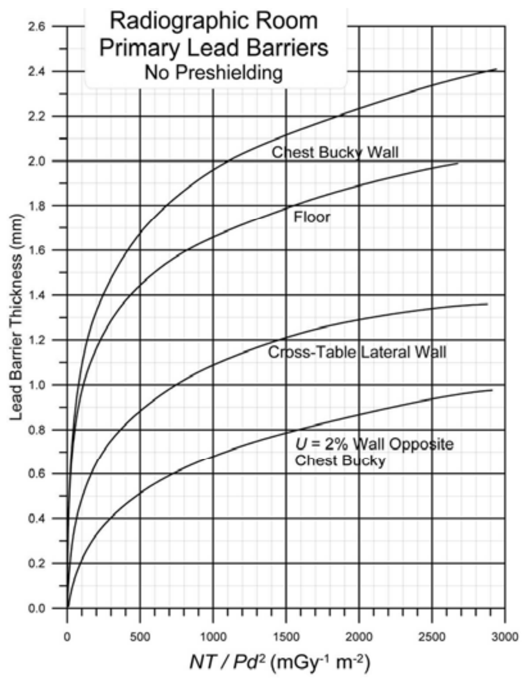

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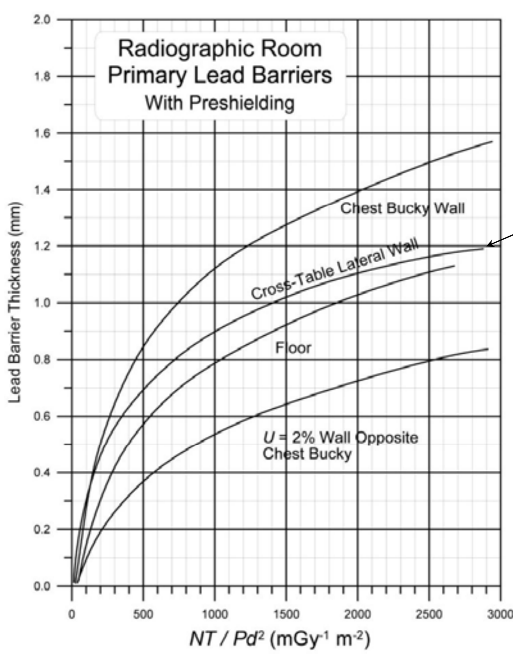

(Error)… mea culpa

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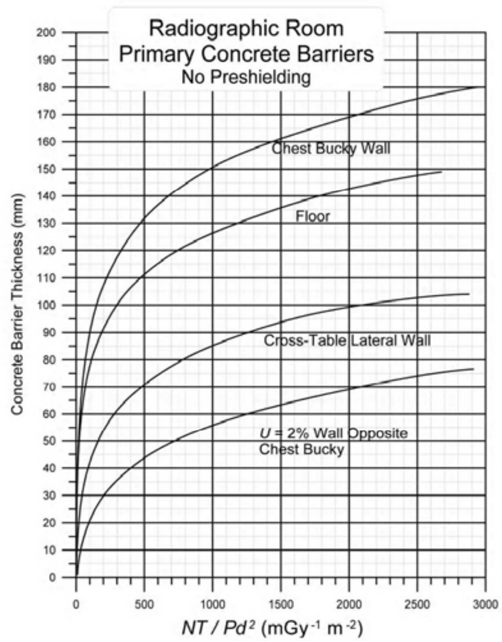

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Equivalency of Shielding Materials

- 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**

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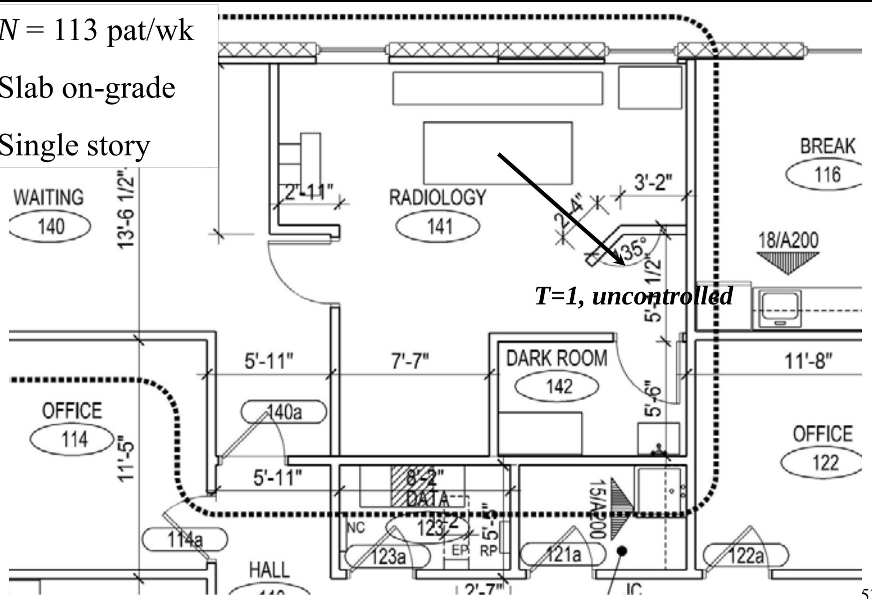
Example: Radiographic Room

N = 113 pat/wk

Slab on-grade

Single story



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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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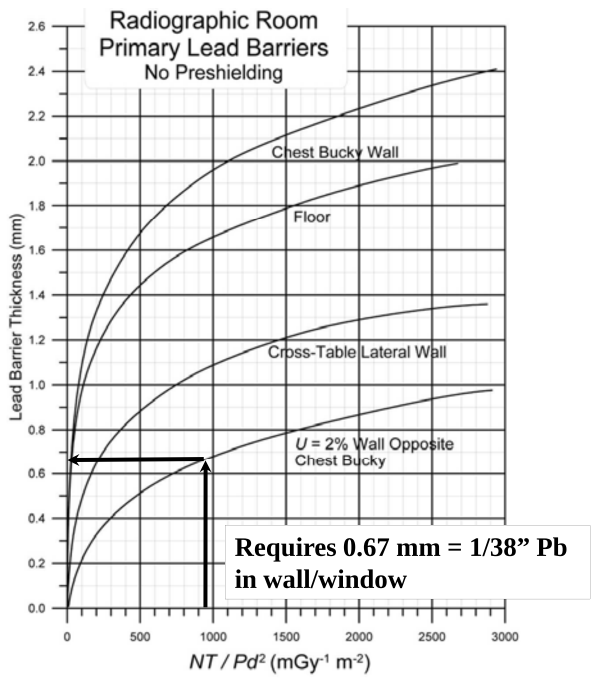

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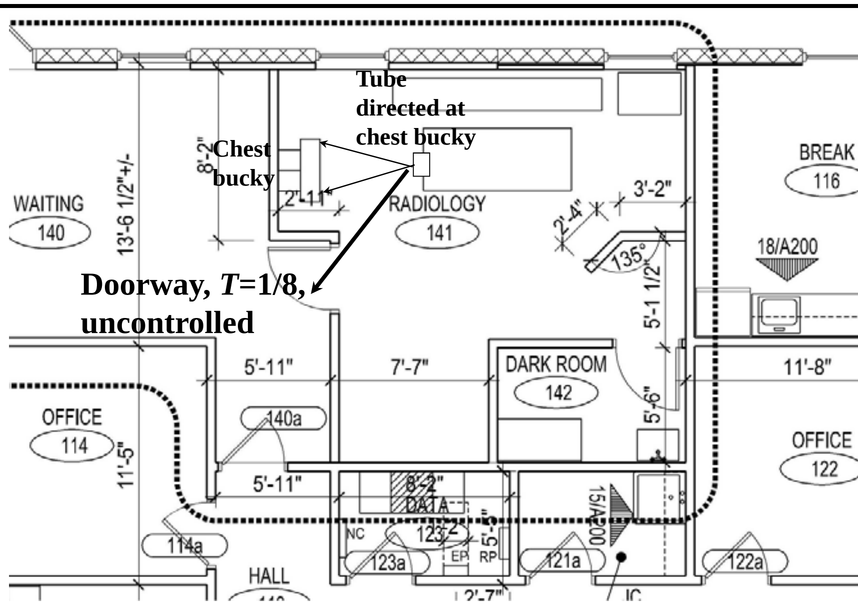
Example: Radiographic Room



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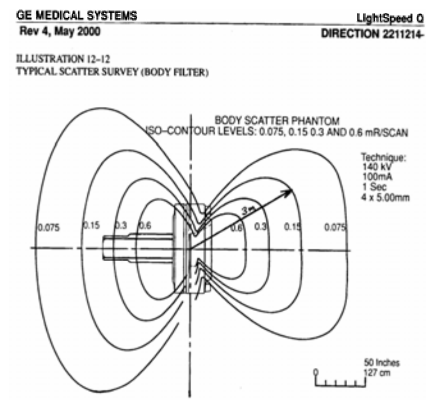
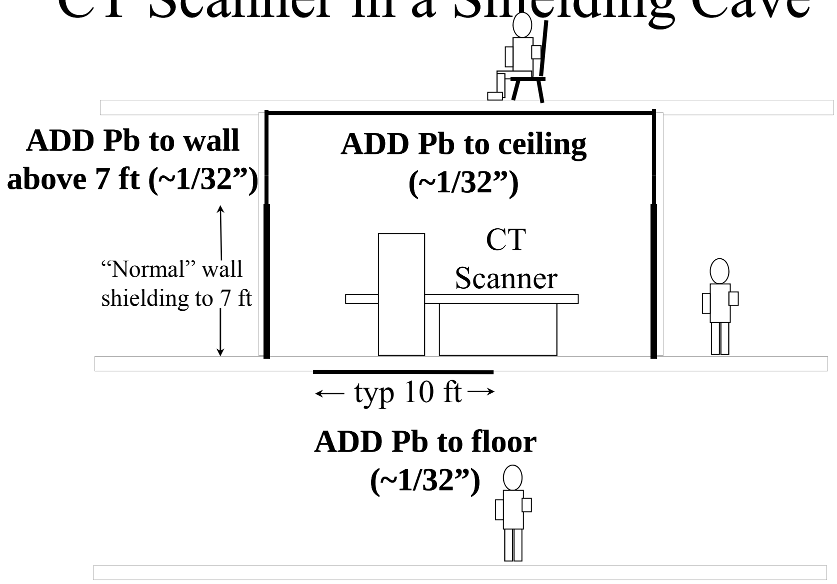
CT Scanners: Estimate Unshielded Kerma

- 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



Surveys

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

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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?)

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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

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Surveys For Adequacy

- Assure that thickness of barrier material installed will decrease kerma in occupied area to ≤ *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

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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

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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

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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

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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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