Calculation of Shielding Requirements for PET/CT and SPECT/CT

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Planning: Layout and Barriers

- Avoid interference between sources and equipment

  eg. Biograph64 <10µGy/h at 1.83m
- Minimise close contact with injected patients

- Meet a dose constraint:

<< 20 mSv/year for staff

< 1 mSv/y for public

In general ….

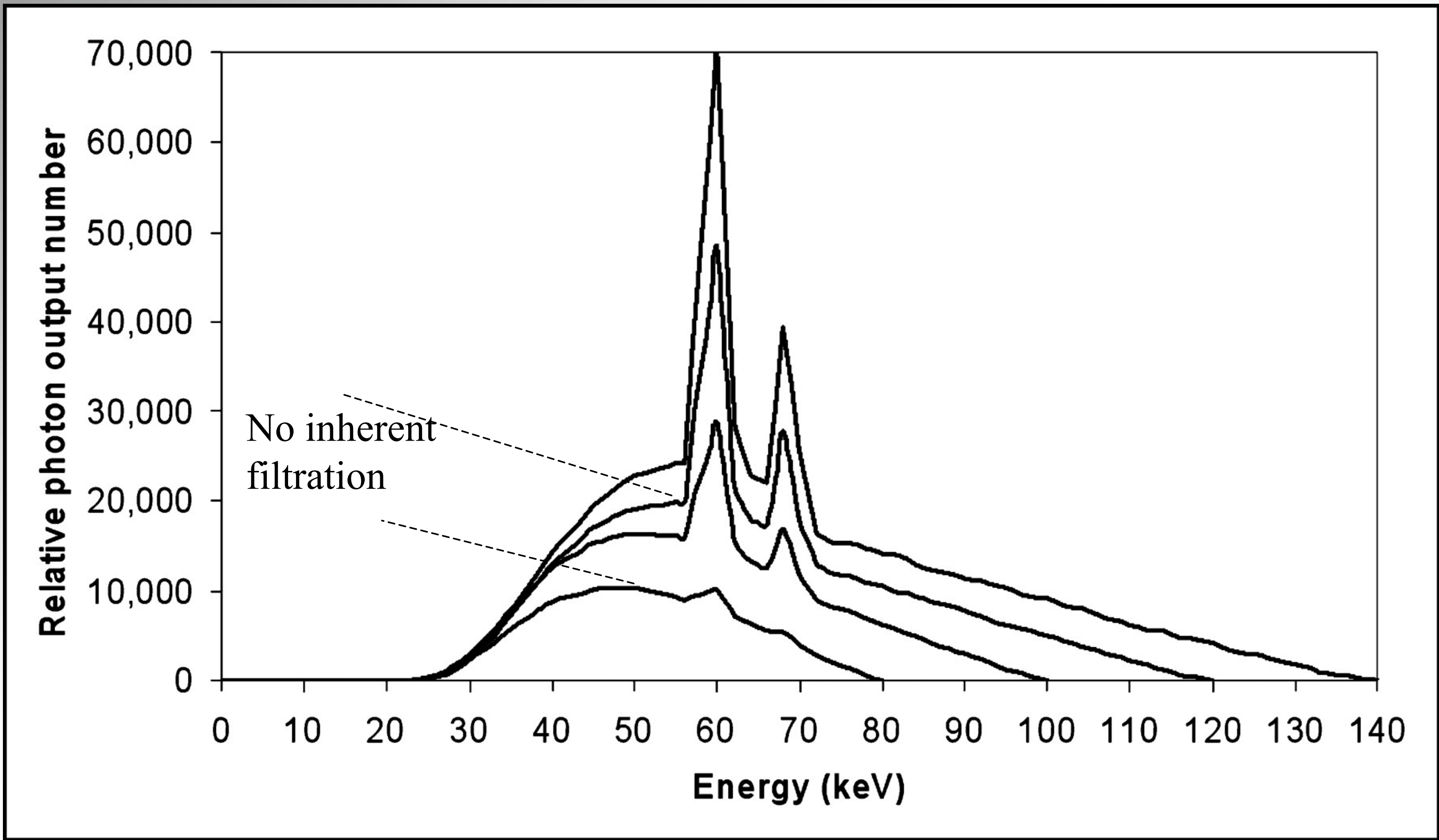
- Walls of SPECT camera rooms with 2mm lead should be adequate for CT
- Walls of PET scanner rooms should also be adequate for CT
- Special requirements if adding CT will have to be addressed eg. Barrier integrity, door rebates, viewing windows

CT radiation

- Much higher radiation output and workload (mA-min per week) than other apparatus
- High tube voltage and current
- Beam is hardened by additional filtration
- MSCT beam widths 40mm or more
- High heat capacity - long runs possible
- Primary beam confined to patient and gantry

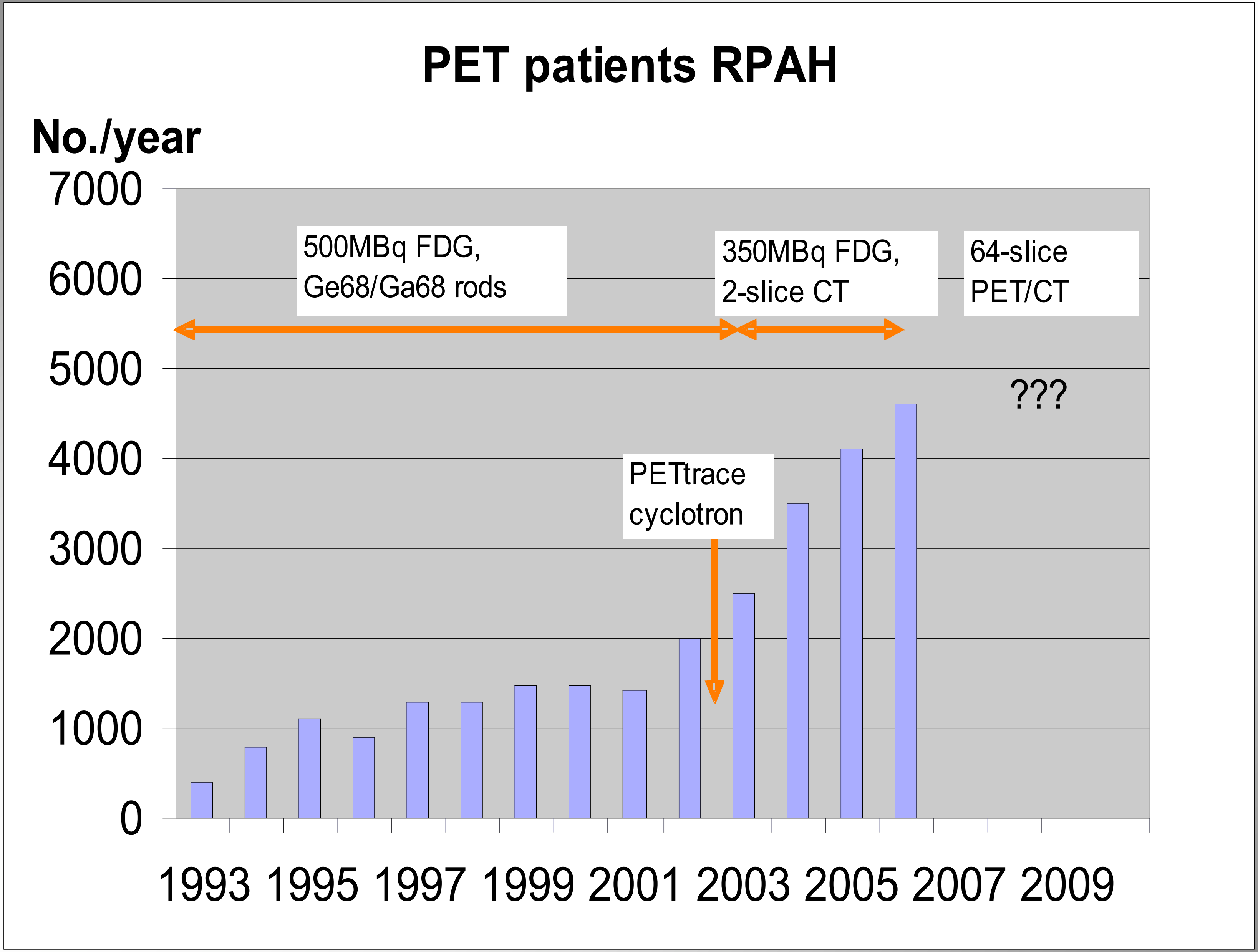
CT PRIMARY BEAM

Tungsten anode, fixed tube current, increasing kVp



Issues

- ‘New build’ or renovation of existing area?
- Which scanner?
- Will CT also be used for diagnostic radiology?
- Space and weight restrictions?
- Impact on other areas of the facility?
- How conservative?
- Allow for future developments?



PET patients RPAH
No./year
7000
6000
5000
4000
3000
2000
1000
0
500MBq FDG,
Ge68/Ga68 rods
350MBq FDG,
2-slice CT
64-slice
PET/CT
???
PETtrace
cyclotron
1993 1995 1997 1999 2001 2003 2005 2007 2009

RPAH PET Suite 2010

NCRP methodology

1. For each barrier, including floor and ceiling, calculate the required transmission B for all x-ray tube configurations in the room and all adjacent accessible areas*
2. Determine the thickness in various materials to achieve B

* Amenable to XL calculations

Shielding Design Goal, P

- From Dose Constraint, use pro rata weekly dose for shielding design
- NCRP147 recommends air kerma:

  - Controlled areas: 5 mSv/y →100 µGy/wk

  - Uncontrolled areas: 1 mSv/y →10 µGy/wk
- TG108 recommends EDE:

  - Controlled areas: 5 mSv/y →100 µSv/wk

  - Uncontrolled areas: 1 mSv/y →20 µGy/wk

Internal corridors are controlled areas, external are not

Basic transmission equation $B = K/K(0)$

Unshielded dose/wk at distance d from 'point source':

$$K(0) = W \text{ (mGy at 1m) } / d^2$$

With shielding, reduce dose/wk to:

$$K = P \text{ (mGy)}/T$$

Hence:

$$B = (P/T)\, d^2/W$$

NCRP occupancy factors

Location	T
Staff areas with full-time occupancy	1
Examination rooms	1/2
Corridors, staff rest rooms	1/5
Corridor doorways	1/8
Storerooms, unattended waiting rooms	1/20
Stairs, lifts, outdoor pathways	1/40

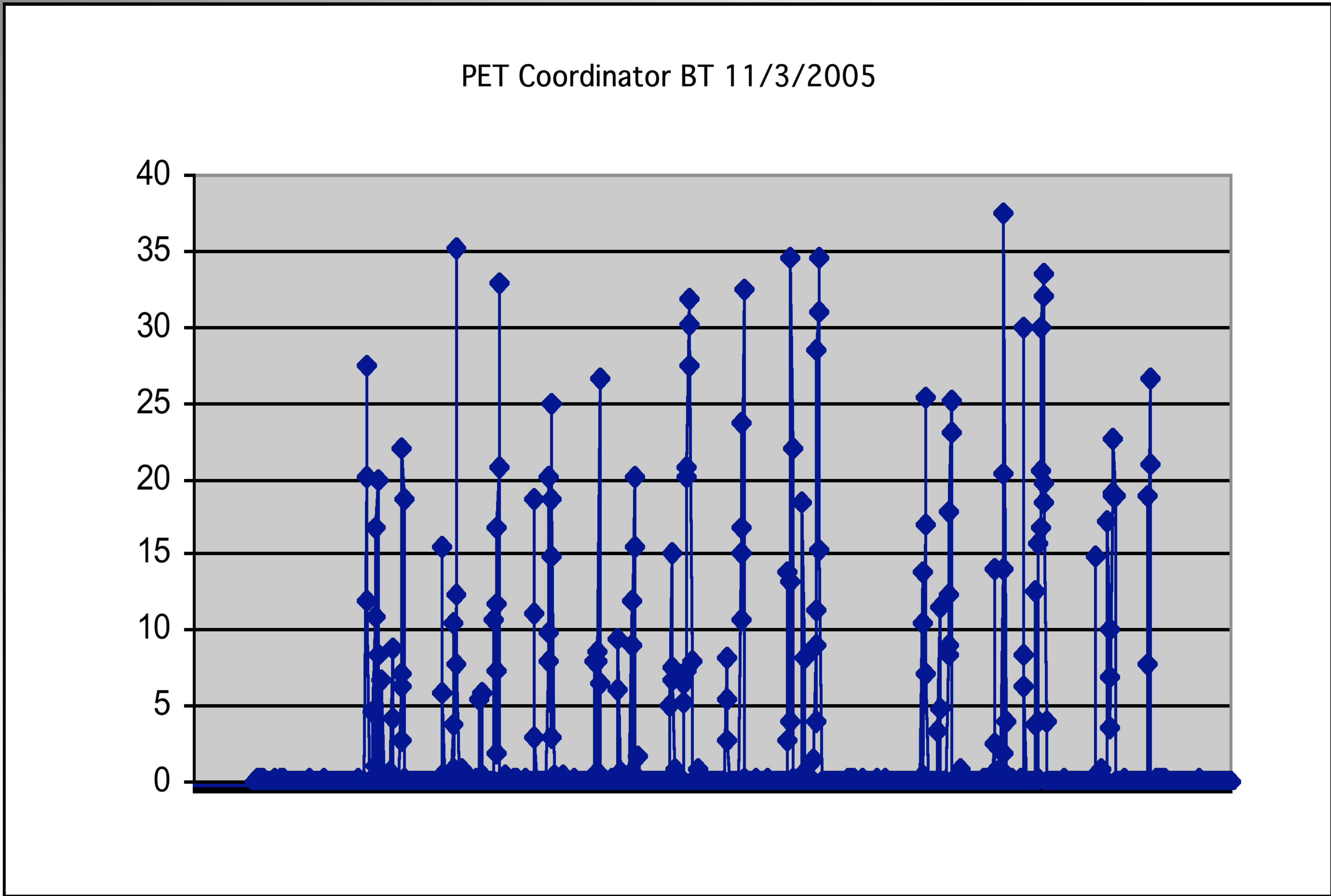
[NCRP147: ‘where data are not available’]

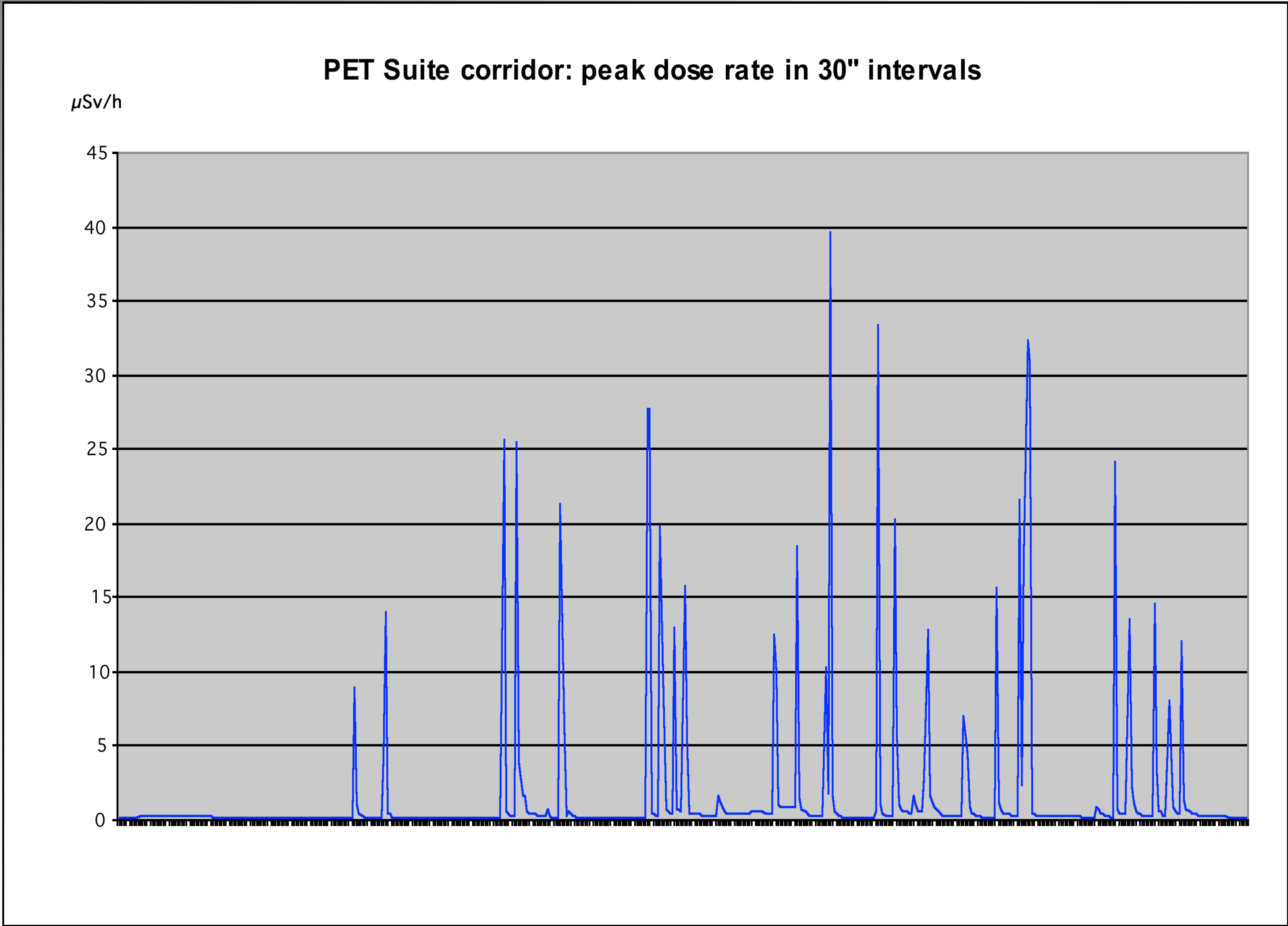
AS2243.4 Occupancy Factors

Location	Assumed occupancy h/yr	Occupancy Factor
Work areas full time occupancy	2000	1
Utility rooms	100	1/20
Waiting rooms, corridors, stairs, lifts, pathways	50	1/40

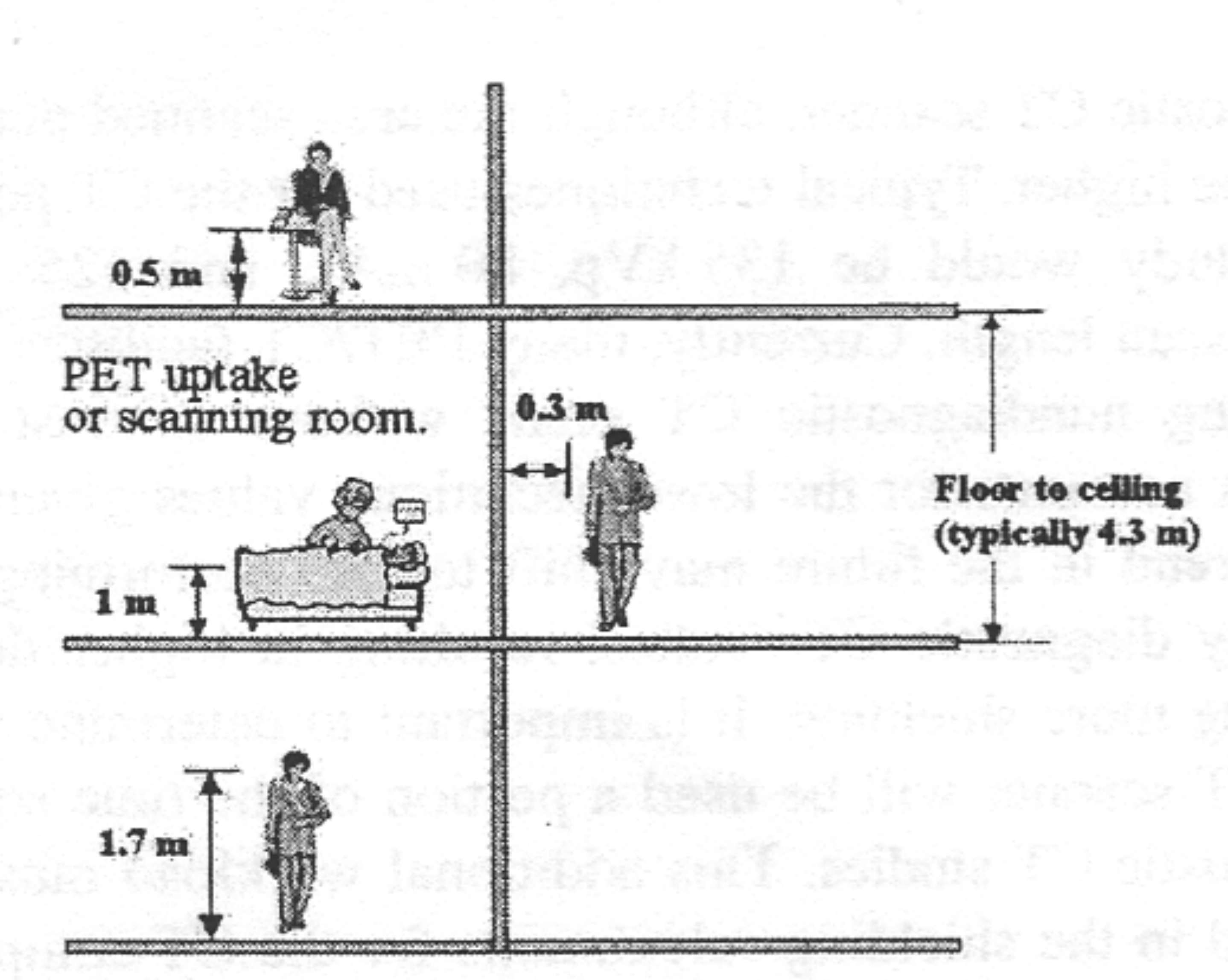
What if employees have significant exposure where shielding is not an option?

- NM techs & nurses receive up to 5mSv/y from direct and indirect contact with patients
- Dose constraint applies to the radiation source *or set of sources*
- Intended to keep a person's *total* exposure below a fraction of the dose limit
- Hence RPAH uses conservative values:
  - Controlled areas: 1 mSv/y →20 µSv/wk, all T=1
  - Uncontrolled areas: 0.5 mSv/y →10 µSv/wk


PET Coordinator BT 11/3/2005
40
35
30
25
20
15
10
5
0


PET Suite corridor: peak dose rate in 30" intervals
µSv/h
45
40
35
30
25
20
15
10
5
0

Distance for use in shielding calculations



From AAPM Task Group 108: PET and PET/CT Shielding

Workloads and distance: nucmed patients

- No. and type of patient procedures per week
- Rate constant @ 1m for nuclide in patient
- Cumulative activity in GBq-h per patient in room: TG108 gives factors for F18 decay
- ISL valid if distance >> source dimensions: TG108 assumes ISL at all distances

  RPAH uses $1/r^{1.5}$ if distance < 3 metres

Example: FDG uptake room

- Assume 0.5 GBq injected
- In room 0-1h p.i., decay reduction factor 0.83
- 7 patients per day, 5 days per week
- 3 metres from reception desk, P = 10 µSv/wk
- 92 µSv/GBq-h from patient @ 1m

$$B = (P/T)d^2/W$$

Hence

$B = (10/1) \times 3^2 / (0.5 \times 92 \times 0.83 \times 7 \times 5)$

$= 0.067$

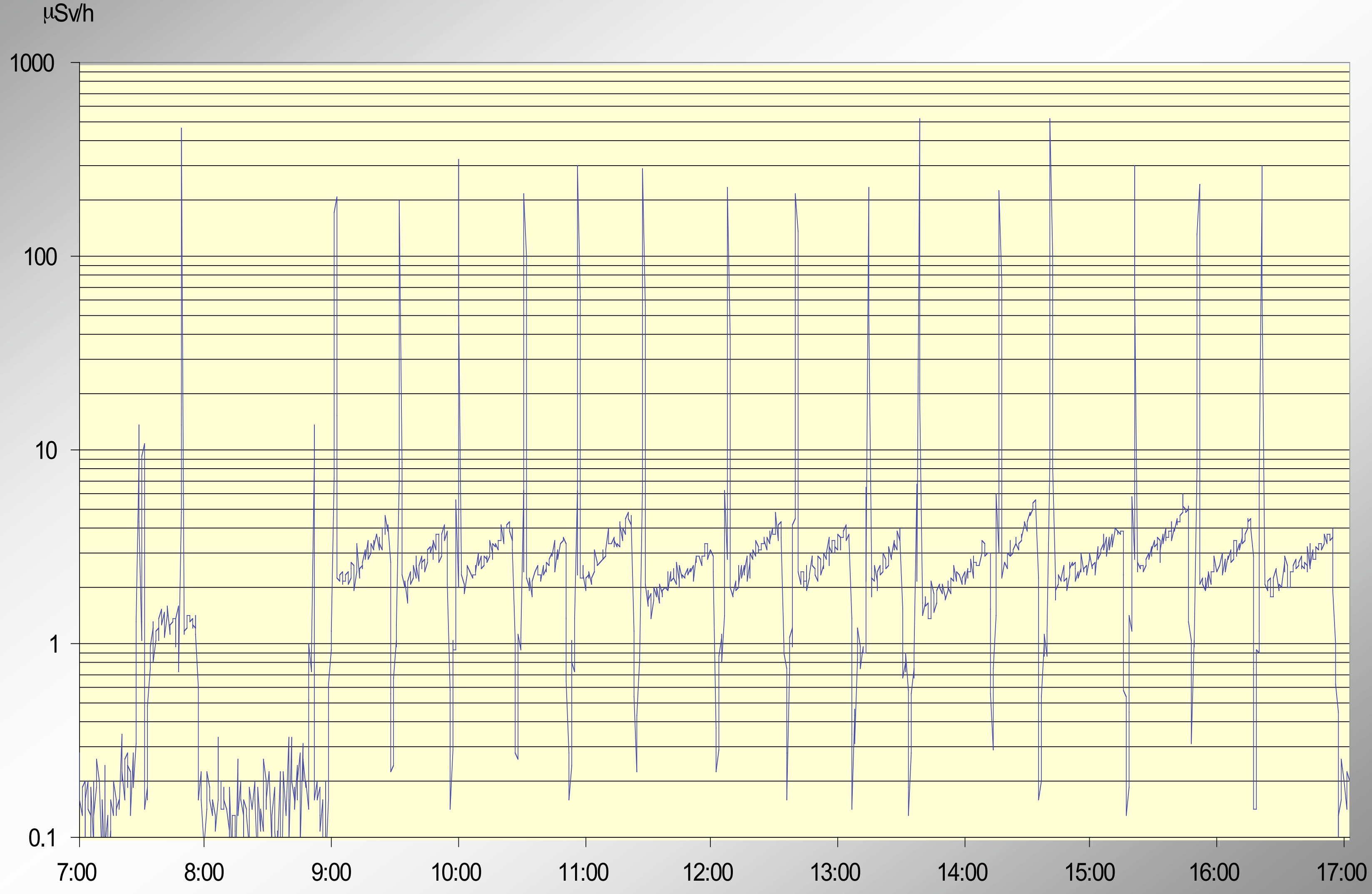
Nucmed patients

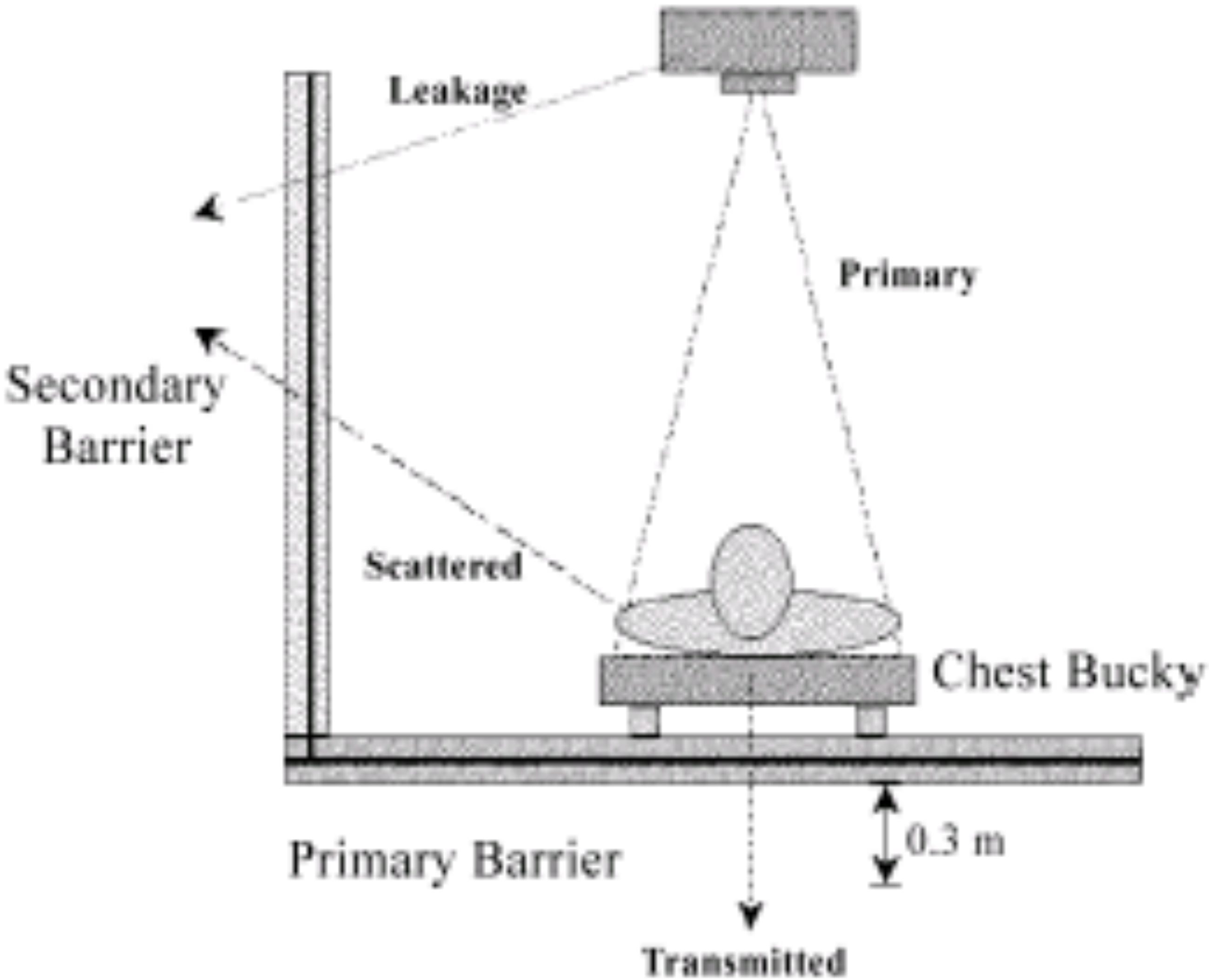
Based on data in Janssen et al. ASUM Bulletin Aug 2000 and Task Group 108

	Injection	Scanned @ hrs p.i.	μSv/h @ 1m from patient
Bone	800MBq Tc99m	2	3
Lung V/Q	240MBq Tc99m	0	2
mIBI 1-day stress/rest	1500MBq Tc99m	1	8
Lymphoma	370MBq Ga67	24	5
PET	550MBq F18	1	30

Adding CT to radionuclide dose

Wall at head end of Biograph




Leakage
Primary
Secondary
Barrier
Scattered
Chest Bucky
0.3 m
Primary Barrier
Transmitted

CT secondary radiation: leakage

- Beam is hardened by tube housing
- Effective energy is close to kVp
- Anisotropic
- Regulatory limit on air kerma rate of 0.876 mGy/h (0.1R/h exposure rate) at 1meter, for continuous operation at maximum kV and maximum mA at that potential

CT secondary radiation: scatter

- Compton α Z/E
- Continuous spectrum
- Angle depends on E
- Anisotropic
- Measured at max kV, mA, beam width in head and body phantoms

Cember: Health Physics

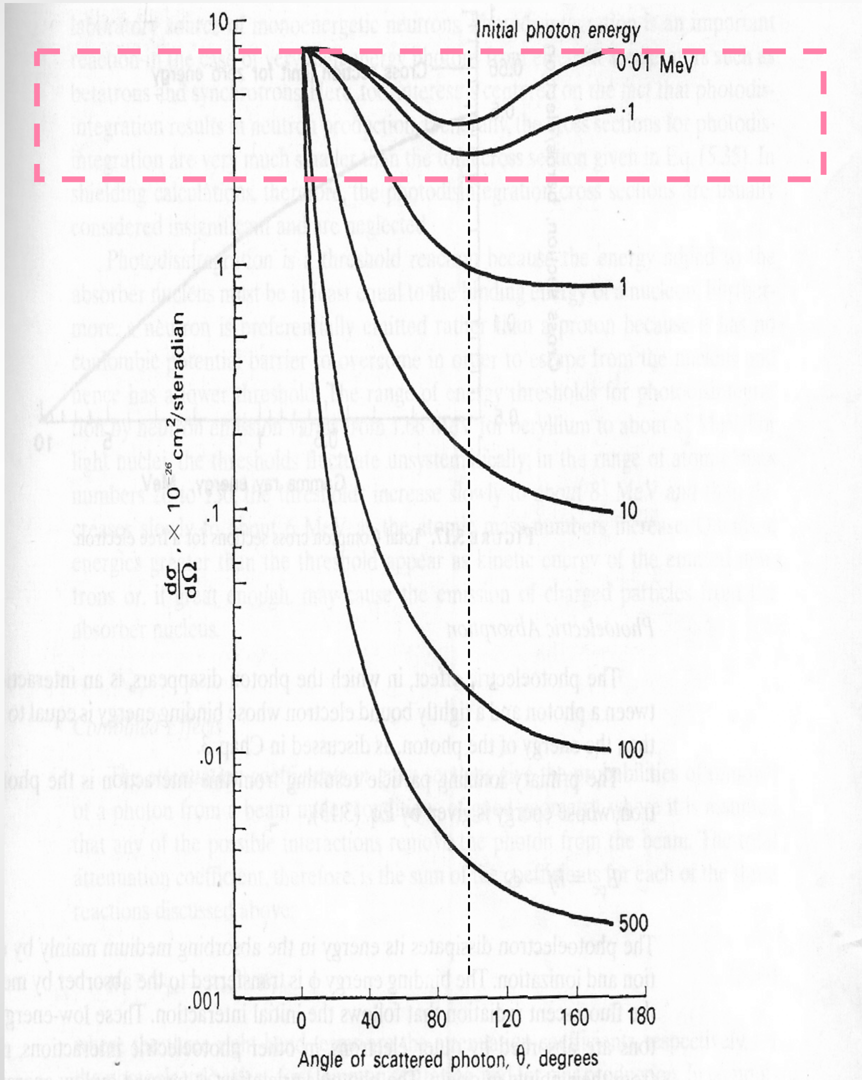
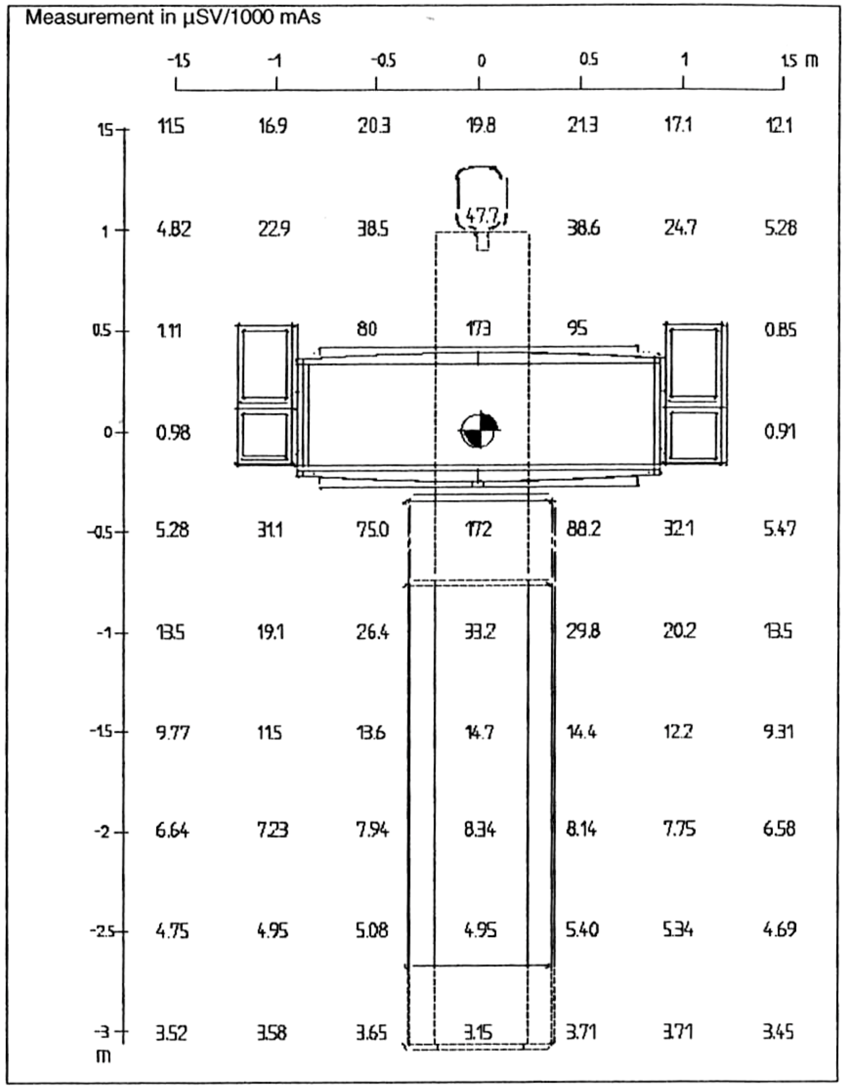


FIGURE 5.16. Differential scattering coefficient showing the probable angular distribution of Compton scattered photons.

Scatter distribution map

[Biographs 2- and 64-slice]



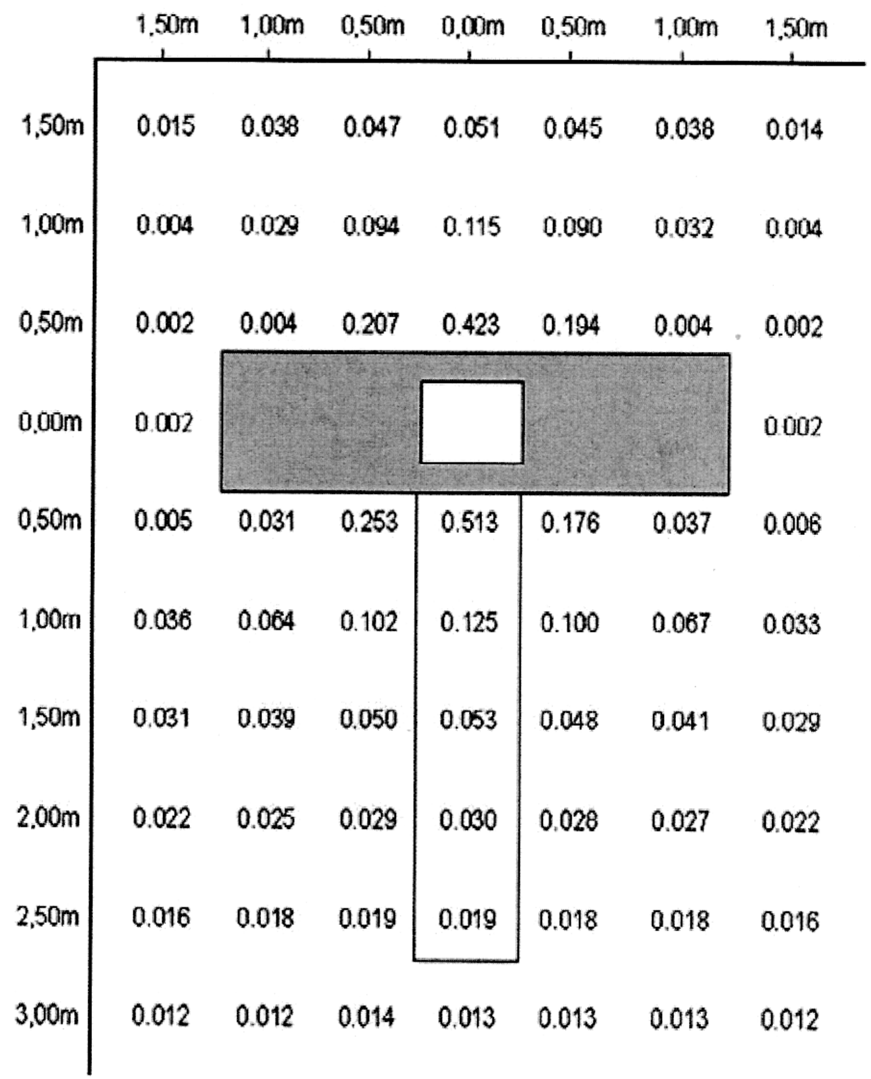


Fig. 5: Local dose distribution - Biograph 64. (Measurements in µGy/1 mAs)

CT workload, distance

NCRP147:

- Air kerma rate @ 1m per patient for head and body scans
- Assume isotropic
- Correct K values with ISL
- Scale up for no. of procedures per week

Estimate air kerma from $CTDI_p$

K is proportional to integral dose along a z-axis, so apply a scatter fraction to CTDI

- Scatter fractions for *peripheral* ${}_nCTDI_{100,p}$ are

  $\kappa_{head} = 9 \times 10^{-5}\ cm^{-1}$

  $\kappa_{body} = 3 \times 10^{-4}\ cm^{-1}$

- Hence the air kerma per head or body scan is

  $K^1_{sec} = \kappa \times (L/P) \times mAs \times {}_nCTDI_{100,p}$ mGy at 1m

(using appropriate κ)

Estimate air kerma from DLP

[NCRP147, says may be more convenient than $CTDI_{100}$ method]

- Apply a scatter fraction to DLP (values from console or default values in NCRP147)
- Use the peripheral scatter fractions, assuming

$${}_{n}CTDI_{100,p} = {}_{n}CTDI_{100,c} \quad \text{in head phantom}$$

$${}_{n}CTDI_{100,p} = 2 \times {}_{n}CTDI_{100,c} \quad \text{in body phantom}$$

- Hence the air kerma per head or body scan is

$$K^{1}_{sec} = \kappa_{head} \times DLP \quad \text{mGy at 1 m}$$

$$K^{1}_{sec} = 1.2 \times \kappa_{body} \times DLP \quad \text{mGy at 1 m}$$

Estimate air kerma from scanner information

K is proportional to Workload (mA-min)

- Use isotropic model based on manufacturer's specification for air kerma at 1m
- Use isodose contours or scatter maps of μGy per mAs for maximum kV, mA and beam width on head or body phantom

Barriers

From Doug Simpkin, AAPM 2002

- No finite barrier thickness will *completely* eliminate the radiation dose outside a diagnostic x-ray room

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

Attenuation

- Narrow beam v broad beam geometry:

  - extended source, barrier and occupied area

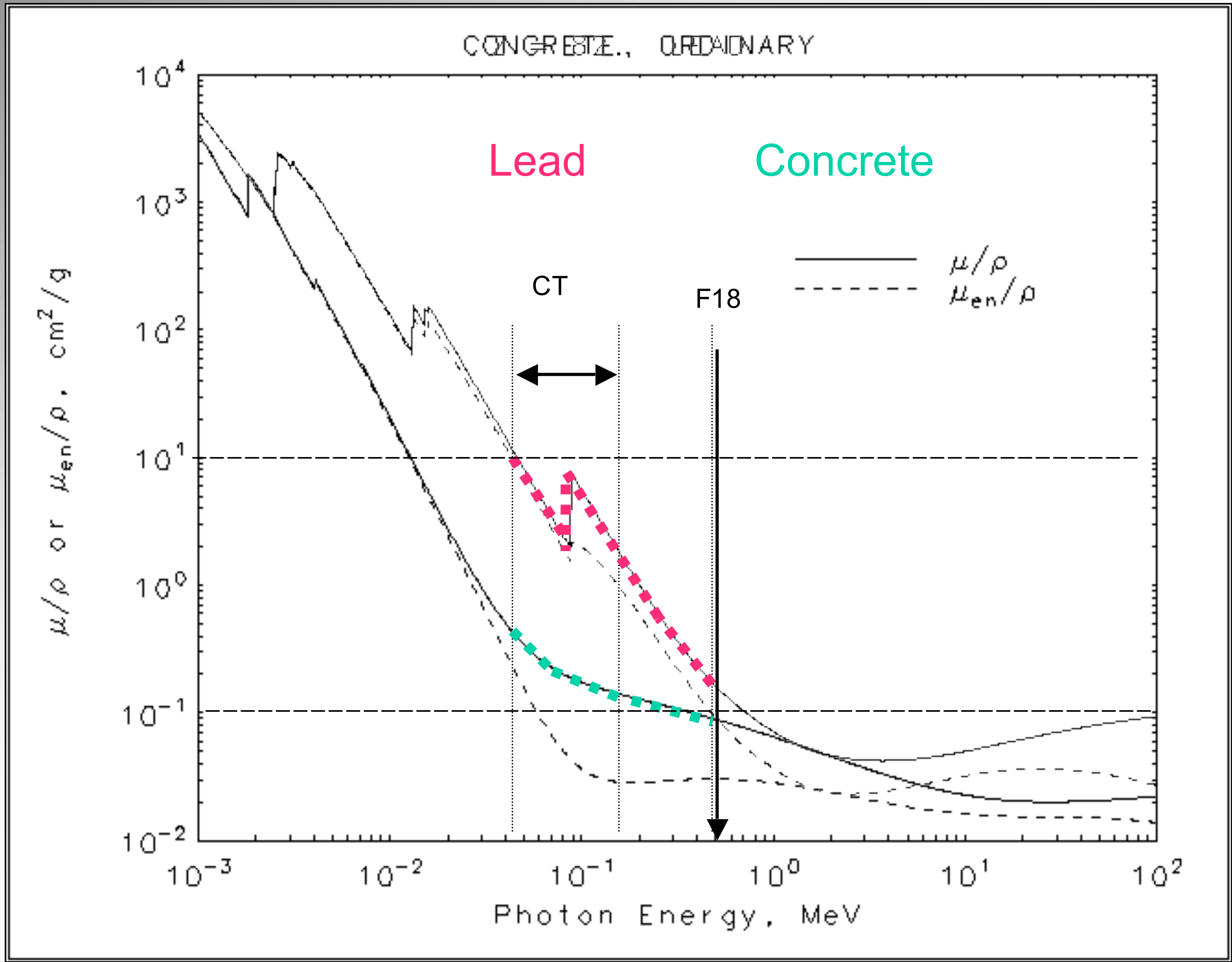
  - 'buildup' region: shoulder on transmission curve due to forward scatter in initial layers of material

- Energy

  - PE ~ Z^4/E^3 so predominant at high Z, low E

  - buildup is more pronounced for low Z materials, high E photons

  - transmission is much more sensitive to kV than workload



Overlaid attenuation coefficients for Lead and Concrete
From http://physics.nist.gov/PhysRefData/XrayMassCoef

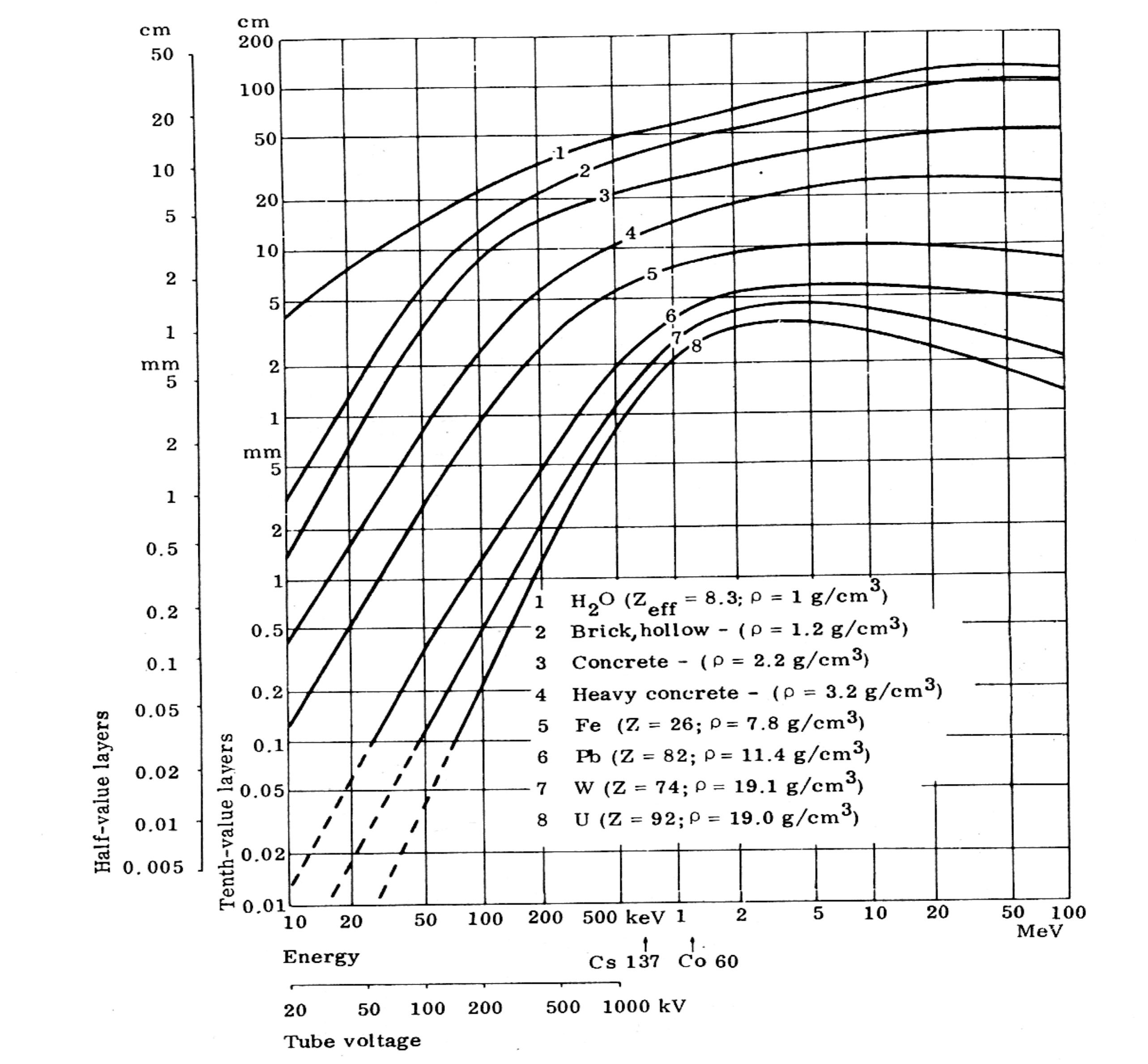
Estimating thickness with radionuclide coefficients

- Narrow beam: published HVL, TVL or attenuation coefficients (μ or μ/ρ)
- Broad beam:

  - published HVL, TVL coefficients

  - Buildup method with narrow beam μ

Average HVLs and TVLs of shielding materials (Broad Beams)



From The Health Physics and Radiological Health Handbook, after Wachsman & Drexler 1975

Estimating thickness from MC modeling / Archer fitting parameters

- Suitable for broad beam geometry, heterogenous beam, any material
- Archer proposed an empirical expression with 3 parameters, based on measured transmission of an x-ray beam at various thicknesses
- Parameters are fitted to MC data
- Curves and parameters for CT are given in NCRP147 and for 511keV in TG108

Archer equations

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

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

Note typographical error in TG108 eqn. for B: omitted minus before 1/γ exponent

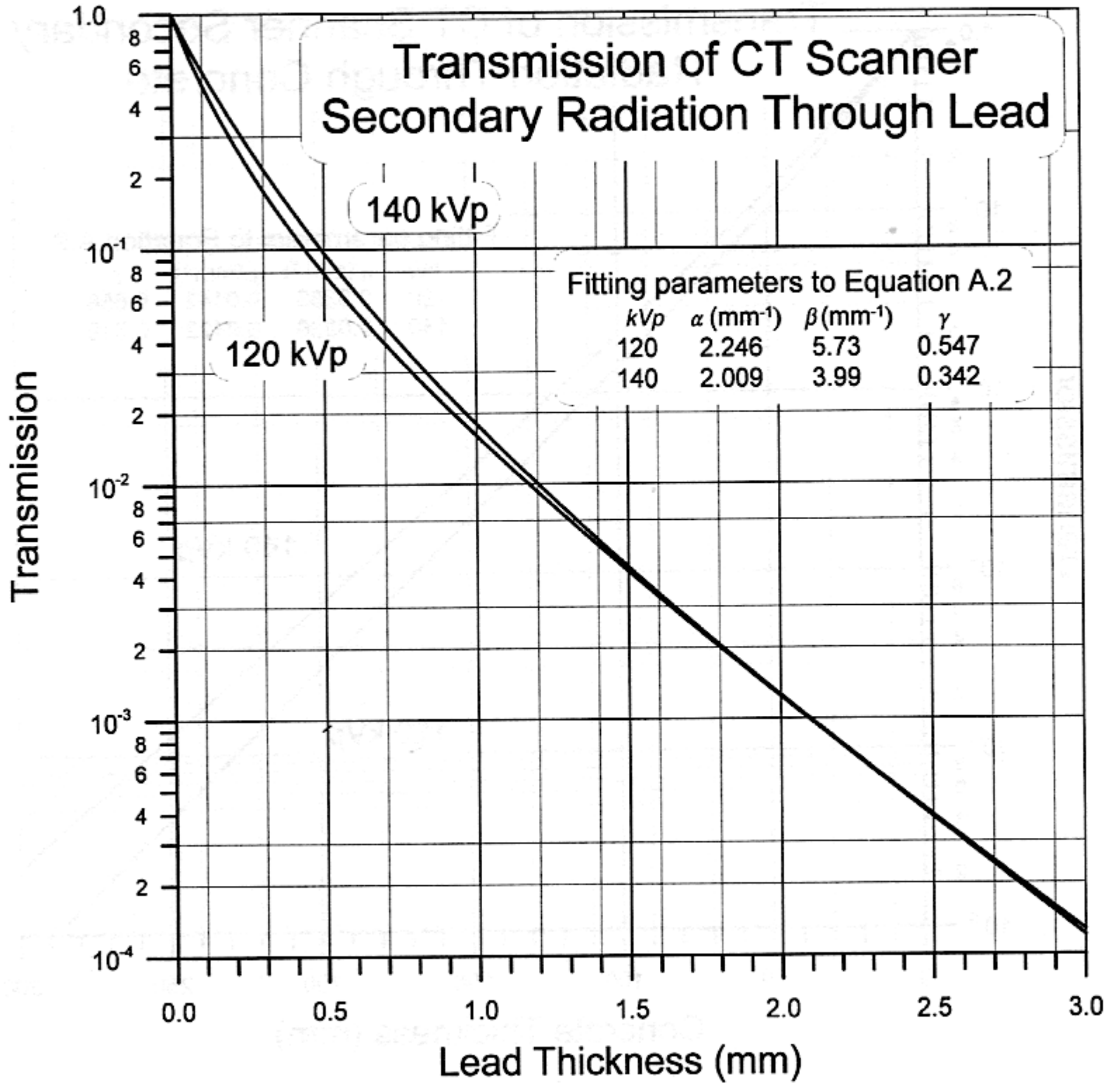


Fig. A.2. Transmission through lead of secondary radiation from CT scanners [data of Simpkin (1991) fitted to Equation A.2].

From NCRP 147: Structural Shielding Design for Medical X-Ray Imaging Facilities

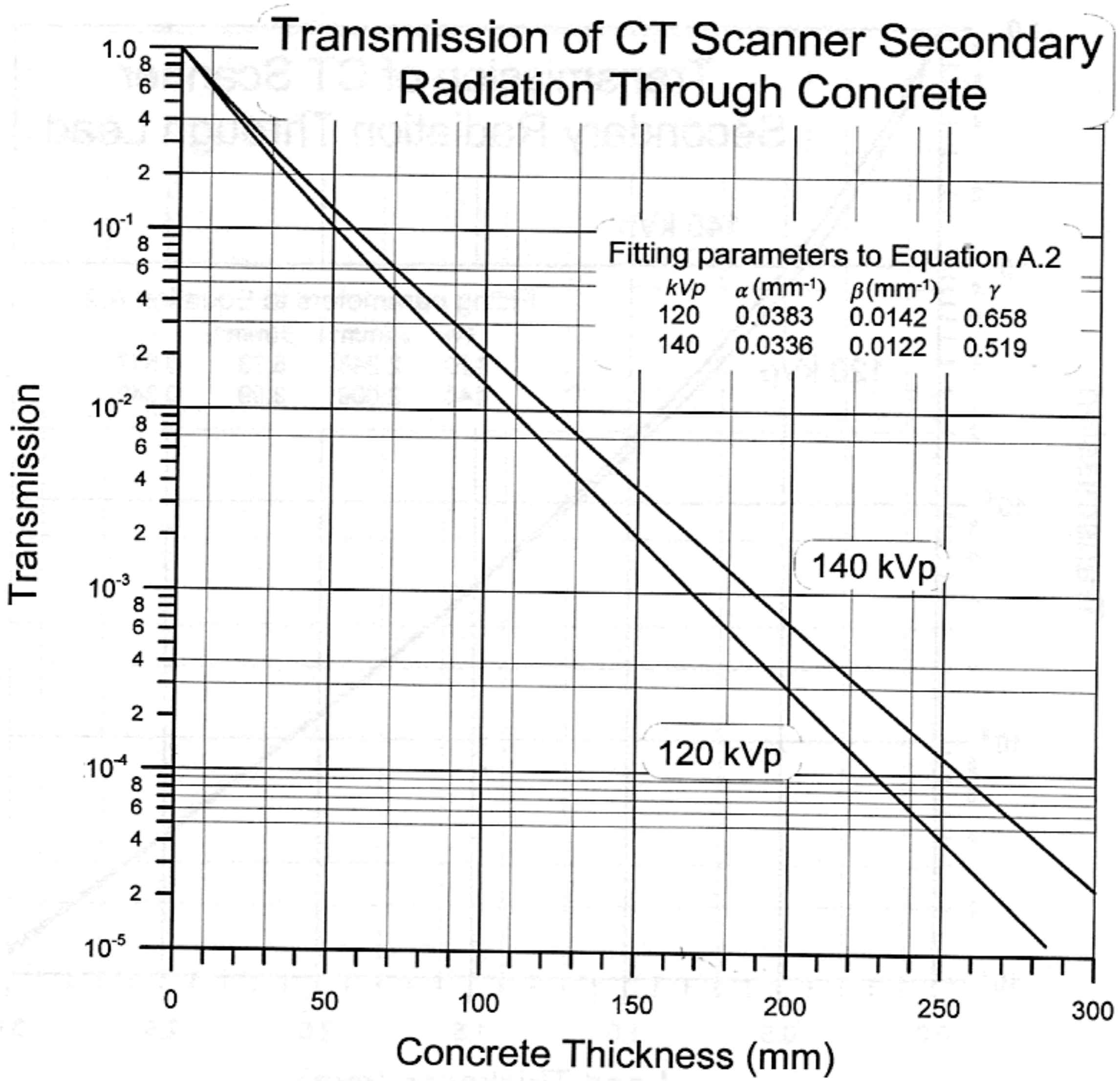
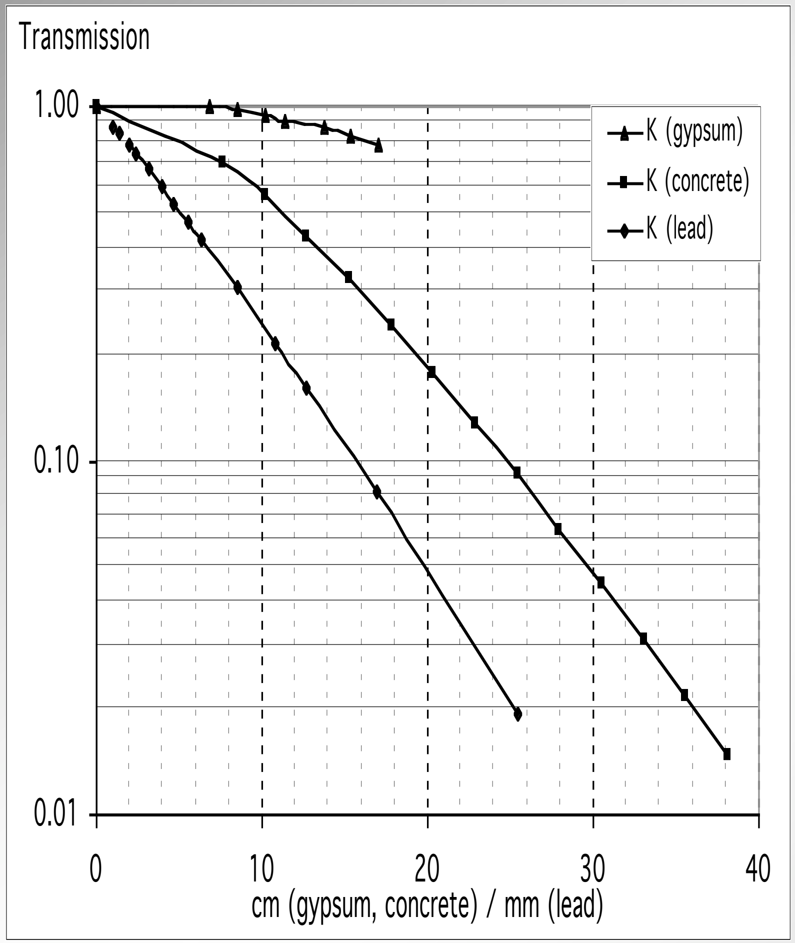


Fig. A.3. Transmission through concrete of secondary radiation from CT scanners [data of Simpkin (1991) fitted to Equation A.2].

From NCRP 147: Structural Shielding Design for Medical X-Ray Imaging Facilities

MC modelling of 511 keV broad beam

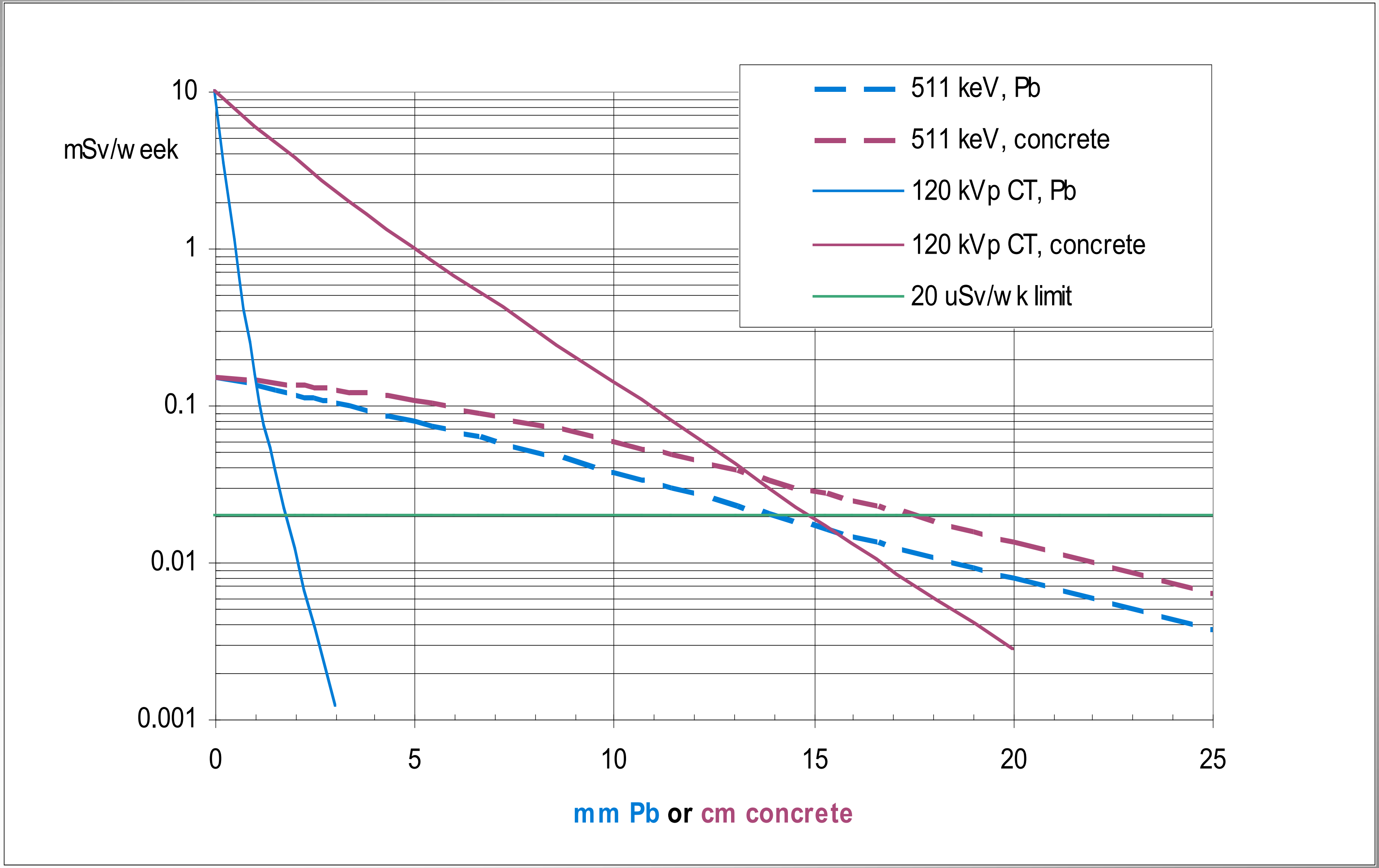


	α (cm^{-1})	B (cm^{-1})	γ
Lead	1.543	-0.4408	2.136
Concrete	0.1539	-0.1161	2.0752
Iron	0.5704	-0.3063	0.6326

From Courtney and AAPM Task Group 108

PET/CT transmission

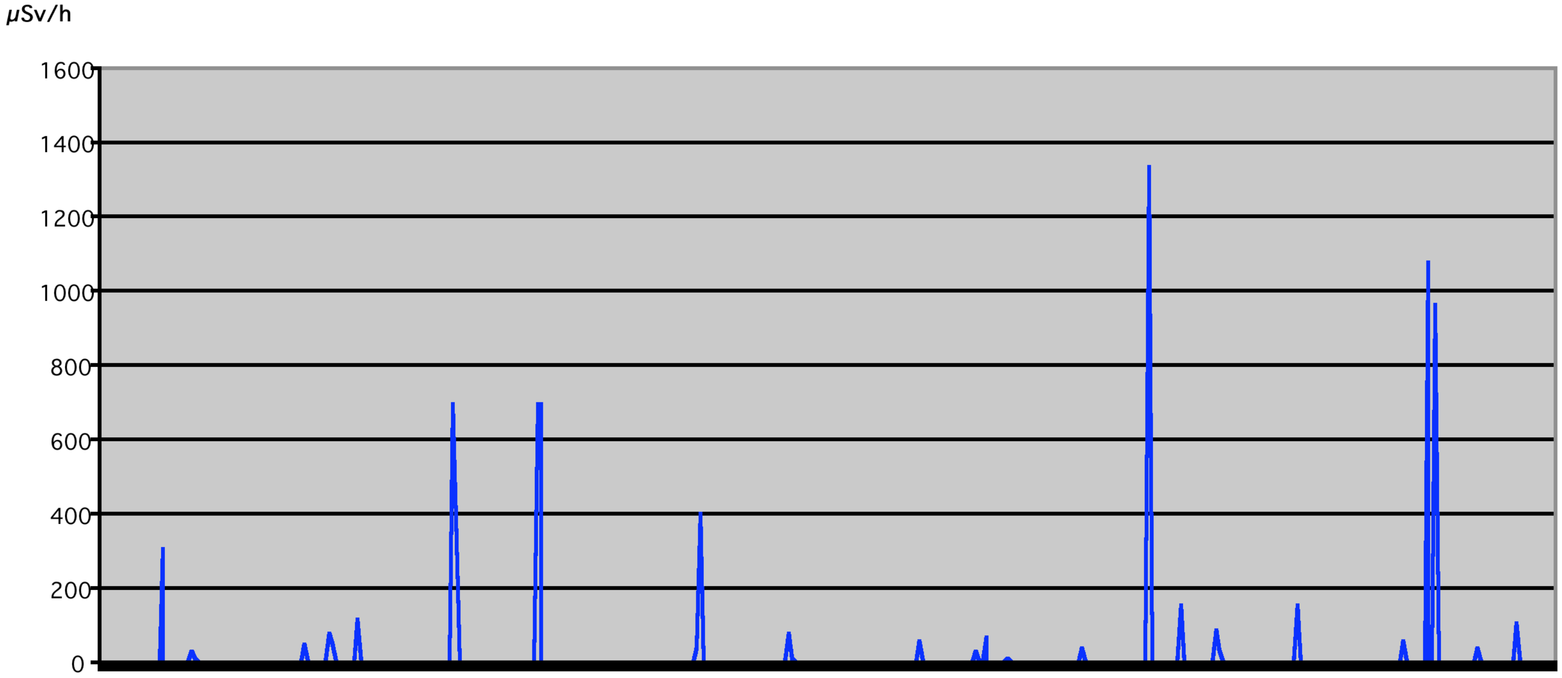
[notional unshielded dose rates]



Practical details

- Barrier heights
- Viewing windows
- Barrier penetrations
- Raised floors
- Barrier labels
- Doors

Doorway of GE Lightspeed Control Room
60sec intervals; net dose 130uSv in 7.5h



References

- AAPM Task Group 108: PET and PET/CT Shielding Requirements. Madsen M et al. Med Phys 33:4-15 (2006)
- NCRP 147 Structural Shielding Design for Medical X-ray Imaging Facilities (2005)
- Archer B et al. Health Phys 44:507-517 (1983)
- Simpkin D. Health Phys 56:151-164 (1989) and 58:363-367 (1990)
- Radionuclide and Radiation Protection Handbook. Delacroix et al. RPD 98 No.1 (2002)