Shielding requirements for PET/CT

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Institute For Medical Physics (IFMP) Workshop
"PET Principles, PET use in hospital, and ongoing developments"
Ohrid, Macedonia; 6-8 September 2015

PET and PET/CT shielding requirements

- AAPM Task Group 108
- IAEA Safety Reports Series No. 58

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

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(Received 21 July 2005; revised 17 October 2005; accepted for publication 18 October 2005; published 19 December 2005)

The shielding of positron emission tomography (PET) and PET/CT (computed tomography) facilities presents special challenges. The 0.511 MeV annihilation photons associated with positron decay are much higher energy than other diagnostic radiations. As a result, barrier shielding may be required in floors and ceilings as well as adjacent walls. Since the patient becomes the radioactive source after the radiopharmaceutical has been administered, one has to consider the entire time that the subject remains in the clinic. In this report we present methods for estimating the shielding requirements for PET and PET/CT facilities. Information about the physical properties of the most commonly used clinical PET radionuclides is summarized, although the report primarily refers to fluorine-18. Typical PET imaging protocols are reviewed and exposure rates from patients are estimated including self-attenuation by body tissues and physical decay of the radionuclide. Examples of barrier calculations are presented for controlled and noncontrolled areas. Shielding for adjacent rooms with scintillation cameras is also discussed. Tables and graphs of estimated transmission factors for lead, steel, and concrete at 0.511 MeV are also included. Meeting the regulatory limits for uncontrolled areas can be an expensive proposition. Careful planning with the equipment vendor, facility architect, and a qualified medical physicist is necessary to produce a cost effective design while maintaining radiation safety standards. © *2006 American Association of Physicists in Medicine.* [DOI: 10.1118/1.2135911]

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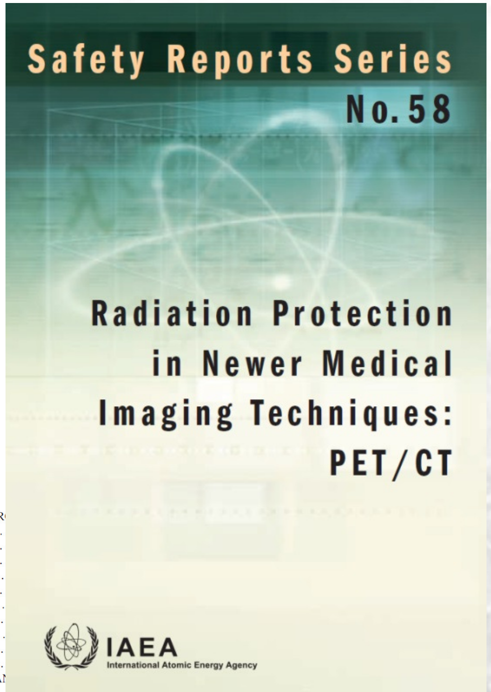
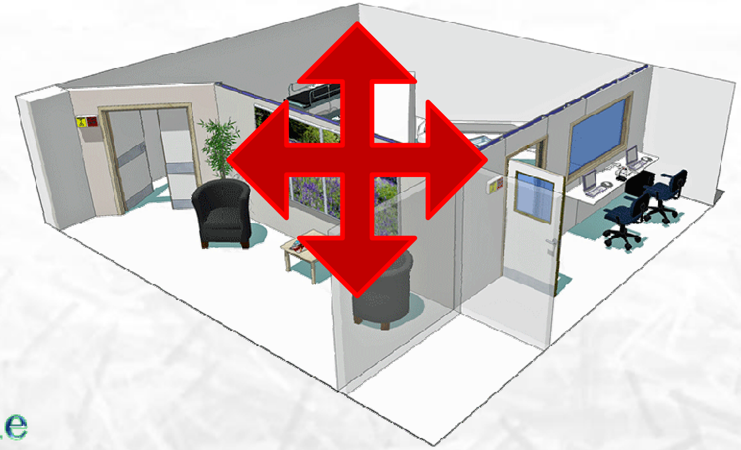


Why Shielding is Different

- High energy annihilation radiation (511keV)
  - Increases exposure rate from syringes
  - Increases exposure rate from patients
  - Increases thickness of shielding
- Diagnostic CT photon radiation (<200keV)
- High flux radiation from CT
- Patient becomes mobile radiation source
- Patient can affect the background and performance of other imaging devices in the department



- Physicist should be consulted in a building project
- Often new clinics are inserted into busy departments

→ can not forget about offices above and below the PET/CT!

Shielding PET Radionuclides

TABLE I. Physical properties of commonly used PET radionuclides.

Nuclide	Half-life	Decay mode	Positron maximum energy(MeV)
^{11}C	20.4 min	$\beta+$	0.96
^{13}N	10.0 min	$\beta+$	1.19
^{15}O	2.0 min	$\beta+$	1.72
^{18}F	109.8 min	$\beta+$, EC	0.63
^{64}Cu	12.7 h	$\beta-$, $\beta+$, EC	0.65
^{68}Ga	68.3 min	$\beta+$, EC	1.9
^{82}Rb	76 s	$\beta+$, EC	3.35
^{124}I	4.2 d	$\beta+$, EC	1.54, 2.17

TABLE II. Effective dose equivalent dose rate constants for commonly used PET radionuclides.

Nuclide	Dose rate constant μSv m^2/MBq h	1 hour integrated dose μSv m^2/MBq
^{11}C	0.148	0.063
^{13}N	0.148	0.034
^{15}O	0.148	0.007
^{18}F	0.143	0.119
^{64}Cu	0.029	0.024
^{68}Ga	0.134	0.101
^{82}Rb	0.159	0.006
^{124}I	0.185	0.184

Focus on FDG shielding:

- most widely used radionuclide
- “long” halflife
- “high” dose rate constant

Obs!

Radionuclides with $t_{1/2} > t_{1/2,FDG}$ or higher gamma emissions in addition to the annihilation radiation might not be adequately shielded if only FDG is considered.

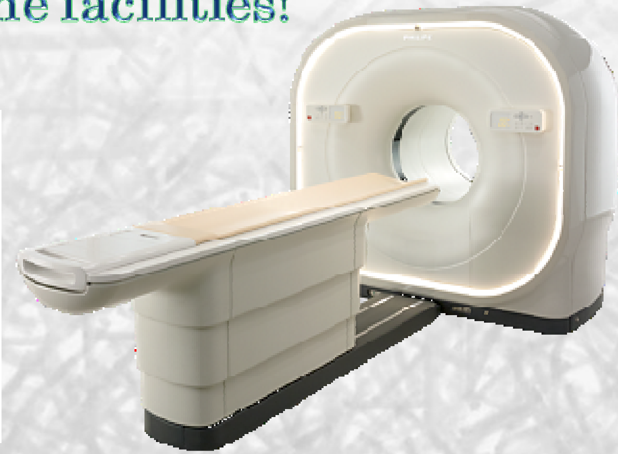
Factors Affecting PET Shielding

- Number of patients
- Administered activity
- Duration of patient stay in the department
- Location of the PET/CT in the hospital

- PET/CT itself may influence the administered activity
  *crystal deadtime (BGO)
  *less activity/patient
  *more patients/day – if you have the facilities!
  *shorter scan time

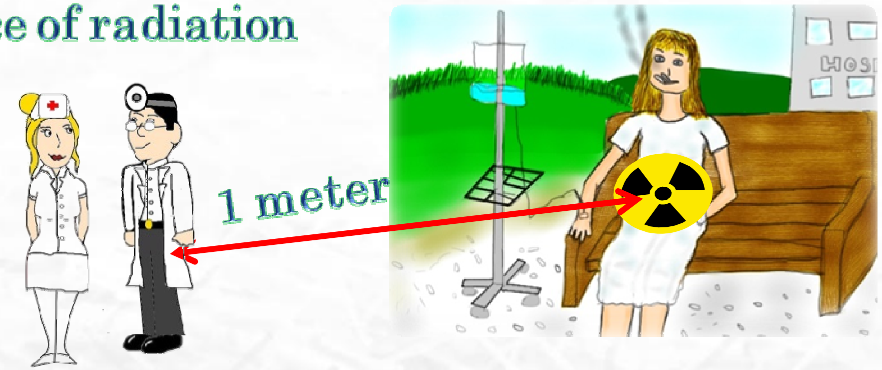
Example

Vereos PET/CT can also help you improve workflow efficiency and patient management through:
- Fast workflows
- Fast scans using shortest bore in the industry
- High image quality at low dose (with iDose[4] Premium Package)



PET Patient is a Mobile Radiation Source

Patient is the primary source of radiation to surrounding areas/people



Dose rate constant for FDG:
0,143µSv ·m²/MBq ·h

Dose rate one meter from unshielded FDG point source of 37MBq:
0,143µSv ·m²/MBq ·h * 37MBq = 5,3µSv/h

The patient is not an unshielded point source!

Assume a patient dose rate:
0,092µSv ·m²/MBq ·h
immediately after injection of FDG

Patient body absorption = Good news for staff!

How thick to make the walls?

Based on regulatory limits

Statens strålevern
Norwegian Radiation Protection Authority

In Norway:

Controlled area: where workers can be exposed to radiation doses > 6mSv/year

Supervised area: where workers can be exposed to radiation doses > 1mSv/year

Outside supervised area: workers can not be exposed to doses > 1mSv/year

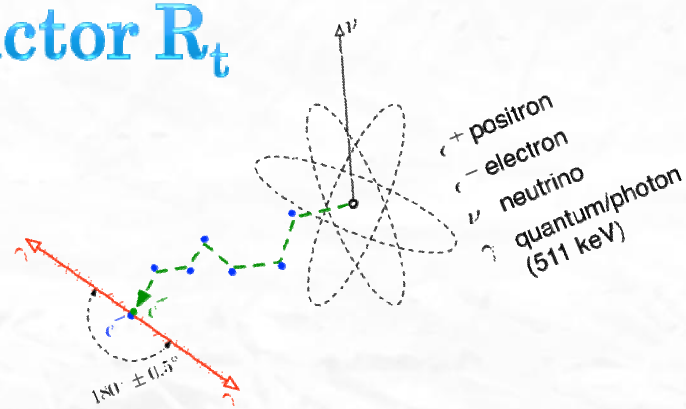
Dose limit for workers: 20 mSv/year

For shielding calculations:

Uncontrolled area: not > 1mSv/year = 1mSv/year*(1year/52weeks) = 20µSv/week

Occupational dose limit: 5mSv/year (consistent with ALARA)

We must reduce the dose!
Dose Reduction Factor R_t



PET radiotracers → short halflives

Total dose after a time t < initial dose rate *t:

$$D(t) = \int_0^t \dot{D}_0 e^{-\lambda t} = \dot{D}_0 \frac{(1-e^{-\lambda t})}{\lambda}$$

In order to define the dose reduction factor:

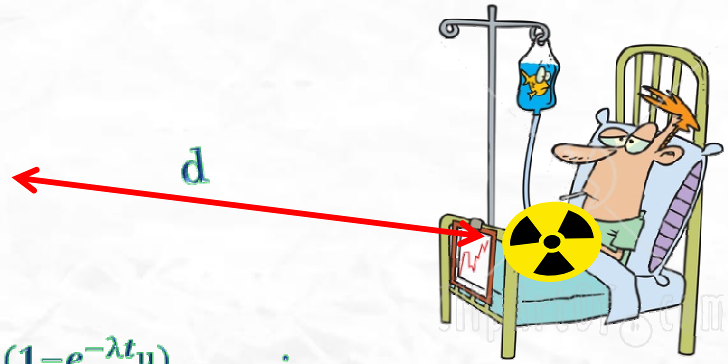
$$D(t) = \dot{D}_0 \frac{(1-e^{-\lambda t})}{\lambda} = \frac{t}{t}\,\dot{D}_0 \frac{(1-e^{-\lambda t})}{\lambda} = t\,\dot{D}_0 \frac{(1-e^{-\lambda t})}{\lambda t} = t\,\dot{D}_0 R_t$$

$$F18 \rightarrow t_{1/2} = 109{,}8\text{min} = \frac{ln(2)}{\lambda}$$

F18	
t (min)	R_t
30	0,911
60	0,832
90	0,763

Dose from an injected patient

Uptake time: t_u
Distance from the patient: d



Total dose after a time t:

$$D(t_u) = \int_0^{t_u} \dot{D}_0 e^{-\lambda t} = \dot{D}_0 \frac{(1-e^{-\lambda t_u})}{\lambda} = t_u \dot{D}_0 \frac{(1-e^{-\lambda t_u})}{\lambda t_u} = t_u \dot{D}_0 R_t$$

Initial dose rate from the patient: $\dot{D}_0$

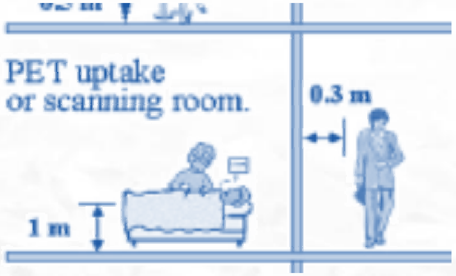
$\dot{D}_0$ = administered activity * patient dose rate constant /d² =

$$= A_0 \frac{(0{,}092 \mu Sv \cdot m^2/MBq \cdot h)}{d^2}$$

Dose: $D(t_u) = (0{,}092 \mu Sv \cdot m^2/MBq \cdot h)\, A_0\, t_u\, R_t \frac{1}{d^2}$

Shielding the PET/CT department

For shielding calculations: Uncontrolled area: 20μSv/week

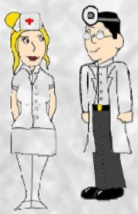


Assume:
40 patients/week
Administered FDG activity: 555MBq
Uptake time: 60min → $R_t = 0,832$

Dose from patients to be <20μSv/week:

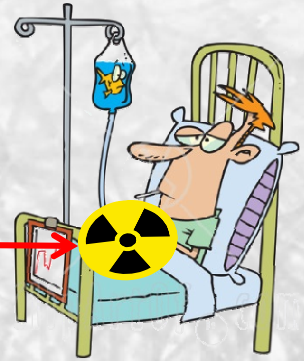
D = 20μSv/week = activity *patients/week* patient dose rate constant /d² =

$$= (0{,}092 \mu Sv \cdot m^2/MBq \cdot h)\, N A_0\, t_u\, R_t \frac{1}{d^2}$$



→ d = 9,2 meters!

Not likely!



New facilities: concrete
Existing facilities: lead

Occupancy Factor

When designing shielding, we must consider how much time a person spends in the vicinity of the injected patient:

Occupancy factor, Γ: The factor (≤1) by which the workload should be multiplied to correct for the degree of occupancy of the area in question while the radiation source is in the "on" position and emitting radiation (ncrponline.org)

→ «fraction of time the location is occupied by a human»

OBS!
The injected patient is always «on»

For an uncontrolled area, Γ=1

TABLE 3. DIFFERENT SUGGESTED OCCUPANCY FACTORS (*T*)
(*whenever possible, the local situation should be assessed before determining the occupancy factor to be used*)

Type of area	NCRP 49 [2]	BIR/IPEM 2000 [12]
Offices, reception areas, laboratories, shops, children's play areas, nurse's stations, staff rooms Control room	1	1
Wards, patient rooms	1	0.2
Patient examination and treatment rooms	—	0.5
Corridors	1/4	0.2
Toilets, bathrooms, outside areas with seating	1/16	0.1
Stairways, unattended waiting rooms, store rooms (not film)	1/16	0.05

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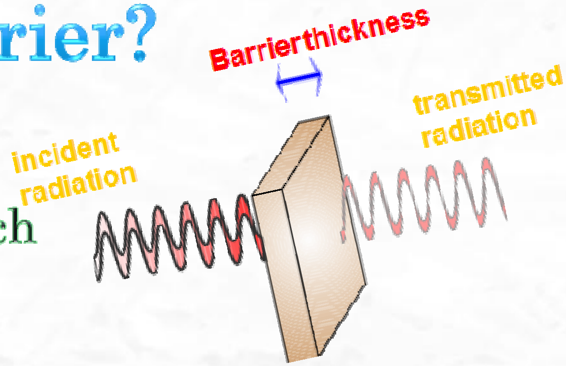
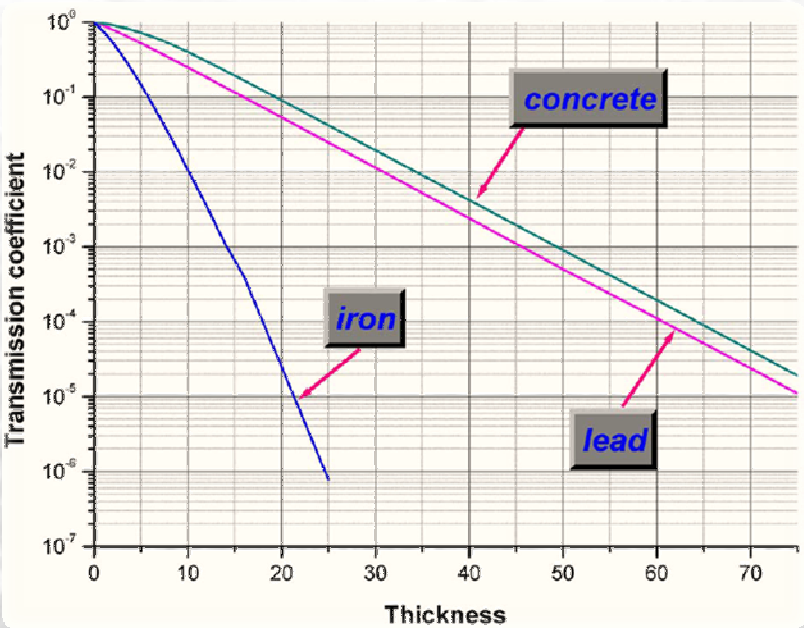
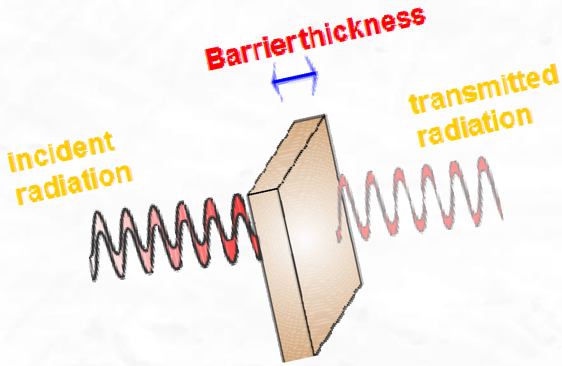
Transmission Factor: How effective is the barrier?



Barrier transmission, B: The ratio of any radiation field quantity at a location behind the barrier on which radiation is incident to the field quantity at the same location without the presence of the shield (ncrponline.org)



Transmission Factor



Barrier transmission, B: The ratio of any "radiation field quantity at a location behind the barrier" (weekly dose limit) to the "field quantity at the same location without the presence of the shield" (injected patient)

$$B = \frac{\text{(weekly dose limit)}}{\text{(dose from the unshielded patient)}} = P / [\Gamma N A_0\, t_u\, R_t \frac{(0{,}092\mu Sv \cdot m^2/MBq \cdot h)}{d^2}]$$

N = number of patients/week
P = weekly dose limit
Remember!

For shielding calculations:
Weekly dose limit for an uncontrolled area: 20µSv/week
Occupational dose limit: 5mSv/year ≈ 100µSv/week (ALARA)

What thickness of barrier do we need?

Assume we b
the Injection

uncontrolled
4 meters fro
Injected FDG
40 patients/v
Uptake time

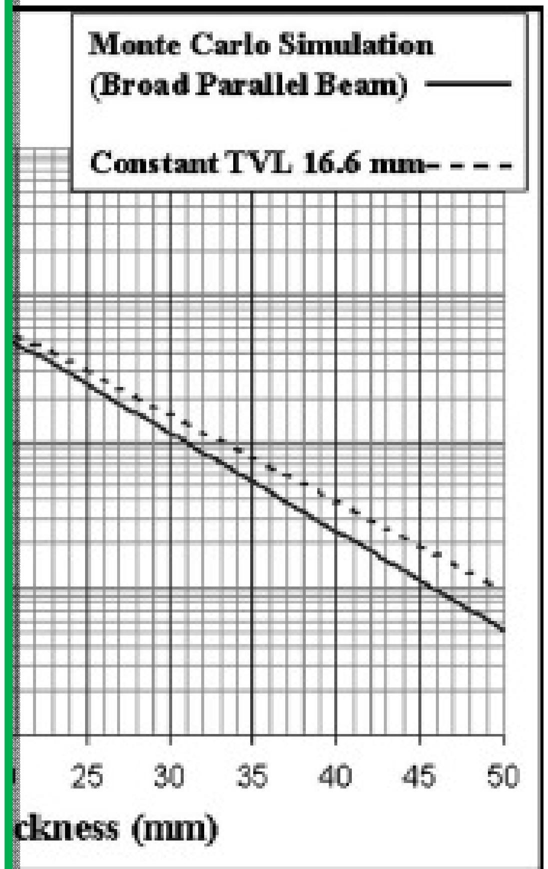
$B = \frac{(we}{(dose\ fro}$

B=0,13

TABLE IV. Broadbeam transmission factors at 511 keV in lead, concrete, iron.

	Transmission Factors		
Thickness[a,b]	Lead	Concrete[c]	Iron
0	1.0000	1.0000	1.0000
1	0.8912	0.9583	0.7484
2	0.7873	0.9088	0.5325
3	0.6905	0.8519	0.3614
4	0.6021	0.7889	0.2353
5	0.5227	0.7218	0.1479
6	0.4522	0.6528	0.0905
7	0.3903	0.5842	0.0542
8	0.3362	0.5180	0.0319
9	0.2892	0.4558	0.0186
10	0.2485	0.3987	0.0107
12	0.1831	0.3008	0.0035
14	0.1347	0.2243	0.0011
16	0.0990	0.1662	0.0004
18	0.0728	0.1227	0.0001
20	0.0535	0.0904	
25	0.0247	0.0419	
30	0.0114	0.0194	
40	0.0024	0.0042	
50	0.0005	0.0009	

[a]Thickness in mm for lead.
[b]Thickness in cm for concrete and iron.
[c]Concrete density=2.35 g/cm³.



mission factors as a function of lead

Outside the imaging room

The patient was injected and rested and voided
Now enters the PET/CT scanner

What activity is coming from the patient?

The patient was injected and rested and voided
→ activity in the patient at the time the patient enters the scanner room:

$$A(t_u) = 0{,}85 * A_0 e^{-\lambda t_u}$$

NB! Voiding removes ~15% A_0

Activity during the imaging time:

dose reduction factor over the imaging time t_i

$$A(t_i) = \int_0^{t_i} 0{,}85 A_0 e^{-\lambda t_u} e^{-\lambda t} = 0{,}85 A_0 e^{-\lambda t_u} \frac{(1-e^{-\lambda t_i})}{\lambda} =$$

$$= 0{,}85 A_0 e^{-\lambda t_u} \frac{(1-e^{-\lambda t_i})}{\lambda} \frac{t_i}{t_i} = 0{,}85 A_0 e^{-\lambda t_u} R_i t_i$$

Outside the imaging room

What thickness of barriers do we need around the scanner room?

Dose from the patient:

D = activity * patient dose rate constant /d² =

$$= A\frac{(0{,}092 \mu Sv \cdot m^2/MBq \cdot h)}{d^2} =$$

$$= 0,85 A_0 e^{-\lambda t_u} R_i t_i \frac{(0{,}092 \mu Sv \cdot m^2/MBq \cdot h)}{d^2}$$

Transmission factor, B:

$$B = \frac{\text{(weekly dose limit)}}{\text{(dose from the unshielded patient)}} = P / [\Gamma N A_0\, t_u\, R_t \frac{(0{,}092 \mu Sv \cdot m^2/MBq \cdot h)}{d^2}]$$

Occupancy factor Γ
N patients/week

Outside the imaging room

What thickness of barriers do we need around the scanner room?

Dose from the patient:

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Transmission factor, B:

$$B = \frac{\text{(weekly dose limit)}}{\text{(dose from the unshielded patient)}} =$$

$$= P / [\Gamma N (0{,}85) A_0 \, e^{-\lambda t_u} t_i \, R_i \frac{(0{,}092 \mu Sv \cdot m^2/MBq \cdot h)}{d^2}]$$

Occupancy factor Γ
N patients/week
Weekly dose limit P

From t

What thickness of barriers
scanner room?

Assume we build an uncon
→ occupancy facto
40 patients/week
Administered FDG activity
t_u = 60min
t_i = 30min → reduction fac

Transmission factor B:

$B = P / [\Gamma N(0,85) A_0 e^{-\lambda t_u} t_i$

TABLE IV. Broadbeam transmission factors at 511 keV in lead, concrete, iron.

Thickness[a,b]	Transmission Factors: Lead	Concrete[c]	Iron
0	1.0000	1.0000	1.0000
1	0.8912	0.9583	0.7484
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6	0.4522	0.6528	0.0905
7	0.3903	0.5842	0.0542
8	0.3362	0.5180	0.0319
9	0.2892	0.4558	0.0186
10	0.2485	0.3987	0.0107
12	0.1831	0.3008	0.0035
14	0.1347	0.2243	0.0011
16	0.0990	0.1662	0.0004
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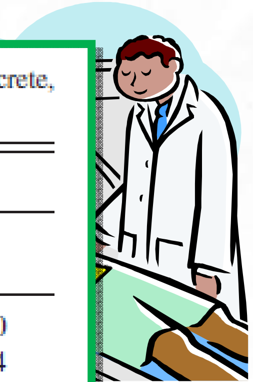


Good news: the scanner shields

Gantry and detectors provide a reduction of the dose rate at some of the walls

Effectiveness depends on geometry and placement of the PET/CT in the room and type of scanning procedures

→ Ask the vendor for shielding characteristics

Activity in the scanner bore is nearly 100% shielded.

We don't need the previous calculation?
Is the scanning room 100% shieled?

Axial width of PET scanners: 16–18 cm
→ for a 5-bed position scan, the scanner conservatively reduces the dose by 20%

The scanner shields, but must be shielded…?!

The PET/CT may be sensitive to ambient radiation

- adjacent uptake rooms

The PET/CT is more sensitive to activity outside the field of view

- the patient being imaged

Ambient radiation sensitivity may be minimized by orientation of the PET/CT

→ ask the vendor for contour maps

The scanner is a PET/CT
What about the CT?

How is the CT used?

Is the PET/CT used for diagnostic CT?
→higher doses → more shielding

In general:
number PET/CT patients < number CT patients
PET/CT area scanned > CT area scanned
CT shielding is insufficient for PET

PET shielding that yields 1mSv/year is likely to shield CT

Minimal PET shielding in controlled areas (5mSv/year) might not be sufficient for CT

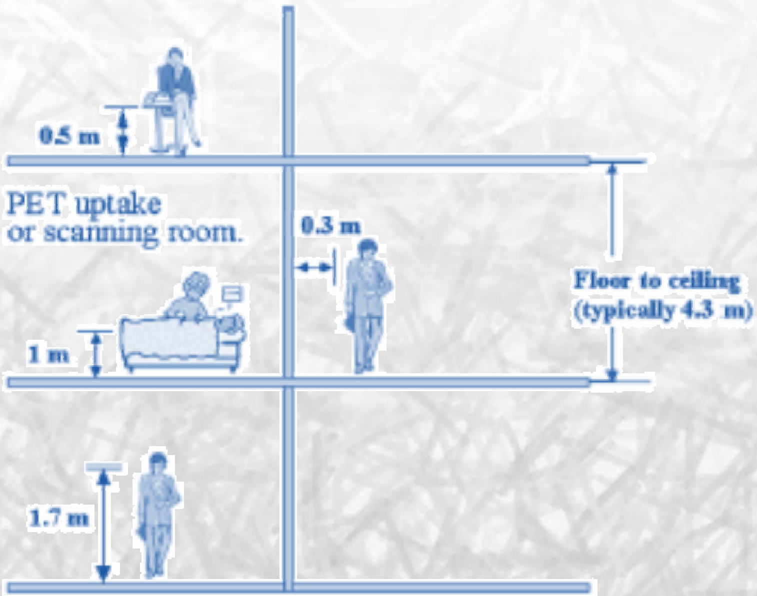
CT shielding applies only to the scanner room!

We need shielding in all directions

511keV annihilation radiation is penetrating

Often new clinics are inserted into busy departments

→ **must remember to shield offices above and below the PET/CT!**



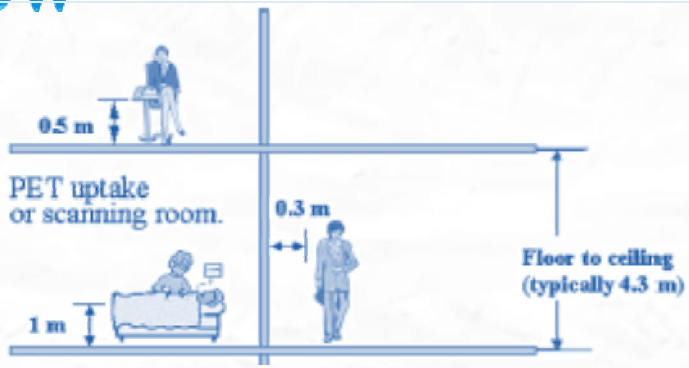
Assume :

patient is 1m above the floor

- Dose rate is calculated 0,5m above the floor of rooms above
- Dose rate is calculated 1,7m above the floor of rooms below

Shielding above and below

What thickness of shielding material do we need in order to create an uncontrolled room above the uptake/injection room?



uncontrolled room

→ occupancy factor Γ=1, weekly dose limit P = 20μSv/week

floor-to-floor distance: 4,3m

10cm concrete between floors

At what distance do we calculate the dose rate?

Dose rate is calculated 0,5m above the floor of rooms over the PET/CT

→4,3m between -1m source +0,5m distance = 3,8m

Shielding abo

uncontrolled room

→ occupancy fact

→ weekly dose lim

floor-to-floor distance: 4,3

10cm concrete between flo

dose rate is calculated at d

As previously, assume:

40 patients/week

Administered FDG activit

$t_u = 60min \rightarrow R_t = 0,832$

Transmission factor B:

$B =$ (weekly dose limi ... h) / (dose from the unshielded p ...]

B=0,17

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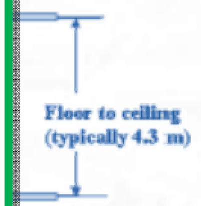
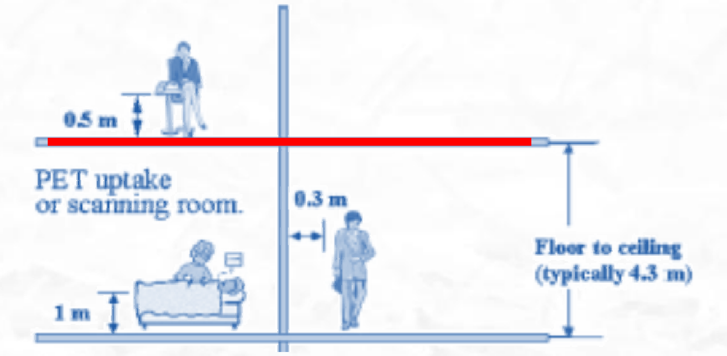


Shielding above an intake room



Transmission factor B = 0,17, but we have help from the floor!

10 cm concrete between floors (equivalent 0,65cm lead)

17cm concrete – 10cm floor concrete =
= 7cm additional concrete

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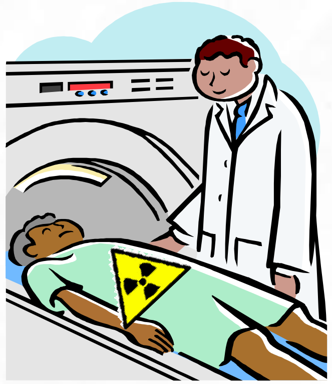
[c]Concrete density=2.35 g/cm^3.

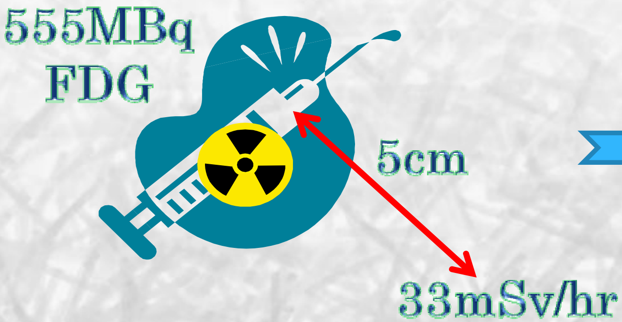
Shielding the staff



Dose limit for workers: 20 mSv/year

Staff working directly with PET patients receives the largest doses:

- syringe preparation
- injecting the patient
- patient positioning to/in the scanner
- dose received during imaging



How far away to put the control room

For shielding calculations:
Occupational dose limit: 5mSv/year

Assume:

40 patients/week = $40 * \frac{50\ work\ weeks}{1\ year}$ = 2000patients/year

Administered FDG activity: 555MBq

Uptake time: 60min

Scan time: 30min → $R_i = 0,911$

Dose from patients to be <5mSv/year:

D = 5mSv = activity *patients/year* patient dose rate constant $/d^2$ =

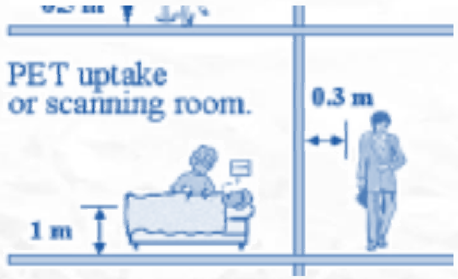
$$= AN \frac{(0{,}092 \mu Sv \cdot m^2/MBq \cdot h)}{d^2}$$

$$\rightarrow d^2 = 0{,}85 N A_0 e^{-\lambda t_u} R_i t_i \frac{(0{,}092 \mu Sv \cdot m^2/MBq \cdot h)}{5mSv}$$

→ d = 2,32m

Shielding in the department

Dose limit for workers: 20 mSv/year

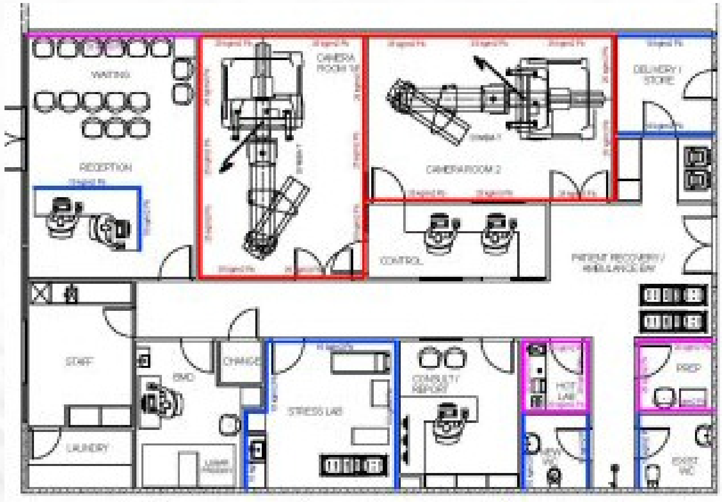


Adjust PET workflow or add shielding for staff sitting all day in offices <4 m from uptake rooms or scanner

Portable lead shields are useful, maybe difficult to use

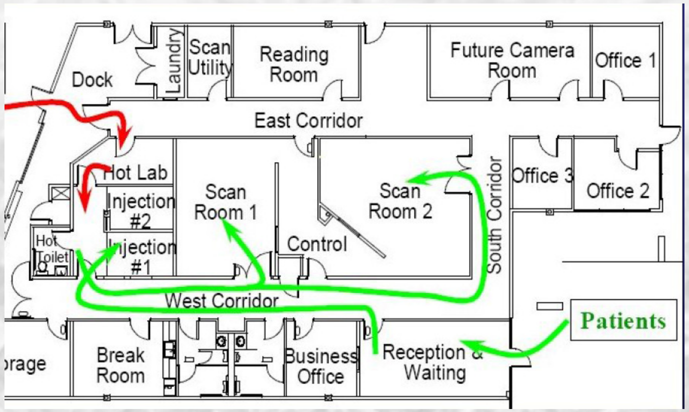
- heavy
- restrict access to the patient(?)

Shielding in the department

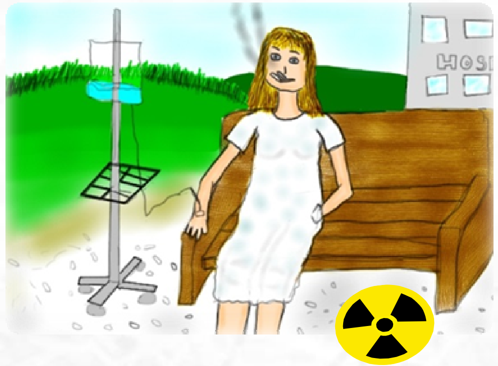


Lead doors are expensive and heavy!

→careful placement of the door can avoid expenses



What else exists in the department?



Injected patients increase background

Annihilation radiation may affect other instruments:

- gamma cameras
- uptake probes
- scintillating counters

Devices most affected by the presence of radioactive PET patients:

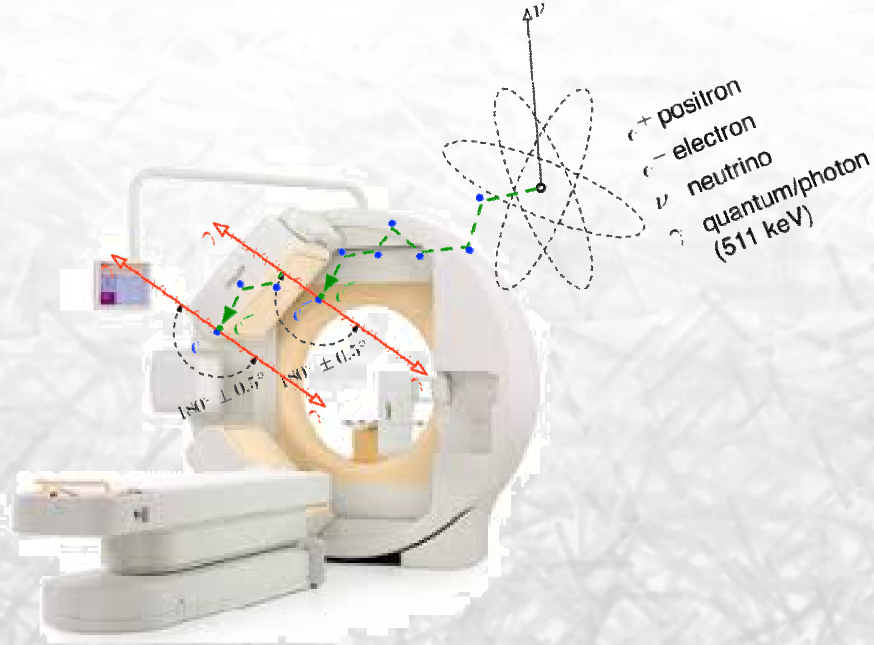
- thyroid uptake probes
- scintillation well counters

What else exists in the department?

Are other instruments affected by PET radiation?
→make background measurements

Measure background:

- at energy window of the scintillation camera exams
- with the scintillation camera rotated to the worst angle



What else exists in the department?

TABLE IV. Broadbeam transmission factors at 511 keV in lead, concrete, iron.

	Transmission Factors		
Thickness[a,b]	Lead	Concrete[c]	Iron
0	1.0000	1.0000	1.0000
1	0.8912	0.9583	0.7484
2	0.7873	0.9088	0.5325
3	0.6905	0.8519	0.3614
4	0.6021	0.7889	0.2353
5	0.5227	0.7218	0.1479
6	0.4522	0.6528	0.0905
7	0.3903	0.5842	0.0542
8	0.3362	0.5180	0.0319
9	0.2892	0.4558	0.0186
10	0.2485	0.3987	0.0107
12	0.1831	0.3008	0.0035
14	0.1347	0.2243	0.0011
16	0.0990	0.1662	0.0004
18	0.0728	0.1227	0.0001
20	0.0535	0.0904	
25	0.0247	0.0419	
30	0.0114	0.0194	
40	0.0024	0.0042	
50	0.0005	0.0009	

[a]Thickness in mm for lead.
[b]Thickness in cm for concrete and iron.
[c]Concrete density = 2.35 g/cm^3.

g will reduce a PET background ps to 1000cps?

factor = 1000cps/592000cps = 0,0017

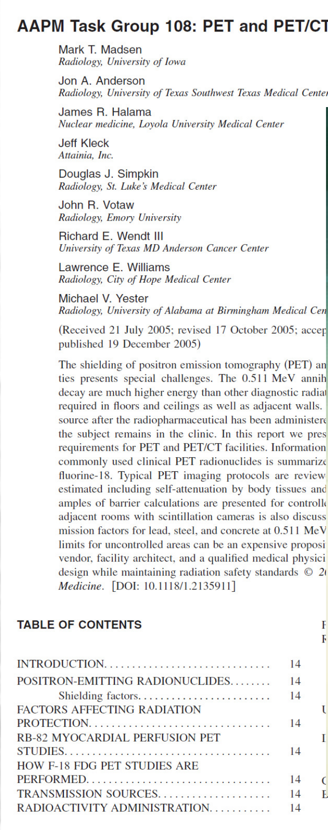
Lead is expensive and heavy!

- **Cover only critical areas**
- **What is the occupancy?**
- **Controlled/uncontrolled area**
- **Mobile shield instead?**

Shielding requirements for PET/CT

Use guidelines, but remember to use the regulatory limits of *your* country

Be effective (radiation exposures, costs, workflow) when designing a PET/CT facility



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

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(Received 21 July 2005; revised 17 October 2005; accep
published 19 December 2005)

The shielding of positron emission tomography (PET) an
ties presents special challenges. The 0.511 MeV annih
decay are much higher energy than other diagnostic radiat
required in floors and ceilings as well as adjacent walls.
source after the radiopharmaceutical has been administere
the subject remains in the clinic. In this report we pres
requirements for PET and PET/CT facilities. Information
commonly used clinical PET radionuclides is summarize
fluorine-18. Typical PET imaging protocols are review
estimated including self-attenuation by body tissues and
amples of barrier calculations are presented for controlle
adjacent rooms with scintillation cameras is also discuss
mission factors for lead, steel, and concrete at 0.511 MeV
limits for uncontrolled areas can be an expensive proposi
vendor, facility architect, and a qualified medical physici
design while maintaining radiation safety standards © 2
Medicine. [DOI: 10.1118/1.2135911]

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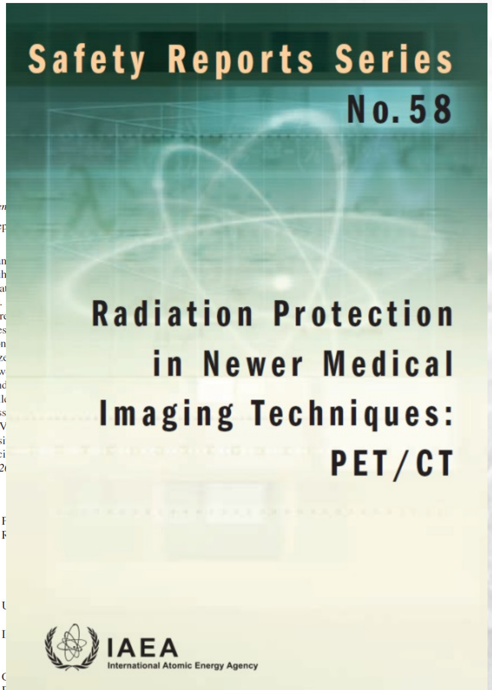
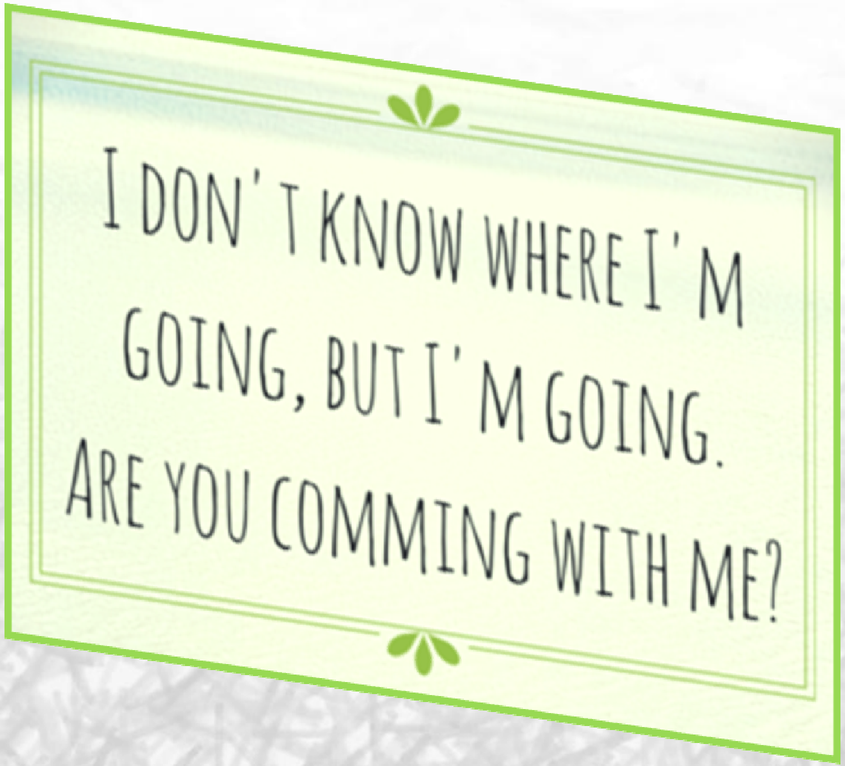


Avoid unnecessary expenses with a group effort:
Vendor
Architect
Medical physicist
Technicians/department workers

Tack!



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