PET Shielding and Radiation Protection

July 2007
American Association of Physicists in Medicine Summer School

Jon A. Anderson, PhD
Department of Radiology
The University of Texas Southwestern Medical Center at Dallas

What Is Different When You Have PET/CT in Your Facility?

1) 511 keV energy
-increases exposure rate from doses, patients
-greatly increases thickness of required shielding

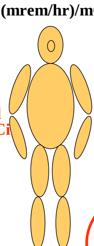
2)Requirements for patient handling during injection and uptake phase

3) Combined modality scanners (PET/CT) require consideration of both gamma-ray and x-ray hazard

The ^{18}F-Injected Patient as a Source

(average of different investigators, 2003)

all at 1 m from surface of body, average value from several investigators



Superior 0.075 (µSv/hr)/MBq 0.279 (mrem/hr)/mCi

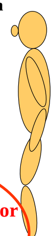
Lateral 0.104 (µSv/hr)/MBq 0.383 (mrem/hr)/mCi

Anterior 0.103 (µSv/hr)/MBq 0.383 (mrem/hr)/mCi

not as anisotropic as it might seem

Inferior 0.018 (µSv/hr)/MBq 0.065 (mrem/hr)/mCi

compare this to 0.014 (µSv/hr)/MBq or 0.05 (mrem/hr)/mCi for ^{99m}Tc: ^{18}F values factor of 8 larger!



A Revealing Comparison of Lead Requirements: X-Ray *vs* PET

#HVL's	Lead Thickness Required mm (in, to next 1/16)	
	X-ray [1] (average primary for rad room)	PET[2]
1	0.044 (< 1/16)	5.3 (1/4)
2	0.103 (< 1/16)	9.9 (7/16)
4	0.278 (< 1/16)	19.0 (3/4)
8	0.718 (< 1/16)	32.5 (1 5/16)
10	1.366 (< 1/16)	46.0 (1 13/16)

Even a single half-value layer for PET is an expensive proposition!

1. NCRP 147: Structural Shielding Design for Medical X-Ray Imaging Facilities
2. Simpkin, 2004, developed for AAPM Task Group on PET Facility Shielding

A Revealing Comparison of Lead Re…

Remember this morning's bottom line: for DX, we can apply 3 models from NCRP 147 and find that 1/16" is (usually) the answer, with some to spare. We usually calculate the "closest" point.

Not true in PET. As we will see, it is true that normally we need 1-3 HVL's of shielding. We tend to put just what we need, due to $$$.

Implication: At every protection point, we need to include all sources that can be contributing to the dose at that point (i.e. multiple injection rooms, scan rooms, etc.). Corresponds to adjusting protection limit downward.

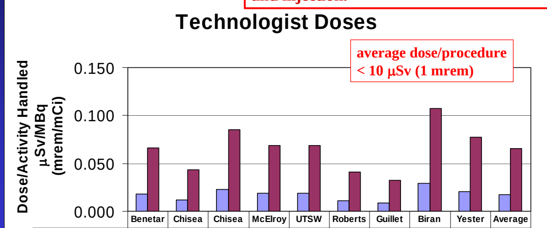
Workflow at the PET Center (FDG Whole Body Scans)

- Arrival of patient
- Pt instruction and prep
- Injection of Pt *
- Receive doses → Assay of dose * (8-20 mCi)
- Uptake of pharmaceutical (30-60 min)
- Have Pt empty bladder
- Transport Pt to scanner *
- Position Pt * (5-10 min)
- Scan (10-30 min)
- QA Check of Scan → Release Pt *
- Read study
- Distribute to PACS or Media

* steps with highest technologist exposure

Magnitude of Technologist Exposure

Consistent with conventional nuclear medicine practice, most of technologist dose comes from positioning, transport, and injection.



	Benetar	Chisea	Chisea	McElroy	UTSW	Roberts	Guillet	Biran	Yester	Average
SI Units	0.018	0.012	0.023	0.019	0.019	0.011	0.009	0.029	0.021	0.018
Conventional Units	0.067	0.044	0.085	0.069	0.069	0.041	0.032	0.107	0.077	0.066

More on Technologist Exposure

1) Technologist dose will probably drop as experience increases

Over a two year period with the same technologists, we saw a 40% decrease in radiation dose per unit activity handled.

2) For 0.018 µSv/(MBq injected)
370 MBq (10 mCi) injected/pt
10 pt/day

Yearly: 16.6 mSv (1660 mrem) (<5 rem, >ALARA trigger)
9 Months: 12.5 mSv (1250 mrem) (> declared pregnancy limit)

Operating Suggestions to Minimize Technologist Dose

Minimize handling time. Use unit doses.

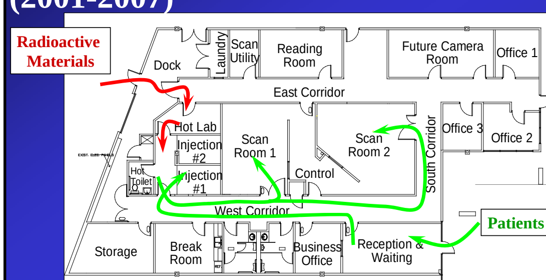
Use tungsten syringe shields, employ syringe carriers, transport carts, etc. to minimize handling exposure.

Instruct patient before injection. Minimize contact afterward.

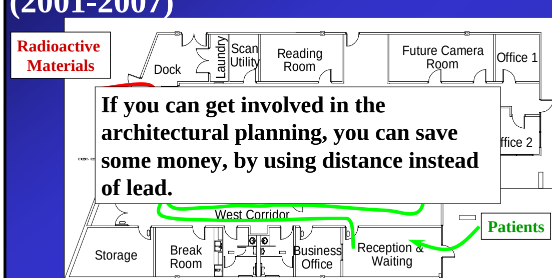
Establish IV access with butterfly infusion set.

Use other personnel for hot patient transport.

PET Facility Tour: University of Texas Southwestern Medical Center at Dallas (2001-2007)



PET Facility Tour: University of Texas Southwestern Medical Center at Dallas (2001-2007)



If you can get involved in the architectural planning, you can save some money, by using distance instead of lead.

Hot Lab Details: Dose Storage Area

Notes:
1) Floor protection (containers weigh > 66 lbs)
2) Space needed depends on how often deliveries are made; may have >100 mCi here at a time, even for one scanner
3) Extra shielding may be required

Hot Lab Details: Dose Assay and Preparation Area

Notes:
1) Calibrator convenient to dose storage
2) L Block close to calibrator
3) Note use of special PET carrier for syringe
4) Note L Block: thick window, 2" lead, 2" lead wrap-around

Hot Lab Details




Notes:
1) All this lead requires solid support -- have a heart-to-heart talk with the cabinet maker
2) Counter mount of calibrator decreases tech exposure
3) Extra shielding required on well counter to shield from sources in scanner, calibration sources, patient in scanner, etc.
4) Use tungsten syringe shields for dose reduction to fingers.

Injection Room Details

Notes:
1) Injection room
Hot lab
PET/CT bay
are most likely areas to need shielding

2) To minimize anomalous uptake
-minimize external stimuli (false uptake!)
-keep patient quiet and still on gurney or in injection chair

3) Need adjacent hot toilet for patients to use after uptake period.

4) Indirect lighting,curtains, noise control are desirable

What You Find in the Scanner Bay:

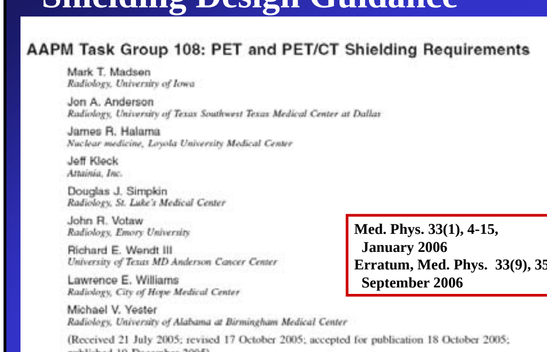
Siemens Biograph Series

GE Discovery Series

Philips GEMINI

You need to know which one you're getting! -- it may affect scan time, injected activity

Shielding Design Guidance



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

Mark T. Madsen
Radiology, University of Iowa
Jon A. Anderson
Radiology, University of Texas Southwest Texas Medical Center at Dallas
James R. Halama
Nuclear medicine, Loyola University Medical Center
Jeff Kleck
Attainia, Inc.
Douglas J. Simpkin
Radiology, St. Luke's Medical Center
John R. Votaw
Radiology, Emory University
Richard E. Wendt III
University of Texas MD Anderson Cancer Center
Lawrence E. Williams
Radiology, City of Hope Medical Center
Michael V. Yester
Radiology, University of Alabama at Birmingham Medical Center

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

Med. Phys. 33(1), 4-15, January 2006
Erratum, Med. Phys. 33(9), 3579 September 2006

Calculation Formalism Proposed by Task Group: General Form

B, the required barrier transmission factor, will be calculated as

$$B = \frac{P * d^2}{\Gamma * T * N_w * (A_0 * F_{tot} * t * R_t)}$$

P = target dose in protected area (per week, hour, etc.) [μSv]
d = distance from source (patient) to protected point [m]
Γ = dose rate constant [(μSv/hr)(m²/MBq)]
T = occupancy factor (NCRP 147 or specific information)
N_w = number of patients per time period corresponding to P
A_0 = injected activity [MBq]
F_{tot} = factor encompassing physical decay of the injected dose and possible elimination from body = $F_{phys} * F_{elim}$
t = integration time (time the source (patient) is in the room) [hr]
R_t = "reduction factor" (accounts for decay during dose integration period)

Site Evaluation for PET Shielding

Uses of adjacent spaces (including above and below) and occupancy factors for them

patients/week
isotopes to be used, activity/pt
types of PET studies to be performed (brains, WB, cardiac)
uptake time and scan time for this equipment/study/center

dose delivery schedule (once a day?, multiples?); maximum activity on hand

CT technique factors (kVp, mAs/scan [depends of # beds])
scans per patient (additional diagnostic scans?)
amount of "non-PET" CT workload expected

Radiation Sources to Include in the Shielding Plan

Doses (pre-injection) in Hot Lab

Calibration sources for scanner

Patient (post injection, in uptake rm)

Patient (in scanner, hot toilet)

TX Sources in scanner (PET)

CT x-ray source (for PET/CT)

require isotopic workload parameters: pts/wk, mCi/pt uptake,scan times isotope type and delivery scheds

require CT x-ray workload factors, techniques, include non-PET CT work

P: Radiation Protection Targets

	Limitations per 10CFR20	ALARA Action Limit
Radiation workers	50 mSv/yr (5000 mrem/yr)	5 mSv/yr (500 mrem/yr)
Pregnant worker's fetus	5 mSv/9 mo (500 mrem/9 mo)	
Members of public (from each licensed operation)	1 mSv/yr (100 mrem/yr)	
in any hour, not to exceed	.02 mSv (2 mrem)	

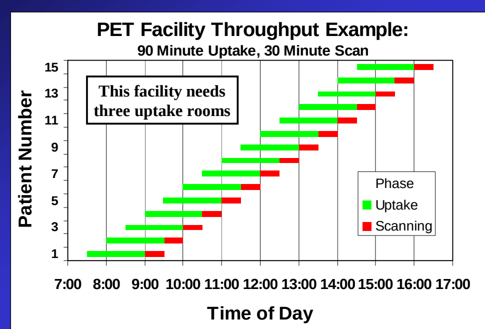
Targets

controlled areas: 100 µSv/wk or 10 mrem/wk

uncontrolled areas: 20 µSv/wk or 2 mrem/wk

GUIDANCE: ALARA -- As Low As Reasonably Achievable

N: Maximum Workload Estimation



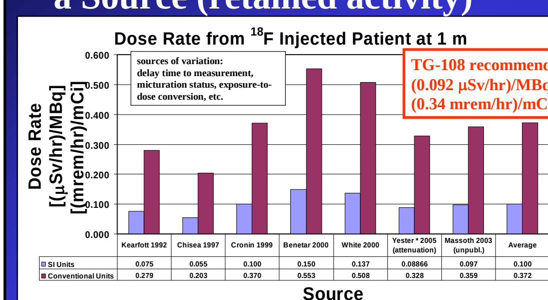
$\#pts/day = (T_{work} - T_{uptake})/T_{scan\_rm}$ $\quad$ $\#\ uptake\ areas = T_{uptake}/T_{scan\_rm}$

18F: A Plethora of Dose Rate Constants for Point Sources (TG-108)

^{18}F Rate Constants	SI Units		Conventional Units	
Exposure Rate Constant	15.5	(µR/hr) m²/MBq	0.5735	(mR/hr) m²/mCi
Air Kerma Rate Constant	0.134	(µSv/hr) m²/MBq	0.4958	(mrem/hr) m²/mCi
Effective Dose Equivalent (ANS-1991)	0.143	(µSv/hr) m²/MBq	0.5291	(mrem/hr) m²/mCi
Tissue Dose Constant	0.148	(µSv/hr) m²/MBq	0.5476	(mrem/hr) m²/mCi
Deep Dose Equivalent (ANS-1977)	0.183	(µSv/hr) m²	[illegible]	[illegible]
Maximum Dose (ANS-1977)	0.188	(µSv/hr) m²	[illegible]	[illegible]

TG-108 recommends 0.143 (µSv/hr)/MBq 0.53 (mrem/hr)/mCi for F-18 bare source

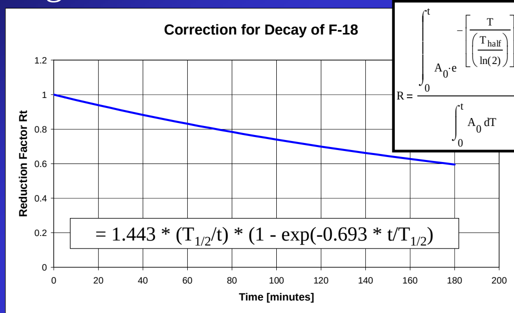
Γ: The ^{18}F-Injected Patient as a Source (retained activity)



	Kearfott 1992	Chisea 1997	Cronin 1999	Benetar 2000	White 2000	Yester * 2005 (attenuation)	Massoth 2003 (unpubl.)	Average
SI Units	0.075	0.055	0.100	0.150	0.137	0.08866	0.097	0.100
Conventional Units	0.279	0.203	0.370	0.553	0.508	0.328	0.359	0.372

about 20% of dose will be in bladder after 1-2 hours;TG108 uses 15%

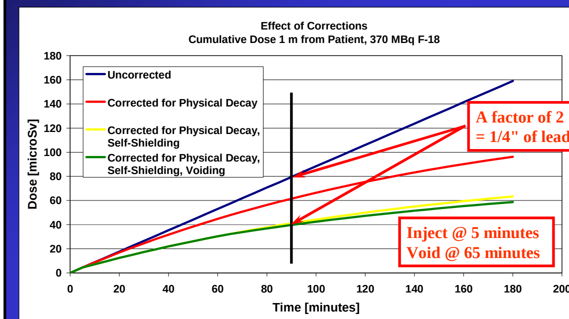
Correction for Decay During Dose Integration Period: Reduction Factor



$$R = \frac{\int_0^t A_0 \cdot e^{-\left[\frac{T}{\left(\frac{T_{half}}{\ln(2)}\right)}\right]} dT}{\int_0^t A_0 \, dT}$$

$= 1.443 * (T_{1/2}/t) * (1 - \exp(-0.693 * t/T_{1/2}))$

Effects of Adding Corrections to Dose Calculation



Simplified Task Group Formalism: Uptake Room

B, the required barrier transmission factor, will be calculated as

$$B = \frac{P * d^2}{\Gamma * T * N_w * (A_0 * F_{tot} * t * R_t)}$$

Uptake Room: $$B = \frac{10.9 * P[\mu Sv] * d[m]^2}{T * N_w * (A_0[MBq] * t_U[hr] * R_{tU})}$$

10.9 is 1/Γ in (hr/μSv)(MBq/m²);

F_{tot} = 1 (no physical decay prior to injection, no elimination)

R_{tU} = reduction factor for uptake time t_U

Simplified Task Group Formalism: Scan Room

B, the required barrier transmission factor, will be calculated as

$$B = \frac{P * d^2}{\Gamma * T * N_w * (A_0 * F_{tot} * t * R_t)}$$

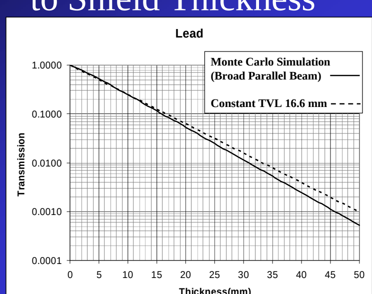
Scan Bay: $$B = \frac{12.8 * P[\mu Sv] * d[m]^2}{T * N_w * (A_0[MBq] * F_U * t_I[hr] * R_{tI})}$$

12.8 includes the value of Γ and the effects of voiding 15% of the injected activity before imaging;

$F_U = \exp(-0.693 t_U/T_{1/2})$, the physical decay of the isotope before the patient enters scan bay

Going from Barrier Transmission to Shield Thickness

Monte Carlo calculations by Douglas Simpkin (2004)



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

Curves and fitting parameters for iron and concrete are also found in the report

Fitting Parameters for Different Materials per TG108

Archer Parameters

	α [cm^{-1}]	β [cm^{-1}]	γ
Lead	1.543	-0.4408	2.136
Concrete	0.1539	-0.1161	2.0752
Iron	0.5704	-0.3063	0.6326

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

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

Example 1: Uptake Room

Protection Goal:	$P := 20\cdot 10^{-6}\,\mathrm{Sv}$
Distance:	$d := 4\cdot\mathrm{m}$
Gamma Constant:	$\Gamma := .092\cdot 10^{-6}\cdot\frac{\mathrm{Sv}\cdot\mathrm{m}^2}{\mathrm{hr}\cdot 10^6\,\mathrm{Bq}}$
Occupancy:	$T := 1$
Number of Patients per Week:	$N_w := 40$
Injected Activity:	$A_0 := 555\cdot 10^6\,\mathrm{Bq}$
Decay/Elimination:	$F := 1$
Source Duration:	$t := 1\mathrm{hr}$
Reduction Factor:	$R(t) = 0.831$

$$B_r := \frac{P\cdot d^2}{\Gamma\cdot T\cdot N_w\cdot (A_0\cdot F\cdot R(t)\cdot t)} \qquad B_r = 0.188$$

$$x_{Pb}(B_r) = 1.184\,\mathrm{cm} \qquad x_{conc}(B_r) = 15.165\,\mathrm{cm}$$

An uncontrolled area with 100% occupancy is 4m from the patient. 40 patients a week are injected in this room with 555 MBq (15 mCi) of FDG and held for a 1hr uptake time.

How much shielding is needed?

Ans: 1.2 cm of Pb or 15.2 cm of concrete

Example 2: Scan Room

Protection Goal:	$P := 20\cdot 10^{-6}\,\mathrm{Sv}$
Distance:	$d := 3\cdot\mathrm{m}$
Gamma Constant:	$\Gamma := .092\cdot 10^{-6}\cdot\frac{\mathrm{Sv}\cdot\mathrm{m}^2}{\mathrm{hr}\cdot 10^6\,\mathrm{Bq}}$
Occupancy:	$T := 1$
Number of Patients per Week:	$N_w := 40$
Injected Activity:	$A_0 := 555\cdot 10^6\,\mathrm{Bq}$
Decay/Elimination:	$F := e^{-\left[\ln(2)\cdot\frac{(1\mathrm{hr})}{T_{half}}\right]}\cdot(1-15\%)$
Source Duration:	$t := 0.5\mathrm{hr}$
Reduction Factor:	$R(t) = 0.91$

$$B_r := \frac{P\cdot d^2}{\Gamma\cdot T\cdot N_w\cdot (A_0\cdot F\cdot R(t)\cdot t)} \qquad B_r = 0.334$$

$$x_{Pb}(B_r) = 0.807\,\mathrm{cm} \qquad x_{conc}(B_r) = 11.278\,\mathrm{cm}$$

An uncontrolled area with 100% occupancy is 3m from the patient. 40 pts/week, 555 MBq (15 mCi) FDG/pt, 1hr uptake time. Patients void (15% of the dose) at 1 hr. 30 minutes spent in scan bay.

How much shielding ?

Ans: 0.8 cm of Pb or 11.3 cm of concrete

A Shielding Paradigm for Mixed PET/CT Applications (Just a personal opinion)

0) Use architectural layout to minimize shielding requirements (use distance, low occupancies)

1) Identify magnitude and location of sources, including CT. Integrate over period that source is in place, giving dose/wk or dose/hr at one meter for given workload.

2) Identify all barriers that will contribute to shielding, including pigs, shipping containers, etc. Establish test points at perimeter, sensitive locations. Identify which barriers will shield each point.

A Shielding Paradigm (cont)

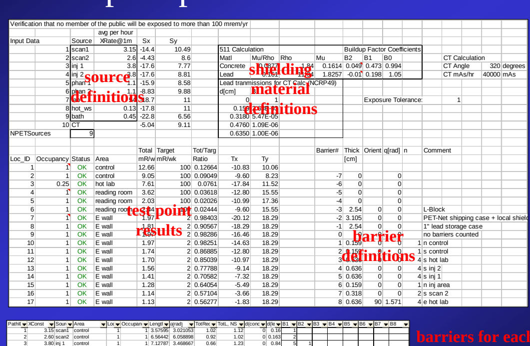
3) Calculate doses (summed over all sources, including CT) without attenuation.

4) Start adding lead or concrete as necessary to the barriers, recalculating the doses as you go. Spread the lead and you may not have to hang really thick sheets!

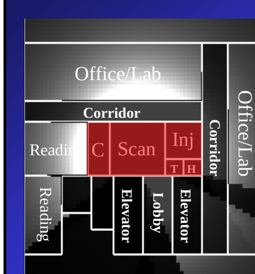
5) Stop when you have met goals (1 mSv/yr, 20 µSv/hr)

A spreadsheet can do all of this (including corrections for anisotropic sources).
Special purpose programs can be developed to do the same.
Pencil and paper can be used, but it is *tedious*!

Example Spreadsheet



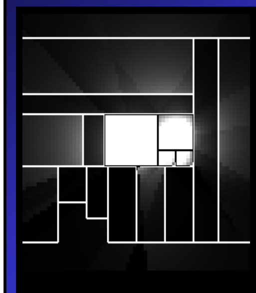
Grid Calculation: No Shielding

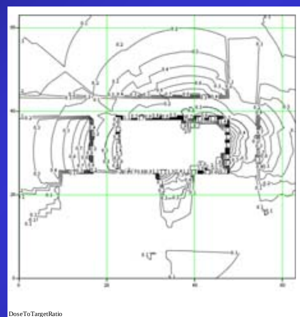


Ratio of calculated dose to target dose, adjusted for occupancy

Sources: Injection room, HL, HWC, Scanner, CT, Cal Source
4 pts/day, 1 hr in uptake, 2 hrs in scan room

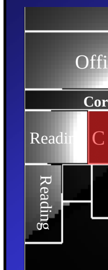
Grid Calculation: Shielded

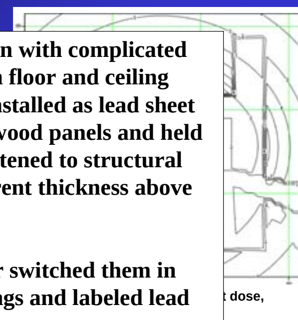




No shielding in walls in excess of 5/16" Pb; did require ceiling, floor shielding. Was not necessary to run "box" to ceiling.

Grid Calculation: No Shielding





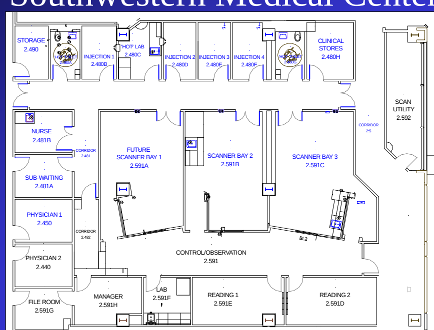
OOPS's happen with complicated schemes: Both floor and ceiling needed lead, installed as lead sheet bonded to plywood panels and held in brackets fastened to structural web, but different thickness above and below.

The contractor switched them in spite of drawings and labeled lead pallets.

Sources: ... Source

4 pts/day, 1 hr in uptake, 2 hrs in scan room

Example: University of Texas Southwestern Medical Center 2007

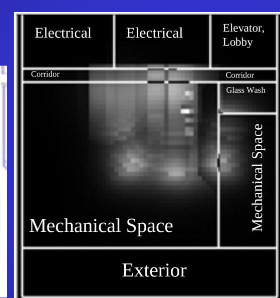


Overall design: No lead in excess of 3/8". North wall of injection rooms, hot lab shielded with 16" of dry-laid, full-density concrete block

Look Up, Down, and Sideways

Duct penetrations in ceiling required separate shielding.

Floor Plan



Relative Dose Map on Floor Above

Dry-Laid Concrete Block as a Flexible Alternative

Use full density concrete blocks (not standard items!).

Lay to offset seams.

Provide cosmetic stud-wall w gypsum board to prevent tampering if area is not controlled.

An Alternative: Shadow Shielding

from JA Anderson, RJ Massoth, and LL Windedahl, 2003 AAPM


jon.anderson@utsouthwestern.edu
Acknowledgements
• Michael Viguet, CNMT
• Dana Mathews, MD
• Thomas Lane, PhD
• Richard Massoth, PhD
• Larry Windedahl
• Doug Simpkin, PhD
• Mark Madsen, PhD


The
End