PET Site Planning and Radiation Safety
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Practice of PET Shielding in 2000: First We Had Chaos
Excerpts from a web discussion thread on shielding control areas at PET facilities:

"...requirements were determined to be 1" and 1/2" of lead...
"...we don't have any special shielding....
"...most do not shield the control room...
"...this leads to lead thicknesses...of about 2 cm...
"...we don't have any lead shielding...
"...we have 2 mm Pb in the walls...
"...we have ...a lead glass window ... 1/4" of lead shielding on this wall...

Then We Had TG-108

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

What Is Different When You Have PET or PET/CT in Your Facility?
The $^{18}$F-Injected Patient as a Source
(average of different investigators, 2003)

Superior: $0.075 \text{ (µSv/hr)/MBq}$

Lateral: $0.104 \text{ (µSv/hr)/MBq}$

Inferior: $0.018 \text{ (µSv/hr)/MBq}$

Anterior: $0.038 \text{ (µSv/hr)/MBq}$

not as anisotropic as it might seem

all at 1 m from surface of body, average value from all applicable reports

compare this to $0.014 \text{ (µSv/hr)/MBq}$ or $0.05 \text{ (mrem/hr)/mCi}$ for $^{99m}$Tc: factor of 8!

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

<table>
<thead>
<tr>
<th>#HVL's</th>
<th>Lead Thickness Required (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray $^1$ (average primary for rad room)</td>
<td>PET $^2$</td>
</tr>
<tr>
<td>1</td>
<td>0.044 (&lt; 1/16)</td>
</tr>
<tr>
<td>2</td>
<td>0.103 (&lt; 1/16)</td>
</tr>
<tr>
<td>4</td>
<td>0.278 (&lt; 1/16)</td>
</tr>
<tr>
<td>8</td>
<td>0.718 (&lt; 1/16)</td>
</tr>
<tr>
<td>10</td>
<td>1.366 (&lt; 1/16)</td>
</tr>
</tbody>
</table>

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

Workflow at the PET Center
(FDG Whole Body Scans)

PET Facility Tour: University of Texas Southwestern Medical Center at Dallas
**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

**Alternate W transport carrier**

**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

**Injection Room Details, UTSW**

Notes:
1. Injection room
   Hot lab
   PET/CT Bay

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
Scan Bay: PET and PET/CT Imaging

Conventional PET
- uses rotating isotopic sources in gantry to make attenuation correction
- 70% E/30% T time split
- typical 15 cm axial FOV
- 2D or 3D acquisitions

PET/CT
- uses coupled CT scanner to make attenuation correction
- provides auto registration of anatomic and functional images
- faster scans through reduced transmission image time

Current PET/CT Implementations

Siemens Biograph Series

GE Discovery Series

Philips GEMINI

You need to know which one you’re getting!

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 (heads, WB, cardiac)
- uptake time and scan time for this equipment/study
- dose delivery schedule (once a day?, multiples?); maximum activity on hand
- CT technique factors (kVp, mA/s/scan [depends of # beds])
- # scans per patient (additional diagnostic scans?)
- amount of “non-PET” CT workload expected

Calculation Formalism Proposed by Task Group

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

\[ B = \frac{P * d^2}{\Gamma * T * N_p * (A_0 * F * t * R)} \]

- P = target dose in protected area [per week, hour, etc.] [µSv]
- d = distance to protected point [m]
- \(\Gamma\) = dose rate constant [µSv/hr/m²/MBq]
- T = occupancy factor (NCRP 147 or specific information)
- \(N_p\) = number of patients per time period corresponding to P
- \(A_0\) = initial activity (patient or point source) at start of integration time [MBq]
- F = factor encompassing physical decay of the dose prior to time period
- t = integration time (time the source/patient is in the room) [hr]
- \(R\) = “reduction factor” (accounts for decay during integration period)
**P: Radiation Protection Targets**

- **Radiation workers**
  - 50 mSv/yr (5000 mrem/yr)
  - 5 mSv/9 mo (500 mrem/9 mo)

- **Pregnant worker’s fetus**
  - 1 mSv/yr (100 mrem/yr)
  - 0.02 mSv (2 mrem)

- **Members of public (from each licensed operation in any hour, not to exceed)**
  - 1 mSv/yr (from each licensed operation)
  - 100 mrem/yr

**GUIDANCE: ALARA -- As Low As Reasonably Achievable**

**ALARA Action Limit**

- 5 mSv/yr (500 mrem/yr)

**Targets**

- Controlled areas:
  - 0.1 mSv/wk or 10 mrem/wk
- Uncontrolled areas:
  - 0.02 mSv/wk or 2 mrem/wk

**PET Facility Throughput Example:**

<table>
<thead>
<tr>
<th>Time of Day</th>
<th>Patient Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>8:00</td>
<td>1</td>
</tr>
<tr>
<td>9:00</td>
<td>4</td>
</tr>
<tr>
<td>10:00</td>
<td>7</td>
</tr>
<tr>
<td>11:00</td>
<td>10</td>
</tr>
<tr>
<td>12:00</td>
<td>13</td>
</tr>
<tr>
<td>13:00</td>
<td>16</td>
</tr>
</tbody>
</table>

**N: Maximum Workload Estimation**

- **PET Facility Throughput Example:**
  - 1 Hour Uptake, 30 Minute Scan

**Possible Radiation Sources to Include in the Shielding Plan**

- **Doses (pre-injection) in Hot Lab**
- **Calibration sources for scanner**
  - require isotopic workload parameters
- **Patient (post injection, in uptake rm)**
  - require CT x-ray workload factors, including additional (non-PET) CT work
- **Patient (in scanner, hot toilet)**
- **TX Sources in scanner (PET)**
- **CT x-ray source (for PET/CT)**

**A0: Example Schedule for 18F FDG Administered Activities for WB Scans**

<table>
<thead>
<tr>
<th>Weight [kg]</th>
<th>Weight [lb]</th>
<th>Dose [mCi]</th>
<th>Dose [mBq]</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>330</td>
<td>20</td>
<td>740</td>
</tr>
<tr>
<td>130</td>
<td>286</td>
<td>17.5</td>
<td>648</td>
</tr>
<tr>
<td>110</td>
<td>242</td>
<td>15</td>
<td>555</td>
</tr>
<tr>
<td>90</td>
<td>198</td>
<td>12.5</td>
<td>462</td>
</tr>
<tr>
<td>70</td>
<td>154</td>
<td>10</td>
<td>370</td>
</tr>
</tbody>
</table>
$^{18}$F: A Plethora of Dose Rate Constants for Point Sources (TG-108)

<table>
<thead>
<tr>
<th>18F Rate Constants</th>
<th>SI Units</th>
<th>Conventional Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exposure Rate Constant</td>
<td>15.5 (mrem/hr)/mCi</td>
<td>0.5735 (mrem/hr)/mCi</td>
</tr>
<tr>
<td>Air Kerma Rate Constant</td>
<td>0.134 (µSv/hr)/MBq</td>
<td>0.4956 (µSv/hr)/MBq</td>
</tr>
<tr>
<td>Effective Dose Equivalent (ANS-1991)</td>
<td>0.143 (µSv/hr)/MBq</td>
<td>0.5291 (µSv/hr)/MBq</td>
</tr>
<tr>
<td>Tissue Dose Constant</td>
<td>0.149 (µSv/hr)/MBq</td>
<td>0.5476 (µSv/hr)/MBq</td>
</tr>
<tr>
<td>Deep Dose Equivalent (ANS-1977)</td>
<td>0.103 (µSv/hr)/MBq</td>
<td>0.3771 (µSv/hr)/MBq</td>
</tr>
<tr>
<td>Maximum Dose (ANS-1977)</td>
<td>0.189 (µSv/hr)/MBq</td>
<td>0.6956 (µSv/hr)/MBq</td>
</tr>
</tbody>
</table>

Conventional Units SI Units

$^{18}$F Rate Constants

TG-108 recommends 0.143 (mSv/hr)/MBq for F-18

$^{18}$F: A Plethora of Dose Rate Constants from Other Point Source Positron Emitters

<table>
<thead>
<tr>
<th>Source</th>
<th>Half-Life (h)</th>
<th>Photon (511 keV) Intensity (per Decay) (µCi)</th>
<th>Photon Energy (MeV)</th>
<th>18F Kerma Constant (µSv/hr)/MBq (µSv/hr)/MBq</th>
<th>Effective Dose Constant (µSv/hr)/MBq (µSv/hr)/MBq</th>
<th>Tissue Dose Constant (µSv/hr)/MBq (µSv/hr)/MBq</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{11}$C</td>
<td>20.3</td>
<td>200</td>
<td>0.061</td>
<td>0.194 (0.717)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{11}$N</td>
<td>9.97</td>
<td>200</td>
<td>1.19</td>
<td>0.194 (0.717)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{15}$O</td>
<td>2.03</td>
<td>200</td>
<td>1.32</td>
<td>0.194 (0.717)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{68}$Ga</td>
<td>1.145</td>
<td>180</td>
<td>1.9, 0.8</td>
<td>0.179 (0.662)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{82}$Rb</td>
<td>1.25</td>
<td>192</td>
<td>3.35,2.5</td>
<td>0.236 (0.779)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^{18}$F-Injected Patient as a Source (retained activity)

These values, from Unger and Trubey (ORNL/RSEC-45) are given in µSv of deep dose as defined in 10CFR20, (a somewhat different measure than the Task Group recommended for $^{18}$F).

18F: The 18F-Injected Patient as a Source (retained activity)

Dose Rate from $^{18}$F Injected Patient at 1 m

Source

about 20% of dose will be in bladder after 1-2 hours

18F: The 18F-Injected Patient as a Source (retained activity)
Sources in the Gantry: Isodose Curves from Vendor

- with phantom in place
- with line source in place
- with transmission rods extended

Cautions: The phantoms for PET and for CT isodose curves do not look very much like patients; the CT values may be for bare CT gantry.

Correction for Decay: The Reduction Factor

\[
R_t = \frac{A_0}{A_0 - \frac{t}{T} \cdot 1 - \left(e^{-\frac{t}{T}}\right)}
\]

Effects of Adding Corrections to Dose Calculation

- Inject @ 5 minutes
- Void @ 60 minutes

Calculation Formalism Proposed by Task Group: Now We Have It All

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

\[
B = \frac{P \cdot d^2}{T \cdot N_w \cdot (A_0 \cdot F \cdot t + R_i)}
\]

10.9 is 1/T in \([\text{hr/µSv}(\text{MBq/m}^2)]; \text{F}=1\)

12.8 includes 15% void before imaging; 
\(P=exp(-0.693t/T_{1/2})\), the physical decay during uptake.
Example 1: How Much Shielding for an Uptake Room?

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: How Much Shielding for a Scan Room?

An uncontrolled area with 100% occupancy is 3m from the patient. 40 patients a week are injected with 555 MBq (15 mCi) of FDG and held elsewhere for a 1hr uptake time. The patients void about 15% of the dose at 1 hr. The scan lasts 30 minutes.

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)

1) Identify magnitude and location (x,y) of all sources, including CT. Integrate over appropriate decay period that source is in location. Express as dose/wk or dose/hr at one meter, given workload.

2) Identify all barriers that will contribute to shielding, including pigs, shipping containers, etc.

3) Establish test points (x,y) 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.

5) Stop when you have met goals (100 mrem/yr, 2 mrem/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

| Source      | Material | Definition | B1 | B2 | B3 | B4 | B5 | B6 | B7 | B8 |
|-------------|----------|------------|----|----|----|----|----|----|----|----|---|
| Injection   | Lead     | 0.161      | 11.34| 1.825| -0.01| 0.198| 1.05| CT  |
| CT          | Concrete | 0.0877     | 1.84 | 0.161 | 4.04 | 0.473 | 0.994| CT  |
| Scanner     |          |            |     |     |     |     |     |     |     |    |
| Cal Source  |          |            |     |     |     |     |     |     |     |    |

Grid Calculation: No Shielding

Sources: Injection, HL, HW, 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
Look Up, Down, and Sideways

Floor Plan

Relative Dose Map on Floor Above

A Suggested Design Philosophy

- Keep the hot areas in interior of space, away from adjacent, uncontrolled occupancies to reduce shielding requirement

- Alternatively, place the hot areas against exterior walls adjacent to very low occupancy spaces (exterior landscaping, etc.); may need to control area (fence)

- Be prepared to use both inclusive (lead-lined or concrete walls) and spot (shadow) shielding in order to meet protection goals and to minimize lead requirements.

Where to Put the Lead:
Shadow vs Complete Coverage

Alternatives:

Complete coverage -- like most x-ray shielding
- contractors are familiar with technique
- facility previously shown had lead thicknesses of 1.6 mm to 6.3 mm, easily managed
- makes sense for PET/CT where CT must be shielded

Shadow shielding -- big slabs next to trouble spots
- can reduce overall cost when thick shield needed
- provides flexibility when remodeling old work

Examples of Shadow Shields

from JA Anderson, RJ Massoth,
and LL Windedahl, 2003 AAPM
**Magnitude of Technologist Exposure**

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

<table>
<thead>
<tr>
<th>Reference</th>
<th>Dose/Acitivity Handled (mrem/mCi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Siemens</td>
<td>0.018</td>
</tr>
<tr>
<td>GE</td>
<td>0.067</td>
</tr>
<tr>
<td>Philips</td>
<td>0.012</td>
</tr>
<tr>
<td>GE</td>
<td>0.150</td>
</tr>
<tr>
<td>Siemens</td>
<td>0.019</td>
</tr>
<tr>
<td>GE</td>
<td>0.041</td>
</tr>
<tr>
<td>Philips</td>
<td>0.032</td>
</tr>
<tr>
<td>Siemens</td>
<td>0.029</td>
</tr>
<tr>
<td>GE</td>
<td>0.066</td>
</tr>
</tbody>
</table>

**Average**

- Siemens: 0.011 mSv/MBq (0.041 mrem/mCi)
- GE: 0.066 mSv/MBq (0.041 mrem/mCi)
- Philips: 0.032 mSv/MBq (0.041 mrem/mCi)

- **Conventional Units**: 0.067 mSv/MBq (0.041 mrem/mCi)
- **SI Units**: 0.012 mSv/MBq (0.041 mrem/mCi)

**Operating Suggestions to Minimize Technologist Dose**

- Lay out hot lab to minimize handling time. Use unit doses.
- Use syringe shields, syringe carriers, carts, etc. to reduce exposure during dose transport, injection.
- Complete patient instruction, interaction before injection. Minimize time near patient after injection.
- Establish IV access with butterfly infusion set before injection.
- Use other personnel for patient transport.
- Shield control area to reduce dose during scan.

**More on Technologist Exposure**

1) It is often seen that the technologist dose per mBq handled drops as a function of experience in the PET clinic.

A 2004 update to the previous UTSW data for the same two technologists as shown on preceding slide showed a normalized WB dose of 0.011 μSv/MBq (0.041 mrem/mCi), down by 40% since 2002.

2) Assuming an average dose of 0.018 μSv/MBq injected, 8 MBq and 370 MBq (10 mCi) injected, this would yield a yearly dose of 13.3 mSv (1330 mrem), within regulation but above usual ALARA investigational limits. Over nine months, it would be 10.4 mSv (1040 mrem), well above the declared pregnancy limit.

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