Estimating Patient Dose
SPECT/PET (& all of NM)

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Thanks to S. James Adelstein, S. Ted Treves,
Keith Strauss, Matthew Palmer, Marilyn Goske,
James Brink
Disclosures

- Sadly, none that pay me any money! 😞
- SNM Dose Estimation Task Force
- Image Gently
- Image Wisely
- MITA Dose Reduction Task Force Advisory Board
Learning Objectives

After attending this lecture, participants will be able to:

• List 3 items that affect radiation dose from the administration of radiopharmaceuticals
• Describe 3 ways that body habitus can affect radiation dose from the administration of radiopharmaceuticals
• Define 3 approaches that may lead allow for a reduction in administered activity in nuclear medicine
Estimated Annual Per Capita Adult Effective Dose in US

1980-1982

Medical 0.5 mSv
Total 3.1 mSv

2006

Medical 3.0 mSv
Total 5.5 mSv

from NCRP 160
• Studied insurance records of over 900,000 patients (18-65 YO) over 3 years
• 69% had at least 1 radiologic exam
• Annual effective dose
  – Mean 2.4 ± 6.0 mSv
  – Median 0.1 mSv (inter-quartile range 0.1-1.7 mSv)
  – 78.6% < 3 mSv; 19.4% 3-20 mSv
  – 1.9% 30-50 mSv; 0.2% >50 mSv
### Table: Average Effective Doses (AEDs) and Annual Effective Doses per Capita (% of Total Effective Doses)

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Ave ED (mSv)</th>
<th>Ann’l ED per cap</th>
<th>% Total ED</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Myo Perf Img</td>
<td>15.6</td>
<td>0.540</td>
<td>22.1</td>
</tr>
<tr>
<td>2. CT Abdomin</td>
<td>8</td>
<td>0.446</td>
<td>18.3</td>
</tr>
<tr>
<td>3. CT Pelvis</td>
<td>6</td>
<td>0.297</td>
<td>12.2</td>
</tr>
<tr>
<td>4. CT Chest</td>
<td>7</td>
<td>0.184</td>
<td>7.5</td>
</tr>
<tr>
<td>5. Dx Card Cath</td>
<td>7</td>
<td>0.113</td>
<td>4.6</td>
</tr>
<tr>
<td>6. Rad Lumbar</td>
<td>1.5</td>
<td>0.080</td>
<td>3.3</td>
</tr>
<tr>
<td>7. Mammo</td>
<td>0.4</td>
<td>0.076</td>
<td>3.1</td>
</tr>
<tr>
<td>8. CT Ang Chest</td>
<td>15</td>
<td>0.075</td>
<td>3.1</td>
</tr>
<tr>
<td>12. Bone Scan</td>
<td>6.3</td>
<td>0.035</td>
<td>1.4</td>
</tr>
<tr>
<td>17. Thyroid Uptk</td>
<td>1.9</td>
<td>0.016</td>
<td>0.7</td>
</tr>
</tbody>
</table>
**Lifetime Attributable Risk 10 mGy in 100,000 exposed persons (BEIR VII Phase 2, 2006)**

<table>
<thead>
<tr>
<th></th>
<th>All Solid Tumors</th>
<th>Leukemia</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Male</td>
<td>Female</td>
</tr>
<tr>
<td><strong>Excess Cases</strong></td>
<td>80</td>
<td>130</td>
</tr>
<tr>
<td><strong>Excess Deaths</strong></td>
<td>41</td>
<td>61</td>
</tr>
</tbody>
</table>

Note: About 45% will contract cancer and 22% will die.
Lifetime Attributable Risk 10 mGy in 1,000,000 exposed persons (BEIR VII Phase 2, 2006)

Lifetime attributable cancer risk per 10^6 individuals exposed to 10 mGy

Age at Exposure

Female

Male
MIRD Equation

Medical Internal Radiation Dosimetry Committee of the SNM
MIRD Equation

\[ D(r_T) = \sum_S \tilde{A}(r_S) S(r_T \leftarrow r_S) \]

- \(D(r_T)\) is radiation dose to the target organ
- \(\tilde{A}(r_S)\) is time integrated activity for the source organ
- “S” value is a radionuclide specific quantity which is the mean dose to the target organ per integrated activity in the source organ
- \(\sum_S\) indicates that this is summed over all source organs
**Time Integrated Activity (\(\tilde{A}\))**

- Units of activity-time (e.g. Bq-hr) & is total # of decays
- Depends on
  - Administered activity (\(A_0\) in Bq)
  - Fraction of activity that goes to source organ (\(F\))
  - How long the activity stays there (\(T_{\text{eff}}\))

\[
\tilde{A}(r_S) = A_0 \ F \ T_{\text{eff}}
\]

\(F\) depend on the particular radionuclide administered, and the specific uptake of the patient.
Effective Half-Life

- Combination of biological clearance and physical radioactive half-life ($T_p$)
- Biological clearance is often model as exponential ($T_B$) although there are exceptions (hopefully bladder)

$$T_{eff} = \frac{T_B \ast TP}{T_B + TP}$$

- Shorter of $T_B$ and $TP$ dominates
Time Integrated Activity ($\tilde{\lambda}$)

- $\tilde{\lambda}$ is a physiologic parameter as it depends on both the uptake and the clearance of the radiopharmaceutical.
- Ratio of $\tilde{\lambda}$ and administered activity $A_o$ is sometimes referred to as “residence time” ($T_R = \tilde{\lambda} / A_o$) but this is a misnomer as it also depends on fractional uptake.
- Typically estimated using biokinetic data from either animals or humans.
- Although these estimates may be reasonable in most cases, they may not apply to a specific patient!
S Factor

\[ S(r_T \leftarrow r_S) = \sum_i \Delta_i \phi_i / M_T \]

- \( \Delta_i \) is the mean energy per nuclear transformation for the \( i \)th radiation emitted by the radiopharmaceutical
- \( \phi_i \) is the fraction of energy emitted by the source organ that is absorbed by the target organ of the \( i \)th radiation which depends on the radiation and the size and anatomy of the patient
- \( M_T \) is the mass of the target organ
- \( \sum_i \) Indicates that this is summed over all radiations
**S Factor**

- Physical parameter relying on the radionuclides decay scheme and orientation, size and spacing of organs within the patient
- Models for different types of patients (standard man, women (pregnant or not), and children
- $\varphi_i$ is often considered to be 1.0 for non-penetrating radiation (e.g. beta particles including positrons) and less than unity for gamma and x-rays. Also, $\varphi_i/M_T$ is referred to as the specific absorbed fraction (SAF).
Evolution of Computational Phantoms

- Simple to complex
- Homogeneous to heterogeneous
- Rigid to deformable
- Stationary to moving
- “Reference Man” to “reference library” or “person-specific” (?)
Anatomical Models for Radiation Dosimetry

Traditional vs Realistic Phantom

- Use of non-uniform rational B-splines or “NURBS”
- Easier to compute and more scalable than voxel based approaches

Effect of Differences in Adult Patient Size

Variations in SAFs in Adult Males (15-30%)
Effect of Differences in Adult Patient Size

Obese vs Standard Varying BMIs

Top - Spleen → Lungs
Bottom – Heart → Pancreas

Not appreciably different than standard man since organs basically in the same place.

Uncertainties

Uncertainties in Internal Dose Calculations for Radiopharmaceuticals

Michael G. Stabin

The combined uncertainties in most radiopharmaceutical dose estimates will be typically at least a factor of 2 and may be considerably greater.


Most of uncertainty in physiologic factors.
**Effective Dose**

Effective Dose is equivalent to the absorbed dose given to the whole body of the patient that would result in the same biological effect as the actual clinical dose given to a fraction of the patient’s whole body.

It is calculated by taking a weighted sum of the absorbed doses delivered to individual organs where each organ is weighted by its radiation sensitivity.

The unit is sievert (Sv) or millisievert (mSv)

(1 rem = 10 mSv and 1 Sv = 100 rem)
Effective Dose (ED)

\[ ED = \sum H_T \times W_T \]

Where \( H_T \) is radiation dose to organ, \( T \), and \( W_T \) is the radiosensitivity weight assigned to that organ.

Note: that the \( W_T \) values are averaged over age and sex and may not reflect the risks for a particular patient including children.
**Effective Dose**

**TABLE 1: Tissue-Weighting Factors for International Commission on Radiological Protection (ICRP) Publications 26, 60, and 103**

<table>
<thead>
<tr>
<th>Tissue or Organ</th>
<th>ICRP 26</th>
<th>ICRP 60</th>
<th>ICRP 103</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gonads</td>
<td>0.25</td>
<td>0.20</td>
<td>0.08</td>
</tr>
<tr>
<td>Red bone marrow</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Lung</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Colon</td>
<td>0.12</td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Stomach</td>
<td></td>
<td>0.12</td>
<td>0.12</td>
</tr>
<tr>
<td>Breast</td>
<td>0.15</td>
<td>0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>Bladder</td>
<td></td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Liver</td>
<td></td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Esophagus</td>
<td></td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Thyroid</td>
<td>0.03</td>
<td>0.05</td>
<td>0.04</td>
</tr>
<tr>
<td>Skin</td>
<td></td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Bone surface</td>
<td>0.03</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Brain</td>
<td></td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>Salivary glands</td>
<td></td>
<td></td>
<td>0.01</td>
</tr>
<tr>
<td>Remainder</td>
<td>0.30</td>
<td>0.05</td>
<td>0.12</td>
</tr>
<tr>
<td>Total</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
</tbody>
</table>

From Christner et al. AJR 2010;194:881-889
Factors Affecting Dose in NM and SPECT

- Injected activity
  - Total counts and imaging time
- Choice of camera
  - Detector thickness and material
  - Number of detectors
- Choice of collimator
  - Hi Sens, Gen Purpose, Hi Res, Pinhole
- Image processing and reconstruction
# Patient Effective Dose (mSv)

<table>
<thead>
<tr>
<th>Summary</th>
<th>1 Year</th>
<th>5 Year</th>
<th>10 Year</th>
<th>15 Year</th>
<th>Adult</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (kg)</td>
<td>9.7</td>
<td>19.8</td>
<td>33.2</td>
<td>56.8</td>
<td>70</td>
</tr>
<tr>
<td>Tc-MDP (20 mCi*)</td>
<td>2.8</td>
<td>2.9</td>
<td>3.9</td>
<td>4.2</td>
<td>4.2</td>
</tr>
<tr>
<td>Tc-ECD (20 mCi*)</td>
<td>4.1</td>
<td>4.6</td>
<td>5.3</td>
<td>5.9</td>
<td>5.7</td>
</tr>
<tr>
<td>Tc-MAG3 (10 mCi*)</td>
<td>1.2</td>
<td>1.3</td>
<td>2.2</td>
<td>2.8</td>
<td>2.7</td>
</tr>
</tbody>
</table>

*max admin activ

ICRP 80 and 106
### Patient Effective Dose (mSv)

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<td>33.2</td>
<td>56.8</td>
<td>70</td>
</tr>
<tr>
<td>Tc-MIBI Rest (10 mCi*)#</td>
<td>2.7</td>
<td>2.9</td>
<td>3.2</td>
<td>3.6</td>
<td>3.3</td>
</tr>
<tr>
<td>Tc-MIBI (30 mCi*)#</td>
<td>6.9</td>
<td>7.2</td>
<td>8.4</td>
<td>9.0</td>
<td>8.8</td>
</tr>
<tr>
<td>Tc-Tetrafosmin Rest (10 mCi*)#</td>
<td>2.2</td>
<td>2.3</td>
<td>2.3</td>
<td>2.9</td>
<td>2.8</td>
</tr>
<tr>
<td>Tc-Tetrafosmin Rest (30 mCi*)#</td>
<td>5.3</td>
<td>5.6</td>
<td>6.3</td>
<td>7.3</td>
<td>7.7</td>
</tr>
<tr>
<td>Tl-201 (3 mCi*)@</td>
<td>20.0</td>
<td>24.8</td>
<td>29.5</td>
<td>18</td>
<td>15.5</td>
</tr>
</tbody>
</table>

*max admin activity

ICRP 80, ICRP 106
Nuclear Cardiology

57% of Patient Visits

85% of Collective Dose
In summary, radionuclide MPI can provide scientifically validated, accurate, and in certain cases unique information for management of patients with known or suspected coronary artery disease at risk for major cardiovascular events. The radiation exposure risk associated with radionuclide MPI, albeit small and long term as opposed to the higher and more immediate risk for major cardiovascular events, mandates careful adherence to appropriateness criteria and guidelines developed or endorsed by [SNM, ASNC, ACC and AHA]. With recent developments in technology, there are many opportunities to further reduce radiation exposure and further enhance the benefit-to-risk ratio of this well-established, safe imaging modality.”
Cardiac SPECT

DSPECT (10 CZT detectors)

GE Discovery 530c
(Shown with CT)
- 19 stationary CZT detectors, 32x32 (5mm) array
- Multiple pinhole (5mm) apertures

Potential for dose reduction as well as greater throughput.

- GE Discovery NM 530c Camera
- Low-dose (12.5 mCi) stress only, high-dose (25-36 mCi) stress only, standard rest-stress (8-13 mCi for rest) => 4.2, 8.0 & 11.8 mSv ED, respectively
- Subjective grading of image quality on a 4-point scale by 2 readers

- Acquired with conventional dual-head gamma camera
- Wide beam reconstruction (WBR): utilizes system information in reconstruction, suppresses noise, enhances signal-to-noise
  - Group A: Full-time with OSEM: 9-12 mCi rest, 32-40 mCi stress
  - Group B: Half-dose with WBR: 5.7 and 17.6 mCi for rest, stress

Table 2. Image quality of “full-time” OSEM and “half-dose” myocardial perfusion SPECT processed with Wide Beam Reconstruction

<table>
<thead>
<tr>
<th></th>
<th>Full-time Group A</th>
<th>Half-dose WBR Group B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rest</td>
<td>3.6 ± 0.7</td>
<td>4.3 ± 0.8*</td>
</tr>
<tr>
<td>Stress</td>
<td>3.8 ± 0.7</td>
<td>4.6 ± 0.6*</td>
</tr>
<tr>
<td>Post-stress gated</td>
<td>3.9 ± 1.0</td>
<td>4.7 ± 0.6*</td>
</tr>
</tbody>
</table>

For grading image quality 1 = poor, 2 = fair, 3 = average, 4 = good, 5 = excellent.
* P < .001 vs full-time OSEM.

- Subjective image quality of 5-pt scale by 2 observers
  Half dose WBR: 5-6 mCi compared to Full-time OSEM ~11 mCi
Use of OSEM-3D Reconstruction in SPECT

Sheehy et al. Radiol 2009; 251:511-516

Stansfield et al. Radiol 2010; 257:793-801

FBP Full Cts      OSEM Full Cts    OSEM Half Cts

FBP Full Cts      OSEM Full Cts    OSEM Half Cts

A.     B.
Factors Affecting Dose in PET

• Injected activity
  – Total counts and imaging time

• Choice of scanner
  – Crystal material and thickness
  – 2D vs 3D
  – Axial field of view

• Image processing
### Patient Dose from FDG (mSv)

<table>
<thead>
<tr>
<th>Summary</th>
<th>1 Year</th>
<th>5 Year</th>
<th>10 Year</th>
<th>15 Year</th>
<th>Adult</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass (kg)</td>
<td>9.7</td>
<td>19.8</td>
<td>33.2</td>
<td>56.8</td>
<td>70</td>
</tr>
<tr>
<td>Act (mCi)</td>
<td>1.46</td>
<td>2.97</td>
<td>4.98</td>
<td>8.52</td>
<td>10.5</td>
</tr>
<tr>
<td>Bladder*</td>
<td>25.6</td>
<td>35.9</td>
<td>44.4</td>
<td>48.8</td>
<td>50.5</td>
</tr>
<tr>
<td>Eff Dose*</td>
<td>5.2</td>
<td>5.9</td>
<td>6.6</td>
<td>7.3</td>
<td>7.4</td>
</tr>
</tbody>
</table>

ICRP 106
Factors Affecting Radiation Dose in Multi-Detector CT

- Tube current or time ($\alpha$ mAs)
- Reduce tube voltage ($\alpha$ kVp$^2$)
- Beam collimation
- Pitch (table speed) ($\alpha$ 1/pitch)
- Patient size
- Region of patient imaged
CIRS Tissue Equivalent Phantoms

<table>
<thead>
<tr>
<th>Phantom</th>
<th>AP x Lat (cm)</th>
<th>Circum (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newborn</td>
<td>9 x 10.5</td>
<td>32</td>
</tr>
<tr>
<td>1 Year Old</td>
<td>11.5 x 14</td>
<td>42</td>
</tr>
<tr>
<td>5 Year Old</td>
<td>14 x 18</td>
<td>53</td>
</tr>
<tr>
<td>10 Year Old</td>
<td>16 x 20.5</td>
<td>61</td>
</tr>
<tr>
<td>Med Adult</td>
<td>25 x 32.5</td>
<td>96</td>
</tr>
</tbody>
</table>

• Dosimetric CT phantoms
  • Simulated spine
  • Five 1.3 cm holes
  • Five different sizes

Dosimetry of PET-CT and SPECT-CT

- PET/CT
  - GE Discovery LS

- SPECT/CT
  - Philips Precedent
Dose from CT of PET-CT GE Discovery LS (4-slice)

ED from 10 mCi of FDG
5-7 mSv
ImPACT CT Dose Calculator

120 kVp, 100 mAs, Pitch 1:1
“eyes to thighs” (95 cm)
CTDIvol = 11.1 mGy
DLP = 1053 mGy-cm
Effective Dose = 16 mSv
Quality of CT-based Attenuation Correction

80 kVp
10 mA
0.5 s/rot
1.5:1

140 kVp
160 mA
0.8 s/rot
1.5:1
Initial Experience with weight-based, low-dose pediatric PET/CT protocols


- 0.144 mCi/kg FDG (1 & 10 mCi min & max)
- 120 kVp
- Weight-based (Broselow-Luten color scale) 10-40 mAs
- 45 patients (9.2-109 kg, 1.4-23 YO)
- Dosimetry extrapolated from standard phantoms
- WB PET/CT effective dose from 5.4 to 10.0 mSv for 9 and 70 kg patient, respectively
Axial Extent of CT

• “Whole Body” PET typically acquired “Eyes to Thighs”
• Potential for SPECT acquisitions to all be extended, particularly with more efficient reconstruction
• Thus CT component can be combination of head & neck, thoracic, abdominal and pelvic CT
• Is “One size fits all” appropriate?
• Alternative paradigm suggested by George Segall of Stanford and Palo Alto VA Medical Center
• Standardization of technique
## Adult Effective Doses (mSv)

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Ave ED (mSv)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Radiograph of Extremity</td>
<td>0.001</td>
</tr>
<tr>
<td>Posterior/Anterior and Lateral Chest Radiograph</td>
<td>0.1</td>
</tr>
<tr>
<td>Mammography</td>
<td>0.4</td>
</tr>
<tr>
<td>Abdominal Radiograph</td>
<td>0.7</td>
</tr>
<tr>
<td>Head CT</td>
<td>2.0</td>
</tr>
<tr>
<td>$^{99m}$Tc MAG3 Renal Scan</td>
<td>2.7</td>
</tr>
<tr>
<td>Intravenous Urography</td>
<td>3.0</td>
</tr>
<tr>
<td>$^{99m}$Tc MDP Bone Scan</td>
<td>4.2</td>
</tr>
<tr>
<td>$^{99m}$Tc ECD Brain Scan</td>
<td>5.7</td>
</tr>
<tr>
<td>Pelvic CT</td>
<td>6.0</td>
</tr>
<tr>
<td>Chest CT</td>
<td>7.0</td>
</tr>
<tr>
<td>$^{18}$F FDG PET Scan</td>
<td>7.4</td>
</tr>
<tr>
<td>Abdominal CT</td>
<td>8.0</td>
</tr>
<tr>
<td>$^{99m}$Tc MIBI for Stress/Rest Cardiac Scan</td>
<td>11.8</td>
</tr>
<tr>
<td>Coronary Angiographic CT</td>
<td>16.0</td>
</tr>
</tbody>
</table>

Mettler et al. Radiol 2008;248:254-263, ICRP 80 and 106
Pediatric Administered Dose Survey

- Surveyed 15 dedicated pediatric hospitals in North America (13 responded)
- Requested information on 16 studies commonly performed in pediatric NM
  - Administered dose/kg, Max admin dose, Min admin dose
- Consider the maximum/minimum as the range factor
- For Admin dose/kg and Max dose the range factor varied, on average, by factor of 3 (max 10)
- Min dose range factor varied, on average, by factor of 10 (max 20)

Image Gently

Gelfand MJ, Parisi MT, Treves ST
Available from Image Gently, SPR and SNM
Image Wisely
Nuclear Medicine Project

• Image Wisely initially concentrated on CT
• Now expanding to nuclear medicine
• Kick-off Meeting October 27, 2011
• SNM and ASNC asked to participate in addition to ACR, RSNA, ASRT and AAPM
Image Wisely
Nuclear Medicine Project

• IW Leadership
  – Jim Brink (RSNA)
  – Donald Peck (AAPM)
  – Greg Morrison (ASRT)
  – Rick Morin (ACR)

• SNM/SNMTS
  – Fred Fahey
  – Kevin Donohoe
  – Brenda King

• ACR
  – Murray Becker
  – Beth Harkness

• AAPM
  – Larry Williams

• ASNC
  – Gordon DePuey

• RSNA
  – Hossein Jadvar
Image Wisely
Nuclear Medicine Project

• Develop material for imaging professionals first followed by that for referring physicians and patients
  – General Nuclear Medicine
  – Cardiac Nuclear Medicine
  – PET and PET/CT

• Target Date – Summer 2012
Questions?

Safe Travels!