QUALITY CONTROL AND DOSIMETRY IN THE NUCLEAR MEDICINE CLINIC

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Conflict of Interest Statement

- No conflicts to disclose.
- No business or professional relationships that could be construed as influencing what I am about to present.
Outline

• Quality Control in Nuclear Medicine – an overview
• QA Modernization efforts at BIDMC
• A Phantom for Annual PET/CT testing
• Dosimetry for Clinical Nuclear Medicine
• PET/CT Dosimetry
• PET/CT Dose Reduction
Part I – Quality Control

• Quality Control in Nuclear Medicine – an overview
• QA Modernization efforts at BIDMC
• A Phantom for Annual PET/CT testing
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• PET/CT Dose Reduction
Quality Control

• Instrument QC in the clinic consists of:
  • Measurement Devices: daily checks for all devices, quarterly and annual tests for dose calibrators, well-counters, and survey instruments
  • Diagnostic Imaging Equipment:
    • Gamma Cameras: Daily checks for all cameras then weekly, monthly, quarterly and annual tests
    • PET Scanner: Daily checks, quarterly tests and annual tests.

• Non Instrument QC
  • Radiopharmacy (off site) performs quality control for radiopharmaceuticals. We only verify activity prior to injection.
  • Physicians are QC’d – they perform randomized double-reads and do followup of cases that are referred to cath-lab or surgery.
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Camera Quality Control – Why?

• Quality control (QC) for gamma cameras is mandated by the State (DPH).
  ➢ we have to do it.

• Our QC program guidelines since Nuclear Medicine
  ➢ we have to do it well.

• Scope: 9 gamma cameras (one SPECT/CT), PET/CT, distributed over 3 sites, and we perform daily, weekly, monthly, quarterly and annual testing.
Nukes Imaging Equipment at BIDMC

- ADAC Fortes
- Siemens E.CAM
- Philips Precedence SPECT/CT
- ADAC Argus
- Digirad Cardius X-ACT
- GE Discovery LS – PET/CT
Daily QC – “Machine Checks”

- Daily machine checks are rapid and sensitive tests that certify basic operation.
- They test:
  - uniformity of response over the field of view
  - constancy of detector sensitivity
  - accuracy of energy gain calibration
  - (cardiac cameras) uniformity of transmission scan reference map
The Daily Flood

- On most cameras, a sheet source containing Co-57 is placed between the heads. 10 million counts are acquired.
- Transmission scan reference maps are acquired with the built-in Gd-157 rod sources.
- Floods are analyzed with software.
Uniformity Calculations

- Defined by NEMA
- Flood image rebinned as 64x64 pixels
- Useful field of view (UFOV) is “area of detector used for imaging…”
- Central field of view (CFOV) is 70% of the UFOV.
- In each FOV, we calculate:
  
  Integral Uniformity (%) = \(100 \times \frac{\text{max-min}}{\text{max}+\text{min}}\)

  Differential Uniformity = same calc in 5-column/row subfields
Camera QC: Before Modernization
QC Log

- Reduce paperwork, reduce errors.
- Central, consistent, standard procedure independent of manufacturer.
- Automatic tagging/flagging of problems.
- Enable trend analyses and generate periodic reports.
Web-based Analysis and Log

- We were already sending daily studies to our PACS – we just had to modify the protocol to maintain data integrity.
- Implementation (phase I – for daily floods):
  - Retrieve daily flood images from PACS
  - Extract pertinent information (energy, sensitivity) and perform uniformity analysis.
  - Interact with technologist to present results and then maintain them in a database.
Monitoring & Auditing

Physicist

Web Browser

QC Server
Web Database
Analysis

QC Image
QC Analysis
Trends Analyses

NM PACS Image Archive
- Web server uses ASP
- Coded in VBScript
- Launches Compiled MATLAB executable to perform calculations
Flagging Out of Bounds Values

### Uniformity Analysis Log for ADAC 2 (10 entries)

#### Detector 1 - emission

<table>
<thead>
<tr>
<th>Date</th>
<th>UFOV Index (%)</th>
<th>CFOV Index (%)</th>
<th>Duration (s)</th>
<th>Source</th>
<th>Energy (keV)</th>
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#### Detector 2 - emission

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<th>Energy (keV)</th>
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<td>3.09</td>
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<tr>
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<tr>
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<td>S5</td>
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<td>ldcabral</td>
<td>View</td>
</tr>
</tbody>
</table>
Future Additions

- Weekly QC tests
- Bar Phantoms for resolution and linearity.
  - 1/4”, 3/16”, 5/32”, 1/8”
  - 1/6”, 1/8”, 1/10”, 1/12”
  - 3.5mm, 3.0mm, 2.5mm, 2.0mm
Future Additions

- Monthly QC Tests
- Center of Rotation (COR) check performs a SPECT study of a point source and tracks its motion in the field of view.
Part II – PET/CT Annual Testing

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• PET/CT Dosimetry
• PET/CT Dose Reduction
PET/CT Annual Testing

- For PET scanners, ACR gives guidance on annual testing but does not prescribe specific tests as they do for gamma cameras
- I do:
  - Basic physical, mechanical, laser-alignment, …
  - SUV calibration check (actually quarterly)
  - In-plane spatial resolution and z-axis, slice profile
  - Check of PET/CT alignment
  - Subjective image quality (ACR phantom)
  - Count-rate linearity
PET/CT Annual Testing

- For PET scanners, ACR gives guidance on annual testing but does not prescribe specific tests as they do for gamma cameras
- I do:
  - Basic physical, mechanical, laser-alignment, …
  - SUV calibration check (actually quarterly)
  - In-plane spatial resolution and z-axis, slice profile
  - Check of PET/CT alignment Using a custom phantom
  - Subjective image quality (ACR phantom)
  - Count-rate linearity
PET/CT Alignment/Resolution Phantom

- Styrofoam block with three pairs of glass capillary tubes
- Tubes are <1mm ID, about 8 cm long. Filled with about 0.1 mCi per ml of F-18.
- Scanned with clinical protocols in both 2D (15 minutes) and 3D mode.
- Reconstructed with FBP (minimal filtering) and with iterative reconstruction using clinical defaults.
Identify lines in PET&CT – Semi automated
Reference Points

• The 6 lines are located in 3D in each of the PET and CT coordinates from the best-fit straight line through points on about 10 axial slices (~4 mm intervals).
• From each pair of lines, for each modality, we find the midpoint along the minimum distance orthogonals.
• At the 3 midpoint/reference points determined by each modality, the distances are calculated.
• It’s also possible to calculate the rigid-body translation/rotation relating PET and CT.
## Sample Results

- **GE DVCT (700 mm FOV)**

<table>
<thead>
<tr>
<th>Point</th>
<th>PET (x,y,z) (mm)</th>
<th>CT (x,y,z) (mm)</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(-89.7, 66.0, 53.0)</td>
<td>(-90.5, 66.0, 52.4)</td>
<td>1.0</td>
</tr>
<tr>
<td>2</td>
<td>(85.8, 90.1, 50.4)</td>
<td>(85.7, 89.6, 50.6)</td>
<td>0.6</td>
</tr>
<tr>
<td>3</td>
<td>(1.8, -69.8, 105.1)</td>
<td>(1.4, -70.7, 105.4)</td>
<td>1.1</td>
</tr>
</tbody>
</table>

- **GE DLS (55 mm FOV)**

<table>
<thead>
<tr>
<th>Point</th>
<th>PET (x,y,z)</th>
<th>CT (x,y,z) (mm)</th>
<th>Displacement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(-90.0, 71.8, 11.8)</td>
<td>(-89.2, 73.0, 11.5)</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>(85.0, 96.5, 11.8)</td>
<td>(86.7, 97.6, 11.7)</td>
<td>1.9</td>
</tr>
<tr>
<td>3</td>
<td>(1.3, -63.8, 23.7)</td>
<td>(2.6, -63.0, 23.6)</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Optimal translation/rotation: (1.3, 1.0, -0.1), 0.1°
Spatial Resolution for PET

- From the z-aligned tubes, we determine in-plane resolution.
- The PET Line-spread function (LSF) is well-characterized by Gaussian distribution so we fit a Gaussian and specify the FWHM.

![Image of Line-spread function with FWHM=7.33]
Spatial Resolution: Z-Axis (slice profile)

- From the oblique tubes we fit a Gaussian to the LSF both horizontally and vertically.
- If the PSF in 3D is separable (which is certainly true for a Gaussian) and assuming that the in-plane resolution in $x$ and $y$ are the same (true near the center), then the image of a line at 45° to the z-axis is just the convolution

$$p(x) = h_z(x) \otimes h_y(x)$$

$$\text{FWHM}_z = \sqrt{9.22^2 - 7.33^2} = 5.59$$

$$\text{FWHM}_x^2 = \text{FWHM}_y^2 + \text{FWHM}_z^2$$
Part III – Dosimetry

• Quality Control in Nuclear Medicine – an overview
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• Effective Dose from PET/CT
• PET/CT Dose Reduction
Evolving picture of dose to the public

1985

Radon 36%

2006

Medical 47%

Plain Film/Fluoro 5%

Interventional 7%

Nuclear Medicine 12%

CT 23%

Nuclear Medicine 3%

Occupational/Industrial 3%

Background 13%

Radon 36%

Medical 14%

Radiology

Internal

Terrestrial

Cosmic

Consumer Products

Other

Radon

1985

2006
Radiological Exams – Relative Dose

Effective dose as a multiple of one AP Chest radiograph (0.02 mSv)
The approach to dosimetry with internal emitters, like other modalities, is based on a simple, idealized phantom model of a 70 kg human.

Effective dose is calculated as a weighted sum of absorbed doses to organs.

\[ ED = \sum W_i D_i \]

Weights are defined in ICRP30(1979), ICRP60(1991), and now ICRP103(2008)
Dosimetry in Nuclear Medicine

• The added complication here is that activity distributes spatially and temporally throughout the body.
• Each organ is both a source and a target. Activity washes in, washes out (biological decay) and decays (physical decay).
• So for dosimetry, we have to make our standard geometrical human become a **standard physiological human**.
The MIRD Method

• For each radiopharmaceutical used in nuclear medicine the MIRD committee (SNM) has figured out the **cumulative activity**. This is the total number of disintegrations in an organ per unit of administered dose.

• They have also figured out by Monte Carlo simulation, for each radionuclide, “S-factors” which relate the absorbed dose in each target organ per disintegration in each source organ.

\[ D_k = \sum \bar{A}_j S_{ij} \]
PET(/CT) – The future of Nuclear Medicine?

• First PET scanner was built in early 1950s by Gordon Brownell at MGH. It had two detectors.
• Modern PET scanners were used through the 70s and 80s and then clinical PET really took off in late 1990s, early 200s
• Two key developments:
  • $^{18}$F-DG as an almost universal tracer
  • Hybrid PET/CT scanners
PET(/CT) – The future of Nuclear Medicine?

- PET/CT is the current bright spot in nuclear imaging. Volume is steadily increasing.
- New agents for Alzheimer’s screening and $^{18}$F-based agents for cardiac imaging will likely accelerate that trend.
Effective Dose From PET/CT

- Effective dose is dose due to $^{18}$F plus dose from CT scan.
- Even though the CT techniques are usually “low-dose”, the near whole-body coverage means that effective doses are large.

<table>
<thead>
<tr>
<th>Year</th>
<th>F-18</th>
<th>CT</th>
<th>Total Dose</th>
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<tr>
<td>2003</td>
<td>20 mCi</td>
<td>140kV/120 mAs</td>
<td>32 mSv</td>
</tr>
<tr>
<td></td>
<td>14 mSv</td>
<td>18 mSv</td>
<td></td>
</tr>
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<td>2008</td>
<td>15 mCi</td>
<td>140kV/40 mAs</td>
<td>16 mSv</td>
</tr>
<tr>
<td></td>
<td>10 mSv</td>
<td>6 mSv</td>
<td></td>
</tr>
<tr>
<td>2013</td>
<td>&lt;10 mCi</td>
<td>?</td>
<td>&lt;8 mSv?</td>
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<tr>
<td></td>
<td>&lt;7 mSv</td>
<td>&lt;6 mSv</td>
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</table>
Low-Dose PET/CT of the Future

The key to enable low dose PET/CT in the future will be to lower the CT dose
Effective Dose Equation

- Dose scales linearly with mAs.
- Dose scales quadratically with kVp.
  - Effective dose from eyes-to-thighs (torso) CT for 40 mAs calculated from the ImPACT calculator for GE LS(4) scanner:
Attenuation Correction and Anatomical Localization

- CT devices on modern PET/CT scanners are full multi-slice (16/64) diagnostic-quality CT units.
- BUT, they are rarely used as diagnostic CTs.
  - They are often read by non-radiologists
  - They are usually done as free-breathing, non-contrast studies.

2005: Female, 5’4” 135 lb colorectal CA, arms-down, 32 mSv

2012: Female, 5’3” 134 lb breast CA, arms-down, 16 mSv
Attenuation Correction and Anatomical Localization

- Predicting the CT image quality needed for anatomical localization is difficult. We have thought about this problem but haven’t done any work on this.
- Understanding the quality needed for adequate attenuation correction is more tractable, or at least more in the realm of physics and engineering, and we have done some work on that.

Female, BMI=44, arms up
140 kVp, 96 mAs

Male, BMI=27, arms down
140 kVp, 60 mAs
Attenuation Correction in PET/CT

- Attenuation correction in PET is the most important correction to ensure accuracy. Attenuation factors for 511 keV photons at the center of the body are on the order of 20, and at the center of the head are on the order of 7.

Attenuation maps are prepared from the CT cross-sections by mapping Hounsfield units to 511 keV equivalent coefficients. Typically this is a multi-linear transform:
Two problems with low-dose CT for AC

• A bias is introduced to the AC map because of non-linear mapping of noisy samples. This propagates to the PET reconstruction.

Fahey, Palmer et al., Radiology, 2007
Photon Starvation

- Streak artifacts due to photon starvation appear along rays that traverse a lot of dense bone.
- They are particularly severe in low-dose CT studies, especially at lower kVp.
- If we are going to lower the CT dose even further, photon starvation is probably the limiting effect.
- This is a non-linear phenomenon that isn't handled well by filtered backprojection algorithms. It is our hope that emerging iterative CT reconstruction algorithms will help.
Data Spectrum Torso Phantom

- As a first step, we’ve begun to characterize the phenomenon and test newly-available iterative CT reconstructions.
- Slabs of Al+Cu (Z=19 versus ~20 for dense bone) varying thickness (x3.5cm) attached to phantom.
Starvation Artifact Phantom Experiment

- Scanned in the 4-slice GE LS scanner (PET/CT) with 4x2.5 mm collimation and techniques from 80 kVp/5 mAs to 140 kVp/160 mAs.
- Circular ROIs, ~2 cm diam (1300 pixels), calculate mean and SD.
- Plot versus “inverse dose index” = $10^6/(kVp^2mAs)$.
- Graph for ROI#2, 3.5cm bone →

![Graph](image)
Photon Starvation vs Bone Thickness

- The more bone, the greater the bias due to starvation.
- Composite data for 80 mAs:

  - Relationship, especially with kVp, appears complex and non-linear. May be difficult to characterize.
Iterative (?) Reconstruction

- Similar experiment with metal slabs simulating bone and Data Spectrum torso phantom scanned in a GE CT750 HD scanner and the images reconstructed with ASiR (100%).
- ROI Statistics:
Summary (so-far)

- Both noise and photon starvation in low-dose CTAC contribute to an underestimate of 511 keV attenuation.
- ASiR (GE’s early “iterative recon”) may reduce noise but has no effect on photon starvation.
- Effect on PET quantitation is complex function of mAs, kVp and bone thickness.
- Possible next-step is to fill phantom and perform emission scans, correct them and define an error threshold (say 10%), then produce charts like →

![Diagram showing mAs vs. kVp for Low BMI (<25)]
Acknowledgements

• Frederic Fahey, Boston Children’s Hospital
• Robert Zimmerman
• Larry Barbaras
• Many other colleagues and mentors