Dose Optimization in PET/CT & PET/MR

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NIH, Gordon & Alpert Endowments

OUTLINE: Approaches to Dose Optimization

- Rationale
- Image Quality, Dose Reduction
- PET-CT, PET-MR and Dedicated PET Scanners
- Discussion
**RATIONALÉ : Excess Atributable Risk**

Excess Atributable Risk (Deaths) from All Solid Tumors per 10,000 Person-Year-Sv by 60Y (BEIR VII 2006)

<table>
<thead>
<tr>
<th>Age at Exposure (Y)</th>
<th>EAR (Mortality)</th>
<th>Relative to &gt;30Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35.1</td>
<td>2.92</td>
</tr>
<tr>
<td>5</td>
<td>30.3</td>
<td>2.52</td>
</tr>
<tr>
<td>10</td>
<td>25.2</td>
<td>2.19</td>
</tr>
<tr>
<td>20</td>
<td>17.4</td>
<td>1.45</td>
</tr>
<tr>
<td>&gt;30</td>
<td>12.0</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Thus, if 1,000,000 10 YOs receive 10 mSv, 25 will die from solid tumors at age 60 due to this exposure.

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**PET or PET/CT not in Top 20**

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Ave ED (mSv)</th>
<th>Ann 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 Upk</td>
<td>1.9</td>
<td>0.016</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Petit et al., NEJM 2009; 361:841-843

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**OUTLINE : Approaches to Dose Optimization**

- Rationale
- Image Quality, Dose Reduction
- SPECT, SPECT-CT and Dedicated SPECT Scanners
- PET-CT, TOF-PET, PET-MR and Dedicated PET Scanners
- Discussion
METHODS : MIRD Equation

\[ D = \frac{\bar{\Delta} f}{m} \]

Where:
- \( D \) is radiation dose in Gy
- \( \bar{\Delta} f \) is mean energy per disintegration in g-Gy/MBq-h
- \( \bar{A} \) is the cumulated activity in MBq-h, \( \bar{A} \propto A_0 \)
- \( m \) is mass of the target organ in g
- \( \Delta f / m \) is S factor, i.e., the mean dose to target organ per cumulated activity of the source organ

METHODS : Approaches to Dose Optimization

Bases for Approaches to Dose Optimization:

- Assess image quality objectively by signal-to-noise ratio (SNR) for a clinical task (e.g., lesion detection, activity estimation)
- Assume Poisson statistics, a doubling of counts (and dose) yields 41% (\( \sqrt{2} \)) improvement in SNR (and image quality)
- Conversely, if a physics or instrumentation approach yields an improvement of SNR of 41%, this gain could be used to halve the injected dose without changing image quality.

OUTLINE : Physics Approaches to Dose Optimization

- Rationale
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- Dose Reduction in CT of PET-CT
- Discussion
Factors Affecting Radiation Dose in Multi-Detector CT

- Tube current or time (α mAs)
- Reduce tube voltage (α kVp^2)
- Beam collimation
- Pitch (table speed) (α 1/pitch)
- Patient size
- Region of patient imaged

CT-Based Attenuation Correction

- Acquire CT Scan and reconstruct
- Apply energy transformation
- Reproject to generate correction matrix
- Smooth to resolution of PET
- Apply during reconstruction

Dose from CTA of PET-CT

ED from 10 mCi of FDG 5-7 mSv
Quality of CTAC

80 kVp
10 mA
0.5 s/rot
1.5:1

140 kVp
160 mA
0.8 s/rot
1.5:1

ED 7800%

Outlook: Physics Approaches to Dose Optimization

- Rationale
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- Dose Reduction by using iterative reconstruction and 3D geometry
- Discussion
Assessment of Dose Reduction with 3D vs. 2D PET

- 3 sphere sizes were acquired in 10 different locations (e.g., lungs, soft tissue, bone) to avoid errors associated with lesion simulation
  - Ø 1.0 cm
  - Ø 1.3 cm
  - Ø 1.6 cm

- Each sphere was acquired separately in 2D and 3D and scaled to ensure marginal detectability in each patient.

Generation of synthetic lesion-present WB studies

Sphere in air

Scale \( K(2D) = K(3D) \)

Decay correct

Attenuate

Sphere in patient

Sum to Patient Background

Lesion present sinogram

Correct for Scatter, Attenuation, AW OSEM reconstruction

Lesion absent

Lesion present

Lesion-present patient studies

2D WB scan (BMI = 18)

3D WB scan (BMI = 18)
Assessment of Dose Reduction with 2D/3D and Processing

Dose reduction with 2D/AWOSEM and 3D/AWOSEM.

Typical BMI of 26.

Dose reduction compared:
- 2D AWOSEM: 36%
- 2D FBP: 30%
- 3D AWOSEM: 77%
- 3D FBP: 71%

OUTLINE: Physics Approaches to Dose Optimization

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• Dose Reduction with TOF-PET
• Discussion

Image quality depends on patient size:
- Light patient (BMI=23)
- Heavy patient (BMI=40)

1 min/bed, 3 min/bed.
How can TOF improve image quality (reduce dose)?

Image reconstruction from projections:

\[ \Delta x = \Delta l / 2 \]

Signals from different voxels are coupled

TOF information reduces coupling, thus improves SNR

\[ \Delta l = \Delta t_1 - \Delta t_2 \]

Dose Reduction with TOF-PET: how much can we gain?

<table>
<thead>
<tr>
<th>3 min TOF PET</th>
<th>5 min TOF PET</th>
</tr>
</thead>
<tbody>
<tr>
<td>6:1 sphere to background contrast; 35 cm diam. cyl.; 1 cm spheres</td>
<td></td>
</tr>
</tbody>
</table>

Normal patient list data

CT image

Sphere in air list data

Lesion uptake ratio = \( C_B \)

Extracted sphere list data

CT image

Lesion uptake ratio = \( C_B \)

Fused list data

Scatter

CT image

Fully-corrected reconstructed lesion absent volume

Fully-corrected reconstructed lesion present volume

1. Scatter estimate
2. Background activity level, \( C_B \)
RESULTS: Representative lesion-present studies

Non-TOF
1 min/bed position

TOF
1 min/bed position

Non-TOF
3 min/bed position

TOF
3 min/bed position

RESULTS: Representative lesion-present studies (2)

Non-TOF
1 min/bed position

TOF
1 min/bed position

Non-TOF
3 min/bed position

TOF
3 min/bed position

METHODS: Dose Reduction with TOF-PET

Non-TOF PET TOF-PET

Patient with a lung lesion (4:1) and BMI=19

Patient with a liver lesion (6:1) and BMI=42
METHODS: Dose Reduction with TOF-PET

- SNR improvement of 8% in liver, 14% in lung and dose reduction of 14-30%

RESULTS: Dose Reduction with TOF-PET

- Similar SNR with TOF-PET for 33% less TBR

- Dose reduction of 16% in the liver and 30% in the lungs

- Dose reduction of 18% for BMI< 30 and 22% for BMI> 30
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- Dose Reduction in PET-MRI vs. PET-CT
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Integrated Whole-Body PET-MR

Sequential PET-CT vs Simultaneous PET – MR

25 cm axial coverage

60 cm

Rationale: Motion deterioration vs Gating

Uncorrected

Gated

• Blurring
• Lower Noise

• Using all PET data at all motion phases without motion correction

• Freezing Motion
• Higher Noise

• Using some PET data only at one motion phase

• Using all PET data with MR-based motion correction
Methods: Motion Corrected OSEM

- List-mode MLEM reconstruction algorithm with motion modeled in the system matrix:

\[ \hat{a}_n(f) = \sum_{\text{meas}} \hat{a}_m(f) \]

System matrix

\[ \hat{a}_n^{(m,n)} = \sum_{\text{meas}} \hat{a}_m^{(m,n)} \]

Motion corrected system matrix

- Attenuation correction using deformed attenuation maps at each frame:

Transformation using measured motion fields from tagged MR

Attenuation map in the reference frame

Attenuation maps in the deformed frames


Primate Results: Acquisition

- Motion Correction with Primate in simultaneous PET-MR

Gated tagged MR

Gated PET


Nonhuman Primate Results


Dose Reduction 600%
Measure Motion Fields and Track Motion Phases

Motion correction for PET reconstruction

Cardiac PET/MR: pig studies (18F-Flurpiridaz)

No MoCo (standard)  ECG-gating  MoCo (proposed)

Activity Concentration (A.U.)

0.0  1.5  3.0

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Dose Reduction with Dedicated PET Scanners

Dedicated brain PET
FOV 35cm x 24 cm long

Dose \( \downarrow 260\% \)

 Injected dose: 200 MBq of \(^{18}\)FDG.
HR+ scan: 54 min post injection, 30 min acquisition.
NeuroPET scan: 90 min post injection, 30 min acquisition.

 Injected dose: 1.840 MBq of \(^{11}\)C-PiB.
HR+ scan: 45 min post injection, 15 min acquisition.
NeuroPET scan: 70 min post injection, 15 min acquisition.

Same concept applies to other Hi-sensitivity scanners, for example:
If axial FOV = 21.6 instead of 16.2, sensitivity \( \uparrow 75\% \) and dose \( \downarrow 75\% \)

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Current scanners do not maximize the sensitivity for whole-body imaging (<1% of the available signal collected)

T. Jones

<1% of the potential return on the investment in:
- Cyclotron operation
- Labelled tracer production
- PET scanning facilities and resources
- The radiation dose to the patient
Total-Body PET: Maximizing sensitivity and simultaneously imaging the whole body

• 40x gain in effective sensitivity for total-body imaging!
• 4-5x gain in sensitivity for single organ imaging
**Image Gently (Low Dose)**

- 40-fold reduction in dose
  - Whole-body PET at ~0.15 mSv
  - Annual natural background is ~2.4 mSv
  - Return flight (SFO-LHR) is ~0.11 mSv
  - PET can be used with minimal risk – new populations

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**DISCUSSION : Physics Approaches to Dose Reduction**

- Achievable dose reduction today:
  - 300% to 400% with low (Kv, mAs) CTA instead of diag CT
  - 30% in WB with iterative reconstruction
  - 16% in liver with TOF-PET
  - 30% in lungs with TOF-PET

- Achievable dose reduction with PET/MR today:
  - PET-MR eliminates CT dose, reduces PET dose by 600%

- Potential dose reduction with Total Body in the future:
  - Total Body PET can reduce PET dose by 4000%
Dose Optimization in PET/CT & PET/MR

Thank You!