PET Scanner Performance: Quality Assurance and Acceptance Testing

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Introduction

Quality Control

Procedures required to ensure that the distribution of radiation emitted from a patient is accurately reflected in the measured raw data.

Facets

- Quality assurance:
  - verify scanner is operating properly
  - identify problems prior to scanning patients
- Acquisition of corrections to compensate for known imperfections in data measurement

Quality Assurance

Quality Assurance Test Requirements

- Well defined regimen of measurements
  - Quick and easy to conduct
  - Sensitive to modes of failure of the scanner
  - Preferably quantitative, not qualitative

Quality Assurance Data

- Blank Scan Sinograms: On stand-alone PET systems, used with transmission sinograms to create attenuation correction factors
- Emission Sinograms: Scans of uniform cylinder

Sinogram of a Uniform Cylinder

Blank Scan Sinograms

Good blank

Bad block

Sinogram of a Uniform Cylinder
**Quantitative Analysis of QA Data**

- Quantitative analysis is an important aspect of the QA of a PET scanner.
- Quantitative analysis of QA data:
  - Validates system calibration.
  - Provides information on crystal, block or module (bucket) efficiencies with respect to system average.
  - Compares to baseline data - monitors system stability.
  - Ensures validity of normalization.

**Quality Assurance**

Detector and Electronics Characterization:
- Singles mode detector calibration
  - Crystal map
  - PMT gain adjustment
  - Energy map
- Coincidence timing calibration

**Crystal Map**

**Purpose:**
- Map the position of the detected event to a specific crystal.
- Obtained quarterly or after detector maintenance.

**Verification of Crystal Map**

QA of crystal maps created during calibration of the scanner.
PMT Gain Adjustment

Purpose:
• Balances the gain characteristics of the PMTs in a block
• Compensates for PMT gain drift with temperature, age, ...
• Acquired weekly (daily) or after detector maintenance

Coincidence Timing Calibration

Purpose:
• Adjust for timing delays so events from all blocks are timestamped equivalently
• Acquired weekly or after detector maintenance

Daily Quality Assurance

Can the Scanner be Used Today?

Potential Problems
• System stability, drifts
• Detector module/ PMT/ preamp failure
• Loose cables, connectors
• Inoperable gantry motors, source loader

Daily QA Regimen
• Automatic PMT gain adjustment
• Blank scan

• QA will detect but not prevent these problems
Example: NMSE and Block Bias

QA must be sensitive to modes of failure of the scanner

NMSE: Error with respect to baseline scan

NEMA NU 2-2001

PET Performance Measurements

National Electrical Manufacturers Association.

NEMA Standards Publication NU 2-2001: Performance Measurements of Positron Emission Tomographs

Acceptance Testing

Can we use our new scanner?

Annual QA

Is the scanner still performing within specification?

• Measures performance of PET scanners under conditions that attempt to represent whole body studies
  – Phantom of length greater than axial FOV
  – Out of field activity

• Standardizes oblique LOR manipulation in 3D acquisitions

Phantoms for NU 2-2001

NEMA NU 2-2001

Three phantoms:

- Scatter phantom: 203x700mm phantom with activity in line source
- Sensitivity phantom
- Image quality phantom

Performance Measures:

- Spatial Resolution (Transaxial, axial)
- Sensitivity
- Scatter Fraction
- Count Losses
- Count Rate Correction Accuracy
- Image Quality

Spatial Resolution

- Spatial resolution of a system represents its ability to distinguish between two points of radioactivity.
- 18 point sources in air at six locations:
  - (0,1), (0,10) and (10,0) cm
  - Center of axial FOV and ¼ axial FOV from center
- Reconstruct: image pixel < ½ expected FWHM
- Profile width ~ 2 times FWHM
- Report FWHM and FWTM in radial, tangential and axial directions

Spatial Resolution - Transaxial Resolution

<table>
<thead>
<tr>
<th></th>
<th>FWHM @ 1cm</th>
<th>FWHM @ 10cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Philips Allegro</td>
<td>5.5 mm</td>
<td>5.6 mm</td>
</tr>
<tr>
<td>GE DST</td>
<td>6.2</td>
<td>6.7</td>
</tr>
<tr>
<td>CTI HiREZ</td>
<td>6.5</td>
<td>7.5</td>
</tr>
<tr>
<td></td>
<td>4.6</td>
<td>5.8</td>
</tr>
</tbody>
</table>
Sensitivity

- Sensitivity of a scanner represents its ability to detect annihilation radiation.
- Rate of true coincidence counts per unit radioactivity (expressed in cps/kBq) in absence of attenuating media.
- Rationale: need material around source to ensure annihilation of positrons, but this material also attenuates the annihilation photons.

Successive measurements with a 700 mm line source with a known amount of F-18 surrounded by nested, known absorbers.

The count rate with no absorber is extrapolated from these measures.

\[
\text{System Sensitivity} = \frac{R_0}{R_y} \cdot \text{Activity}
\]

Measure at radial locations of 0 and 10cm.

Report system sensitivity and slice sensitivity profile.

<table>
<thead>
<tr>
<th>System</th>
<th>2D</th>
<th>3D</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE DST</td>
<td>2.0</td>
<td>9.3</td>
</tr>
<tr>
<td>Philips Allegro</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>CTI HiRez</td>
<td>4.5</td>
<td></td>
</tr>
</tbody>
</table>
**Scatter Fraction**

- Scatter fraction is a measure of the system sensitivity to scatter.

\[ SF = \frac{\text{Scatter}}{\text{Scatter} + \text{Trues}} \]

- Use 203 mm diameter polyethylene cylinder of length 700 mm, with activity located in a line source of diameter 2.3 mm that is 4.5 mm off axis.
- Measured with low activity (Randoms:Trues < 1%) to avoid random coincidences, deadtime and pulse pileup.

**Count Rate Performance**

- Use 700 mm long polyethylene cylinder.
- Measured with high initial activity of F-18.
  - 3D: 800 MBq; 2D: 5 GBq.
- Acquire data until randoms and deadtime losses are negligible (14 to 18 hrs).

<table>
<thead>
<tr>
<th>Scanner</th>
<th>Scatter Fraction</th>
<th>LLD (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>GE DST 2D</td>
<td>19%</td>
<td>375</td>
</tr>
<tr>
<td></td>
<td>3D</td>
<td>44%</td>
</tr>
<tr>
<td>Philips Allegro</td>
<td>40%</td>
<td>410</td>
</tr>
<tr>
<td>CTI HiRez</td>
<td>36%</td>
<td>425</td>
</tr>
</tbody>
</table>
• Calculate Noise Equivalent Count Rate

\[ R_{NEC} = \frac{R_{Trues}^2}{R_{Trues} + R_{Scatter} + k \cdot R_{Randoms}} \]

- \( R_{NEC} \) Figure of merit relating scanner performance to sinogram SNR after randoms and scatter corrections.
- For NEMA, \( k = 1 \) (calculated Randoms); \( R_{NEC} \)
- Report peak NEC and effective activity concentration at peak.

### 3D Count Rate Performance

- Peak \( R_{Trues} \): 515 kcps @ 44 kBq/ml
- Peak \( R_{NEC} @ 1R \): 117 kcps @ 20 kBq/ml

### Image Quality Measurement

- Standardized imaging situation that simulates a clinical whole body imaging condition
- Phantom consists of a torso phantom with hot and cold lesions in a warm background
- Scatter phantom abutted to image quality phantom

<table>
<thead>
<tr>
<th>Count Rate Performance</th>
<th>Activity (kBq/ml)</th>
<th>Peak ( R_{NEC} ) (kcps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CTI HiREZ</td>
<td>21</td>
<td>85</td>
</tr>
<tr>
<td>GE DST 2D</td>
<td>49</td>
<td>84</td>
</tr>
<tr>
<td>3D</td>
<td>12</td>
<td>63</td>
</tr>
<tr>
<td>Philips Allegro</td>
<td>9</td>
<td>30</td>
</tr>
</tbody>
</table>
**Image Quality Measurement**

- Hot spheres: 10, 13, 17, 22 mm id
- Cold spheres: 28, 37 mm id
- Lung insert
- Activity in hot spheres 8 and 4 times that of background
- Activity in background 5.3 kBq/ml
- Simulated acquisition 100 cm in 60 min
  \[ T_{acq} = \frac{60 \text{ min}}{100 \text{ cm}} \]
- Repeat acquisition three times
- Reconstruct using clinical protocol

**Image Quality Measurement**

- Report image contrast and SNRs for hot and cold lesions, residual error in lung, variability in background
- Visual inspection for artifacts

**Summary**

- Need for QA regimen
- Quantitative analysis of QA data
- NEMA NU 2-2001 Performance Standard procedures

**NEMA and Lutetium-176**

- LSO is inherently radioactive
- Background radiation gives rise to Randoms, some Trues
- Implications for NEMA: cannot obtain Randoms:Trues ratio of < 1%
- For count rate and sensitivity measurements – acquire background scan to estimate intrinsic true and random rates