Learning Objectives:

- Summarize the signal processing steps for coincidence detection
- Understand the components of daily QA
- Identify and troubleshoot sources of failure in daily QA
- List the recommended frequency of QA/QC tests.
- Describe the process of scanner calibration
- Name the different components of the NEMA tests used for PET acceptance testing
- Understand the meaning of the NEMA test results
Disclosures

- ACR reviewer for NM and PET

Learning Objectives

- Describe the PET NEMA acceptance tests
- Understand the results of the NEMA acceptance tests for PET scanners.
- Describe the recommended QA/QC tests for PET imaging and their frequency.
- Troubleshoot potential problems with PET images.

What is NEMA?

The acronym stands for: National Electrical Manufacturers Association

- In 1991 a task group from the SNM published a set of measurements to standardize the performance characterization of PET scanners.
- At the same time, NEMA formed its own committee to address the same issue and ended up publishing a standard that adopted the SNM publication however with some refinements. That standard became the NU 2-1994.
- Also at the same time, the European Economic Community underwent a similar process which resulted in an International Electrotechnical Commission (IEC) standard.
- The NEMA and IEC are two different standards although similar in purpose.
- Recently, the NEMA standard has been updated. The new document is known as the NU 2-2001 which is still different from the IEC standard.
Three NEMA Standards:

- NU2-94: Mainly used for neuroimaging (2D).
- NU2-01: Mainly used for whole Body imaging (2D/3D).
- NU2-07: Mainly to account for radioactive detectors (2D/3D)

The original NEMA standard (NU 2-94) was developed for PET scanners that were used in 2D mode and had a limited axial FOV.

New scanner developments which acquire data in 3D and have large axial FOVs, as well as the major shift in the use of PET from neuroimaging to whole body imaging necessitated updating the first NEMA standard.

Three NEMA Standards:

- The latest NEMA standard (NU2-07) takes into consideration intrinsically radioactive detectors.
  - This will have impact on measurements of count losses and randoms, as well as sensitivity
  - Additionally, spatial resolution has been expanded to include the measurement and reporting of the source position.

Performance Characterization Measurements:

NEMA NU2-94 (2D)
- Transverse/Axial Resolution
- Sensitivity
- Scatter Fraction
- Count Rate and deadtime
- Uniformity
  - Accuracy of count rate, scatter & attenuation correction

NEMA NU2-01 and 07 (2D/3D)
- Spatial Resolution
- Sensitivity
- Scatter Fraction/Count Rate Performance
- Image Quality
- Accuracy of count losses and randoms correction
For systems with 2D and 3D capabilities, acceptance testing should be performed in both modes.

**Performance Characterization we will discuss:**

- NEMA NU2-07 (2D/3D)
  - Spatial Resolution
  - Sensitivity
  - Scatter Fraction/Count Rate Performance
  - Image Quality
  - Accuracy of correction for count losses and randoms

Test results are compared with manufacturer specifications.

Additional tests such as scanner alignment and accuracy of SUV are NOT part of NEMA tests.

*Daube-Witherspoon M. et al JNM, 43(10) 1398-1409, 2002*
Spatial Resolution:

This test measures the capability of the PET system to localize the position of a point source of activity after image reconstruction. The measurement is done using multiple point sources suspended in air at different locations.

- 3 point sources are made from a solution with an activity concentration of 5mCi/cc.
- The point sources are positioned at (0,1), (0,10), and (10,0) in center of axial FOV.
- Images were reconstructed using FBP (2D) and FORE + FBP (3D).
- Use 256x256 matrix, 25cm FOV, centered at (5,-5), with ramp filter at 4mm cutoff.
- No correction for dead time.
- Repeat with sources positioned at 4cm from edge of axial FOV.
- Final results are the average of the two measurements.

Analysis is done by measuring the FWHM and FWTM in the radial and tangential directions.
**Sensitivity:**

This test measures the number of detected coincidence events per second for every unit of activity in the FOV. The test is performed with very low activity levels to minimize the effect of count losses. Measurements of sensitivity are made with increasing amounts of attenuating material, the results are then plotted and extrapolated to give the scanner sensitivity with no attenuation.

- A line source is filled with ~0.1 mCi of F-18 and threaded into an aluminum sleeve.
- Setup is suspended in center FOV, data is acquired for 1min in 2D and 3D modes.
- Add a second aluminum sleeve, repeat acquisition.
- Repeat process for 5 aluminum sleeves.
- Repeat all the process after repositioning setup at R=10cm.

Analysis is done by fitting sensitivity values and extrapolating to zero attenuation.

\[ R_i = \frac{R}{\exp(-2\mu_i)} \]

Slice sensitivity is calculated by:

\[ S = \sum R_i \]
250 uci in the line (2.2 cc)

NU2-01/7 Sensitivity Setup

NU2-01/7 Sensitivity R=0 2D

NU2-01/7 Sensitivity R=10 2D
Count Rate and Scatter Fraction

The scatter fraction (SF) portion of this test measures the sensitivity of the scanner to coincidence events caused by scatter while the count rate test measures the performance of the PET scanner across a range of radioactivity levels. The SF measurement is done at activity levels where system dead time and randoms are negligible.

- Fill line source (70mCi 2D, 40mCi 3D) of F-18 and thread it into the scatter phantom.
- Setup is placed on the couch in the center FOV with the line source close to couch.
- Data is acquired in dynamic mode as 4*15min, 14*25min with 25 min delays.
- Total time is ~13hrs.

- Analysis is done on sinograms with no corrections applied.
- 3D data was processed using SSRB.
- SF was measured using the last frame of the dynamic data.
- Scatter under the peak was estimated by interpolation between ±2cm from center.

Count rate analysis was done in a 24 cm FOV using the following formulas where i and j are the slice number and acquisition number respectively.

\[
R_{ct} = \sum \frac{C_{ct} \cdot T_{ct}}{w_{ct}}
\]

\[
R_{ct}^\prime = \sum \frac{R_{ct} - (R_{ct} \cdot (1 - SF)))}{w_{ct}}
\]

\[
R_{cscct} = \sum \frac{R_{ct}^\prime \cdot R_{ct}}{w_{ct}}
\]

\[
R_{NECR} = \sum \frac{R_{ct}^\prime \cdot R_{ct}}{w_{ct}}
\]

C: counts
T: Time
R: Rate

nu2-01/7 Scatter Fraction/Count Rate Setup

70 mCi in 5.2 cc line
**NU2-01 Scatter Fraction/Count Rate 2D**

- Scatter scatter fraction: 14.744 %
- Event rate: 600 (600)
- Peak table rate: 113,022 (88,614)
- Peak random rate: 17,261 (176,261)
- Peak scatter rate: 11,020 (11,020)
- Peak NE rate: 264 (264)
- Peak NE rate: 256 (256)

**NU2-01 Scatter Fraction/Count Rate 3D**

- Scatter scatter fraction: 14.744 %
- Event rate: 600 (600)
- Peak table rate: 113,022 (88,614)
- Peak random rate: 17,261 (176,261)
- Peak scatter rate: 11,020 (11,020)
- Peak NE rate: 264 (264)
- Peak NE rate: 256 (256)

**Count Rate Performance**

Example from a Philips system

Used 15.6 mCi at 18:00
Image Quality:

This test attempts to measure the performance of the scanner in a condition that simulates a whole body clinical scan. The test uses hot and cold spheres of different sizes in a volume of non-uniform attenuation. Activity is also placed outside the FOV. Image quality is reported in terms of image contrast and SNR of hot and cold spheres.

• The IEC background is filled with ~5.3 kBq/cc
• The 4 smallest spheres of the IEC phantom are filled with 4 times background
• Two largest spheres are filled with regular water
• Scatter phantom was filled with total activity of 116 MBq/cc (~ background)
• Both phantoms were positioned behind one another in the center FOV
• Data was acquired for 8.5 min (2D) and 7.5 min (3D) since CT was used for atten.
• Repeat with 4 smallest spheres of IEC phantom filled with 8 times background

• Analysis is done on images reconstructed using clinical protocols.
• ROIs are drawn on spheres an background.
• 12 background ROIs are drawn on central ±1 cm ±2 cm slices (total 60 rois).

The following parameters are calculated on the ROI values:

• Hot and cold sphere contrast for each sphere (j):

\[ \begin{align*}
Q_{\text{Hot}} &= \frac{C_{\text{HO}}}{C_{\text{BG}}} - 1 \\
Q_{\text{Cold}} &= -1 - \frac{C_{\text{CO}}}{C_{\text{BG}}}
\end{align*} \]

• The percent background variability for each sphere (j):

\[ N_j = SD / C_{\text{BG}} \]

• The average residual lung error summed over all slices (i):

\[ \delta \sum_{\text{lung}} = \sum_{\text{lung}} C_{\text{lung}} / \sum_{\text{lung}} C_{\text{BG}} \]

NU2-01/7 Image Quality Setup

• 0.206 uCi/cc in 10 liter background
• 0.88 uCi/cc sphere concentration
• 4.7 mCi in the scatter phantom
NU2-01/7 Image Quality 2D

Example from a Philips system

NU2-01/7 Image Quality 3D

Used: 146 mCi in spheres, 1.65 mCi in Bkg, and 3.64 mCi in line source, all at 4:11
Accuracy for correction of count losses and randoms:

The accuracy of count losses and randoms corrections is measured by comparing the true rate calculated using count losses and randoms corrections with the true rate extrapolated from measurements with negligible count losses and randoms. The test uses the data acquired during the count rate and scatter fraction test.
Accuracy of Corrections

Example from a Philips system

NEMA Acceptance testing

• Results should be compared to manufacturers specification.

• Each system from each manufacturer has specifications for each of the NEMA tests.

• These specifications are available upon request from the manufacturer.

Quality Control Schedule

• Daily:
  – Check singles, coincidences, timing, energy
  – Sinograms

• Weekly:
  – Update gains

• Quarterly:
  – Normalization and well counter calibration

• Annually:
  – ACR or NEMA tests, TG126.
PET Daily QA Scan

Daily QC
Sample Sinograms

Daily Quality Control
- Pre-calibrated Phantom
Assess quantification accuracy using SUV measurement

Annual ACR Phantom Images

- Uses the ACR (Esser phantom)

Phantom Images - Procedure

From the column on the right, select the administered FDG whole-body dose.

<table>
<thead>
<tr>
<th>Patient Dose</th>
<th>Dose A (mCi)</th>
<th>Dose B (mCi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 mCi</td>
<td>0.140</td>
<td>0.330</td>
</tr>
<tr>
<td>6 mCi</td>
<td>0.210</td>
<td>0.495</td>
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<tr>
<td>8 mCi</td>
<td>0.290</td>
<td>0.660</td>
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<tr>
<td>10 mCi</td>
<td>0.350</td>
<td>0.825</td>
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<tr>
<td>12 mCi</td>
<td>0.420</td>
<td>0.990</td>
</tr>
<tr>
<td>14 mCi</td>
<td>0.490</td>
<td>1.154</td>
</tr>
<tr>
<td>16 mCi</td>
<td>0.560</td>
<td>1.319</td>
</tr>
<tr>
<td>18 mCi</td>
<td>0.630</td>
<td>1.484</td>
</tr>
<tr>
<td>20 mCi</td>
<td>0.700</td>
<td>1.649</td>
</tr>
</tbody>
</table>
Annual ACR phantom images

Contrast  Uniformity  Resolution

NEMA Performance Characterization:

NEMA NU2-01/7 (2D/3D)
- Spatial Resolution
- Sensitivity
- Scatter Fraction/Count Rate Performance
- Image Quality
- Accuracy of count losses and randoms correction

Additional tests such as scanner alignment and accuracy of SUV are NOT part of NEMA tests
O. Mawlawi MDACC

300 lb load

PET/CT scanner alignment

Uniformity

Uniformity within slice  Uniformity across slices
Additional tests

• Timing resolution for TOF systems
• Energy resolution
• Gating functionality
• List mode recording

CT Daily QA Scan

Normal operations include the following 3 tasks (in order):

• Tube Warmup: A built-in prep scan that gradually increases heat loading in the X-ray tube in order to prevent thermal cracking and eliminate the potential for an arc to occur. It includes a series of exposures at incrementing kVp.

• Daily Air Cals: A built-in prep scan that performs a series of exposures at varying techniques in order to normalize and detector response using air as the attenuating media. These scans essentially adjust the detector gains to achieve a uniform response.

• Daily QC Phantom Scan: Provides data for 3 areas of concern in daily quality assurance: linearity, uniformity, artifact analysis.

CT Daily QC Scan

• Linearity
  - Linear attenuation coefficients track linearly with material density
  - Remember that CT numbers are defined WRT the attenuation coefficient of water
  
  \[
  \text{CT}(x,y) = 1000 \left( \frac{\mu_{\text{water}}}{\mu_{\text{water}}} \right) \]
  
  - The mean CT numbers of air (-1000 HU), water (0 HU), and acrylic (120 HU) displayed within an ROI should be consistent with the defined values +/- manufacturer specified tolerance
CT Daily QC Scan

- Uniformity
  - ROIs distributed in homogeneous material should indicate consistent signal (HUs) and noise.

CT Daily QC Scan

- Low Contrast Resolution
  - Qualitative assessment of smallest resolvable hole in a membrane with a CT number similar to that of water.

CT Daily QC Scan

- Artifact Analysis
  - Looking for the presence of artifact
  - Ring artifact is the most clinically prevalent in QA scans
  - Caused by non-uniformity in detector response due to gain imbalance or beam obstruction.
Dose Calibrator

- D.C. Quality Control Tests
  - Linearity
    - "The proportionality of the measurement result to the activity measured, as determined over the intended range of use for the dose calibrator"
    - A known activity of FDG is assayed at a particular time and then assayed again subsequently on the hour.

- D.C. Quality Control Tests
  - Constancy
    - "Reproducibility in measuring the same source, over a period of time, with decay correction"
    - Assay a relatively long-lived source (such as Cs-137) each day before using the calibrator.

- D.C. Quality Control Tests
  - Accuracy
    - "Determination of the dose calibrator’s absolute error resulting from a measurement of a suitable NIST traceable radionuclide activity"
    - Assay 2 calibrated reference sources, decay correct, and determine % error
  - Geometry
    - "Indicated activity does not change with volume or configuration of the source material"
TG 126

- TG 126: PET/CT QA/QC and testing
  - Chair: Osama Mawlawi
  - Charge: to develop a report describing procedures for acceptance testing and routine quality assurance of PET scanners.
  - Representation: Academia, industry, consulting, hospitals.
  - Sources: NEMA, IAEA (QA for PET and PET/CT systems)
  - Current issues:
    - Acceptance testing: NEMA standard + alignment as well other aspects like TOF, Cardiac, dynamic, etc.
    - Annual testing: NEMA-like issues with some vendors
  - Meetings: SNM, AAPM, RSNA, (IEEE – MIC)
  - Expected draft date: 2012

Artifacts

PET/CT ATLAS ON QUALITY CONTROL AND IMAGE ARTEFACTS

International Atomic Energy Agency
Normalization effects

Good Norm

Bad Norm

Effect of bad Normalization

Increased activity due to error in normalization

SUVmax=4.5

Effects of Bad Blocks
Effects of Bad Blocks

Normalized to Baseline for Each Sphere

Bed overlap
Thank you