Quality Assurance in Gamma Camera & SPECT Systems

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Gamma Camera Imaging of Radioactive Sources in Patients

Three major Components:
1. **Collimator** – localizes γ-ray source in patient
2. **NaI(Tl) Crystal** (single or multi-crystal) over width of patient stops the γ-rays.
3. **Array of PMT’s** – localizes γ-ray interaction in crystal

Collimator Types

- Parallel Hole
- Diverging
- Converging
- Pinhole

Energy Rating of Available Collimators

<table>
<thead>
<tr>
<th>Collimator Type</th>
<th>Max. Energy Rating (keV)</th>
<th>Septal Thickness (mm)</th>
<th>Isotopes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Energy</td>
<td>140 - 200</td>
<td>0.2 - 0.3</td>
<td>99mTc, 201Tl, 133Xe, 123I</td>
</tr>
<tr>
<td>Medium Energy</td>
<td>300</td>
<td>1.1 - 1.4</td>
<td>67Ga, 111In</td>
</tr>
<tr>
<td>High Energy</td>
<td>360 - 500</td>
<td>1.3 - 3.0</td>
<td>131I</td>
</tr>
<tr>
<td>Ultra-High Energy</td>
<td>511</td>
<td>3.0 - 4.0</td>
<td>Positron Emitters</td>
</tr>
</tbody>
</table>

Septal Penetration Artifact

- Streak artifacts appear along directions of septa that is thinnest.
- Streaks extend over distances of many cm indicating penetration of many holes.
- Image resulted from using a high energy collimator that has hexagonal holes.

Septal Thickness Requirements

The thickness required is designed for less than 5% transmission:

$$t \geq \frac{6d/M}{l - (3/\mu)}$$

where $$\mu$$ is the linear attenuation coefficient of the absorber, usually lead.

Could use higher Z and density tungsten, tantalum, or gold that have higher $$\mu$$ and hence thinner septal thickness offering improved resolution and sensitivity.
Spatial Resolution

- **Collimator** – Ability of the collimator to localize the γ-ray source in the patient (~6-12 mm)
- **Intrinsic** – Ability of the NaI(Tl) crystal and PMT to localize the γ-ray interactions in the crystal (~3-4 mm)
- **Extrinsic** – Overall system resolution combining collimator and intrinsic factors. Quadratic sum of FWHM of intrinsic and collimator resolution.

Resolution vs. Crystal Thickness

- The thinner crystal has better the intrinsic resolution (e.g. 3/8” has 3.5 mm FWHM vs. 3.9 mm FWHM for 5/8” crystal)

Resolution vs. Number of PMT’s

- The larger number of tubes the better the intrinsic resolution (e.g. 3.9 mm FWHM for 37 tubes vs. 3.6 mm FWHM for 75 tubes)

Resolution vs. Photon Energy

- Intrinsic resolution is better for high energy photons.

### Intrinsic Resolution of $^{99m}$Tc & $^{201}$Tl

- $^{99m}$Tc (140 keV) 3.5 mm FWHM
- $^{201}$Tl (70 keV) 4.0 mm FWHM

### Resolution of a Collimator

\[ \text{FWHM}_c \sim \left( \frac{d}{l} \right) (l+f+c) \]

- d – hole diameter
- l – hole length
- t – septal thickness of lead
- f – collimator to source distance
- c – collimator to crystal center distance

### Geometric Efficiency of a Collimator

\[ \text{Efficiency}_C \sim K \left( \frac{d}{t} \right) \left( \frac{d}{d+t} \right)^2 \]

- \( K = 0.24 \) round hole in hex array
- \( K = 0.26 \) hex hole in hex array
- \( K = 0.28 \) square hole in square array

(Note: for high energy collimators, \( d+t \) is large, and hence \( \text{Efficiency}_C \) becomes too low)

### System Resolution Vs. Distance

- High Sensitivity
- High Resolution
- Ultra-High Resolution

- Source Distance (mm)
- FWHM (mm)
Performance of Available Collimators

<table>
<thead>
<tr>
<th>Collimator Type</th>
<th>Hole Diameter (mm)</th>
<th>Hole Length (mm)</th>
<th>FWHM at 0 cm (mm)</th>
<th>FWHM at 10 cm (mm)**</th>
<th>FWHM at 20 cm (mm)**</th>
<th>Sensitivity (CPM/µCi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Energy All Purpose (LEAP or GAP)</td>
<td>1.43</td>
<td>23.6</td>
<td>4.4</td>
<td>9.1</td>
<td>15.3</td>
<td>530 (± 1%)</td>
</tr>
<tr>
<td>Low Energy High Resolution</td>
<td>1.11</td>
<td>23.6</td>
<td>4.2</td>
<td>7.5</td>
<td>12.5</td>
<td>335 (± 1%)</td>
</tr>
<tr>
<td>Low Energy Ultra-High Resolution</td>
<td>1.08</td>
<td>35.6</td>
<td>4.2</td>
<td>5.9</td>
<td>8.6</td>
<td>100 (± 1%)</td>
</tr>
<tr>
<td>Medium Energy</td>
<td>3.02</td>
<td>40.6</td>
<td>5.6</td>
<td>12.1</td>
<td>19.7</td>
<td>288 (± 6%)</td>
</tr>
<tr>
<td>High Energy</td>
<td>4.32</td>
<td>62.8</td>
<td>6.6</td>
<td>13.8</td>
<td>22.0</td>
<td>176 (± 1%)</td>
</tr>
<tr>
<td>Ultra-High Energy</td>
<td>3.4</td>
<td>75.0</td>
<td>6.9</td>
<td>10.4</td>
<td>15.8</td>
<td>60 (± 1%)</td>
</tr>
</tbody>
</table>

** Siemens Orbiter Gamma Camera System with intrinsic resolution of 3.9 mm FWHM

Gamma Camera Performance & Quality Control

- Resolution
- Uniformity
- Linearity
- Evaluated:
  - Intrinsically - Specific to Crystal and PMT’s
  - Extrinsicly - Includes the Collimator

Spatial Resolution Phantoms

- Orthogonal Hole
- Parallel Line Equal Spacing (PLES)

Intrinsic Spatial Resolution Measurement with 4-Quad. Bar Phantom

4-Quadrant bar phantom replaces the collimator - The image is the shadow of the lead bars on the crystal.

Gamma Camera

4-Quad Phantom

99mTc Point Source (400 – 800 uCi)

Extrinsic Spatial Resolution Measurement with 4-Quad Bar Pattern

Planar Flood Source (10 mCi 99mTc or 57Co)

Gamma Camera

Collimator

Point Sources

- Isotope in 0.1 - 0.2 ml in hub of syringe or in end of the needle cap.
- Requires exchange of needle.
- Do not mishandle and fracture source.
Planar Flood Sources

- $^{57}$Co Flood Source – $T_{1/2}$ 270 days; 122 keV $\gamma$ 10-15 mCi at time of purchase.
- $^{99m}$Tc Flood Source (water filed) – $T_{1/2}$ 6 hrs.; 140 keV $\gamma$ 10-15 mCi at time of filling.

Measure Spatial Linearity with PLES Phantom

- Images of PLES (parallel line equal spacing) phantom with $^{99m}$Tc source

Measure Linearity with 4-Quadrant Bar Phantom

- Note wavey/curve-linear appearance of lead bars throughout the image.

Measuring Intrinsic Uniformity

- Point Source 400-800 nCi
- No Collimator
- 5 UFOV Diameter distance
- Statistical Variation:
  - 3 Mcts. ~ 1600 ct/cm² (± 2.5%)
  - 15 Mcts. ~ 4800 ct/cm² (± 1.4%)

Measuring Extrinsic Uniformity

- Planar Source 10-15 mCi of $^{57}$Co or $^{99m}$Tc
- Edge-Packing shielded by collimator ring.
- 5-15 Million Counts 3-15 min.

Integral Uniformity (IU) Index

- Integral Uniformity (IU)
  - (4000 cts/cm² with 9-pt. smoothing in 6 mm pixels)
  - Max. Pixel - Min. Pixel x 100%
  - Max. Pixel + Min. Pixel
  - Range of sensitivity variations over the UFOV or CFOV
  - IU of 2-3 % expected
Differential Uniformity Index

Differential Uniformity (DU)

- Maximum rate of change in sensitivity across the UFOV or CFOV
- DU of 1.5 – 2.0% expected.

Non-Uniformity from PMT Drift

PMT voltage drift causes peak shift and difference in sensitivity.

Uniformity Dependent on Energy Window Centering

Uniformity is best for single energy isotopes, like $^{99m}$Tc, $^{123}$I, $^{57}$Co, or $^{131}$I. Varies by vendor.

Energy Dependence of Uniformity

Non-Uniformity at High Count Rates

High count rates also lead to loss of resolution and linearity.

Non-Uniformity From a Second Source

A second $^{99m}$Tc source in the room or in the hot lab next door. Susceptible artifact when acquiring intrinsic floods.
Non-Uniformity from Cracked/Broken Crystal

Crystal may cracked:
- from mechanical shock during collimator exchange.
- by thermal shock where the crystal temperature changes by more than 10 deg./hour.

Non-Uniformity from Collimator Structure Artifacts

Large Diameter Holes
Irregular Lead Foil Construction

Non-Uniformity from Collimator Damage

Crushed Lead Septa
Lead Foil Separation

Inter-Relationship of Uniformity, Resolution, and Linearity

Non-Uniformity → Resolution Loss → Linearity Loss

Sequential Improvement in Image Quality with added Corrections

No corrections
First - Energy Correction
Second - Linearity Correction
Third - Uniformity Correction

Uniformity Correction Matrix

High Count Flood Image
Flood Correction Matrix

1.05 high multiplier correction factor

- Applied during or following image acquisition
- Needs ten (10) times the counts of a routine flood image to reduce counting statistic variations to \( \pm 1\% \).
- May be acquired intrinsically or extrinsically.
Uniformity Correction Improvements

<table>
<thead>
<tr>
<th>IU = 4.2%</th>
<th>IU = 2.5%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw flood image</td>
<td>Flood image after correction</td>
</tr>
</tbody>
</table>

- Uniformity correction routinely applied to all gamma camera images. Correction improves IU and truncates edge packing artifact.
- Requires 10 times counts used for daily floods.

Uniformity Correction is a Calibration

- Intrinsic calibration requires
  - Precise point source background and scatter free
  - Correct count rate
- Extrinsic calibration
  - Planar flood source
  - Required for each collimator
  - Includes intrinsic calibration

Uniformity Correction – May Mask Underlying Problems!

- Detector with intrinsic linearity problems
- Damaged collimator with crushed lead septa

Can this be used?

Acquired at 100 Kcps

Fractured Point Source?

- Isotope in 0.1 - 0.2 ml in hub of syringe or in end of the needle cap.
- Requires exchange of needle.
- Do not mishandle and fracture source.

Quality Control Practices

1. Peak daily for $^{57}$Co, $^{99m}$Tc, & other isotopes to be used that day.
2. Uniformity - Flood images of 5-15 million counts each day of use, before imaging begins.
   a) Extrinsic flood image is preferred and tests heavily used collimators.
   b) Intrinsic flood image to test detector only, especially at the periphery of the FOV. Acquired at least one per week.
3. Resolution - Intrinsic (preferred) or extrinsic images of 5-10 million counts of four-quadrant bar phantom once per week.
4. Linearity - Intrinsic (preferred) or extrinsic images of 5-10 million counts with PLES or four-quadrant bar phantom once per week.
5. Uniformity Correction Matrix – Flood images of 100 Mcts or more once per month for each isotope used (vendor dependent).
Quantitate Daily Floods

- High Counts > 10-15 million counts for large area detectors
- Consistent source strength with count rate < 40,000 cps.
- Consistent source positioning.

Pre-Assigned Action Levels

1. Good – no further evaluation needed
2. Marginal – repeat flood once; if still marginal next day/week contact Physicist or supervisor to determine status; re-calibration may be necessary
3. Unacceptable – repeat flood once; if still unacceptable contact Physicist or supervisor to determine status; re-calibration may be necessary

NM Accreditation Programs

- ICANL - The Intersocietal Commission for the Accreditation of Nuclear Medicine Laboratories
  - Society of Nuclear Medicine
  - American Society of Nuclear Cardiology
  - American College of Nuclear Physicians
  - Academy of Molecular Imaging
  - American College of Cardiology
- ACR – American College of Radiology

Program Comparison

<table>
<thead>
<tr>
<th>ICANL</th>
<th>ACR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intersectorial sponsorship</td>
<td>Solely Radiology based</td>
</tr>
<tr>
<td>Accreditation by facility for up to 13 organ systems, PET, &amp; therapy</td>
<td>Accreditation by unit per site for planer, SPECT, cardiac, &amp; PET</td>
</tr>
<tr>
<td>Emphasis on case review</td>
<td>Emphasis on equipment</td>
</tr>
<tr>
<td>Up to 24 cases reviewed</td>
<td>Up to 6 cases per unit</td>
</tr>
<tr>
<td>Extensive protocol and QA protocol review</td>
<td>Planer and SPECT Phantoms and images required</td>
</tr>
<tr>
<td>Mandatory site visit</td>
<td>Random site visit</td>
</tr>
<tr>
<td>$200 application fee plus $3800 fee for comprehensive nuclear medicine &amp; PET (includes site visit)</td>
<td>$1200 facility fee for each for NM &amp; PET Plus $600/module - additional fees for repeat after deficiency</td>
</tr>
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ICANL Quality Control Protocols

**Equipment Quality Control Protocols**

- Equipment Quality Control
  - The Nuclear Medicine Department should have specific system protocols for each equipment and any imaging equipment. These must also be reviewed and maintained.
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**ICANL Quality Control Tests**

1. Intrinsic or System Uniformity: Used daily to verify that components are properly functioning and provide a uniform image in response to a uniform field of solution.
2. Intrinsic or System Spatial Resolution: Used to quantitatively verify that detector spatial resolution is sufficient for clinical imaging.
3. Center of Rotation or Multiple Detector Registration Calibration Test for SPECT Systems: Performed to ensure that the center of rotation is accurately defined for each detector.
4. High-Cut Floods For Uniformity Correction for SPECT Systems: Performed to ensure that sufficient energy resolution is maintained for each detector.
5. Overall System Performance for SPECT Systems: Performed to quantitatively verify that the system has maintained its performance under the conditions and operation of the SPECT systems.
ACR – Acceptance Tests and Annual Survey

Acceptance tests must be performed on systems when they are installed. At least annually thereafter, the performance tests listed below must be performed on all units. These tests do not need to be as rigorous as acceptance tests but must be a comprehensive suite of individual measurements that ensure adequate sensitivity for detecting detrimental changes in performance.

NEMA and Gamma Camera Acceptance Test Guides

- NEMA: NEMA Standards Publication NU 1-2001 Performance Measurements of Scintillation Cameras
- AAPM Report No. 9: Computer Aided Scintillation Camera Acceptance Testing
- AAPM Report No. 22: Rotating Scintillation Camera SPECT Acceptance Testing and Quality Control

Sensitivity Measurement

-1000 µCi ⁹⁹mTc source in dish to measure and compare sensitivity (cpm/µCi) of each detector and collimator combination

- Expect range of sensitivity of each head and collimator combination < 5%
- For LEHR sensitivity ~ 200 cpm/µCi

Energy Resolution Measurement

Energy resolution for ⁹⁹mTc is 10% of the 140 keV photpeak. Acquisition window 20%.

Multiple Window Spatial Registration Measurement

- Image point sources of Ga-67 or Tl-201 with a single energy window at energy peak.
- Measure the position of each image.
- Registration of the point sources vs. energy should be less than ~1 mm over the UFOV.
High Count Rate Measurement

- Dead time of ~4 μsec - measurement no longer specified.
- Maximum achievable count rate in air of ~ 250 kcps.
- Use decay method to generate count rate response curve.
- Observed count rate in air at 20% loss is ~ 100 kcps.
- Note - patient count rates from 1-15 kcps.

Rotating Gamma Camera SPECT

Liver/Spleen SPECT Acquisition

- 120 128x128 images
- 3° step & shoot rotation over 360°
- 15 sec/image/head
- 16 min. total acqu.
- 85,000 cts/image
- 10.88 million cts

Sinogram of Liver/Spleen SPECT

- Sinogram has all count data to reconstruct a single slice
- One sinogram per slice
- Can be used for motion correction

FPB vs. Iterative Reconstructions

- Iterative - OSEM
- FBP

Iterative Reconstruction

- Initial Estimate
- 1 Iteration
- 3 Iterations
- 5 Iterations
- 12 Iterations
- 100 Iterations
3-D Reconstruction

MIP
Isotropic voxels

SPECT Resolution Based on Collimator (at 20 cm radius of rotation)

<table>
<thead>
<tr>
<th>Collimator Type</th>
<th>Hole Diameter (mm)</th>
<th>Hole Length (mm)</th>
<th>FWHM at 8 cm (mm)**</th>
<th>FWHM at 10 cm (mm)**</th>
<th>FWHM at 20 cm (mm)**</th>
<th>Sensitivity (CPM/µCi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Energy All Purpose</td>
<td>1.43</td>
<td>23.6</td>
<td>4.4</td>
<td>5.1</td>
<td>12.5</td>
<td>360 (99m Tc)</td>
</tr>
<tr>
<td>Low Energy High Resolution</td>
<td>1.11</td>
<td>23.6</td>
<td>4.2</td>
<td>7.5</td>
<td>12.5</td>
<td>230 (99m Tc)</td>
</tr>
<tr>
<td>Low Energy Ultra-High Resolution</td>
<td>1.08</td>
<td>35.5</td>
<td>4.2</td>
<td>5.9</td>
<td>8.6</td>
<td>180 (99m Tc)</td>
</tr>
<tr>
<td>Medium Energy</td>
<td>3.02</td>
<td>40.6</td>
<td>5.6</td>
<td>12.1</td>
<td>19.7</td>
<td>288 (67 Ga)</td>
</tr>
<tr>
<td>High Energy</td>
<td>4.32</td>
<td>62.8</td>
<td>6.4</td>
<td>15.8</td>
<td>22.8</td>
<td>176 (131 I)</td>
</tr>
<tr>
<td>Ultra-High Energy</td>
<td>3.4</td>
<td>75.0</td>
<td>6.4</td>
<td>10.4</td>
<td>~20.0</td>
<td>60 (18 F)</td>
</tr>
</tbody>
</table>

** Siemens Orbiter Gamma Camera System with intrinsic resolution of 3.9 mm FWHM

Non-Circular Motion SPECT

- Circular Camera Rotation with translation of the camera and/or patient.
- Improves spatial resolution by moving collimator/patient closer.

180 Degree Acquisition Arc for Heart

Heart sits anterior in the chest.

Heart not visible in posterior projections.

Dual detectors set at 90 degree angle most efficient.

180 or 360 Degree Acquisition Arc?

180 Degree Acquisition Arc

360 Degree Acquisition Arc

Truncation

Portion of the imaging volume falls outside the gamma camera field-of-view during a portion of the acquisition arc.

High density ring at the edge of the reconstruction of arc length proportional to the number of views with truncation.
Small FOV Camera & 180° Acq.

How Many Images to Acquire?
- Typically camera detectors rotate through 360 degrees.
- Stepping angle ($\theta$) = 360 deg. / # stops
- Sampling distance (d) at the organ edge = $D/2$
- For good resolution d must be small which implies small q and a large number of stops.

Low Resolution SPECT - 60 images at 6 degree steps
High Resolution SPECT - 120 images at 3 degree steps

How Many Counts in a SPECT Study?

Total Counts/Study = [Counts/Image] * [Number of Images]
Total Counts/Slice = [Counts/Slice] * [Number of Images]

The total counts in a SPECT study range from 2-8 million counts.

SPECT Low Pass Frequency Filters

Butterworth Filter:
$$B(f) = \frac{1}{1 + \left(\frac{f}{f_{cutoff}}\right)^{2norder}}$$

Hanning Filter:
$$H(f) = \frac{1}{2} \left[ 1 + \cos(\pi f/f_{cutoff}) \right]$$

Low Pass Filters - Butterworth Filter

No Filter
0.5 cycles/pixel Cutoff
0.4 cycles/pixel Cutoff
0.3 cycles/pixel Cutoff
0.2 cycles/pixel Cutoff
0.1 cycles/pixel Cutoff

No Attenuation Correction
Attenuation in the abdomen
With Attenuation Correction
**Chang Attenuation Correction Method**

\[ C = C_0 e^{-\mu t} \]

- \( \mu \) - linear attenuation coefficient in tissue. Assume uniform tissue density (for 140 keV, \( \mu = 0.15/cm \))
- \( t \) - depth in mm

Body Contour change must be consistent from slice-to-slice.

**Measured Attenuation in Chest**

- Perform transmission imaging just like X-ray CT
- Line source of \(^{153}\text{Gd} (T_{1/2} = 242 \text{ days}, \text{photon energies of 97 & 104 keV})\) scans across the camera FOV at every camera stop, or multiple parallel line sources across field-of-view.
- Dual Isotope windows allows for simultaneous emission and transmission data.

**CT \( \mu \)-Map**

- Measured linear attenuation coefficients used instead of uniform coefficients in Chang attenuation correction method.
- Attenuation map is segmented to fixed attenuation coefficients for soft tissue to reduce noise.

**Blank Scan - Transmission Scanning QC**

- Blank scan acquired daily.
- Compared to “mother” original blank scan and analyzed for changes by calculating IU.
- Source strength is evaluated by total counts in the blank scan acquisition.

**Transmission Scan Patient QC**

Look for:
- Insufficient number of counts
- Banding at edge from truncation
- Banding from line source translation problems

**SPECT Quality Control**

- Gamma camera must operate at optimum performance.
- Uniformity is critical
Concentric rings of alternating high and low count densities appear in the transaxial images due to insufficient gamma camera uniformity.

**Bullseye Ring Artifact**

Uniformity Correction By Computer

- 30-100 million count flood images, 10 times daily flood requirements
- Must follow manufacturer recommendations

**Serial Ring Artifacts**

Center-of-Rotation Error

- COR error is propagated as offset during backprojection
- COR study acquired monthly

**Uniformity Correction By Computer**

High Count Flood Image | Flood Correction Matrix

**Center-of-Rotation Error**

**COR Acquisition is a Calibration**

- Used to correct patient images
- Extrinsic calibration for both 180 and 90 degree detector separations
- Must follow manufacturer recommendations regarding number and placement of sources
- Sources must have sufficient activity
- Completed monthly

**Center-of-Rotation Artifact**
Center-of-Rotation Offset Error

9 mm error

3 mm error

0 mm error

Center-of-rotation errors cause loss in transaxial image resolution.

Mis-alignment in Dual Detector SPECT

Top detector mis-aligned with bottom detector, leading to distortion in reconstructed images. Misa-alignment due to either error in COR or detector configuration.

Jaszczak SPECT Phantom

Standard:
- Cold Rods – 16.0, 12.7, 11.1, 9.5, 7.9, 6.4 mm
- Cold Spheres – 38.0, 31.8, 25.4, 19.1, 15.9, 12.7 mm

Deluxe:
- Cold Rods – 12.7, 11.1, 9.5, 7.9, 6.4, 4.8 mm
- Cold Spheres – 31.8, 25.4, 19.1, 15.9, 12.7, 9.5 mm

SPECT Phantom Study

- Quarterly acquire SPECT phantom studies with 2-3 time counts obtained clinically.
- Reconstruct at highest resolution filter.
- Look for bulls-eye artifacts. If present, new intrinsic correction flood needed.
- Look for consistent transaxial resolution. If resolution loss, acquire new COR.

ACR SPECT Phantom Submission

- Phantom images scored by Nuclear Medicine physicists for planar & SPECT uniformity, resolution, and contrast.

Planar Image

Uniformity (3 slices)

Resolution (12 slices)

Contrast (2 slices)

Transaxial SPECT Images

Conclusions

- Standard QC procedures for gamma cameras required in accreditation programs.
- SPECT uniformity corrections and COR are camera calibrations
- SPECT demands strict QC program