Advances and Quality Assurance in Gamma Camera & SPECT Systems

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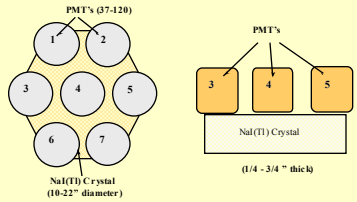
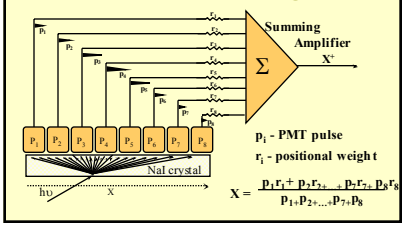
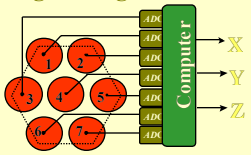
"Anger-Type" Gamma Camera



Localization - Position Weighed Sum

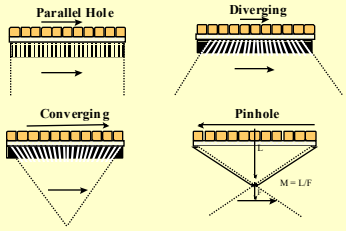


Digital Anger Camera



Signals from each PMT is digitized and X, Y, and Z are determined by computer software.

Gamma Camera Collimators

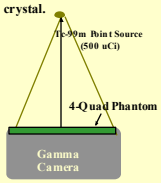


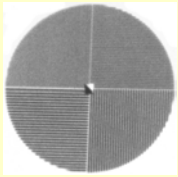
Gamma Camera Performance & Quality Control

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

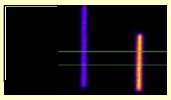
Measure Intrinsic Spatial Resolution

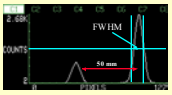
4-Quadrant bar phantom replaces the collimator – The recorded image is the shadow of the lead bars on the crystal.





FWHM of Line Spread Function





- Image two 1 mm slits in a lead sheet placed on top of the crystal. The slits are separated by a distance of 50 mm.
- The line spread function (LSF) is formed by plotting the count density across a slit.
- Resolution is the full-width-at-half-maximum (FWHM) of the LSF.
- FWHM of the LSF is approximately 0.9 times the resolution measured in mm/lp.

Resolution Vs. NaI(Tl) Crystal Thickness

Crystal Thickness (inches)	FWHM (mm)	Photopeak Efficiency 140 keV	Photopeak Efficiency 511 keV
1/4	3.0	0.70	-
3/8	3.5	0.80	0.055
1/2	3.7	0.85	0.07
5/8	3.9	0.90	0.09
3/4	4.4	0.96	0.10
1.0	4.5	0.99	0.30

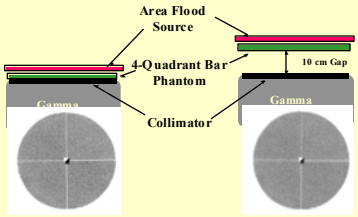
Resolution vs. Number of PMT's

- **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)

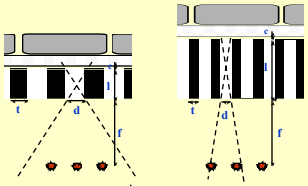
Resolution vs. Photon Energy

- **Intrinsic resolution is better for high energy photons.**

Measure Extrinsic Resolution



Geometric Collimator Resolution



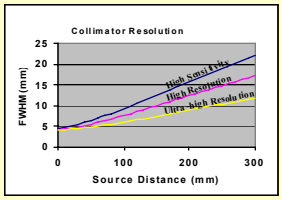
$FWHM_g \sim \alpha\,(l+f+c)$, where $\alpha = \frac{d}{l}$

Extrinsic Resolution

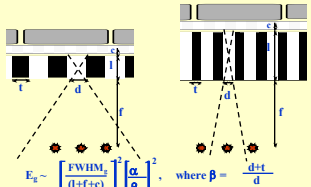
Extrinsic resolution is the quadrature sum of the geometric resolution of the collimator and the intrinsic resolution of the detector.

$$FWHM_E = \sqrt{(\text{Collimator FWHM})^2 + (\text{Detector FWHM})^2}$$

Extrinsic Resolution Vs. Distance



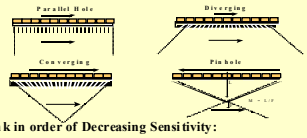
Geometric Collimator Efficiency



$E_g \sim \left[\frac{FWHM_g}{(l+f+c)}\right]^2 \left[\frac{\alpha}{\beta}\right]^2$, where $\beta = \frac{d+t}{d}$

$E_g \sim \alpha^2 \left[\frac{\alpha}{\beta}\right]^2$, where $FWHM_g \sim \alpha\,(l+f+c)$

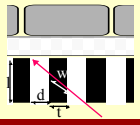
Collimator Sensitivity



Rank in order of Decreasing Sensitivity:

Collimator	Sensitivity (CPM/μCi)	% Efficiency
1. Converging	450	0.020
2. Parallel Hole	300	0.014
3. Diverging	150	0.007
4. Pinhole	75	0.004

Septal Thickness



W is the minimum path length for a γ-ray to be stopped for hole length l, hole diameter d, and septal thickness t.

For less than 5% transmission:

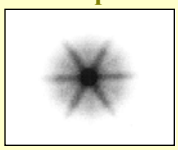
$$t \geq \frac{6d/\mu}{1-(3/\mu)}$$

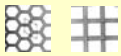
where μ is the linear attenuation coefficient of the absorber, usually lead. Could use higher Z and density tungsten, tantalum, or gold that have higher μ and hence thinner septal thickness offering improved resolution and sensitivity.

Energy Rating of Available Collimators

Collimator Type	Max. Energy Rating (keV)	Septal Thickness (mm)	Isotopes
Low Energy	140 - 200	0.2 - 0.3	^{99m}Tc, ^{201}Tl, ^{133}Xe, ^{125}I
Medium Energy	300	1.1 - 1.4	^{67}Ga, ^{111}In, ^{123}I
High Energy	360 - 500	1.3 - 3.0	^{131}I
Ultra-High Energy	511	3.0 - 4.0	Positron Emitters

Septal Penetration





Collimator Holes Shapes

- Image Resulted from imaging a ^{131}I point source using a LEHR collimator.
- Penetration artifacts appear along directions of septa that is thinnest.
- The LEHR collimator has hexagonal holes

Resolution of Available Collimators

Collimator Type	Hole Diameter (mm)	Hole Length (mm)	FWHM at 0 cm (mm)**	FWHM at 10 cm (mm)**	FWHM at 20 cm (mm)**	Sensitivity (CPM/µCi)
Low Energy All Purpose	1.43	23.6	4.4	9.1	15.3	360 (^{99m}Tc)
Low Energy High Resolution	1.11	23.6	4.2	7.5	12.3	230 (^{99m}Tc)
Low Energy Ultra-High Resolution	1.08	35.6	4.2	5.9	8.6	100 (^{99m}Tc)
Medium Energy	3.02	40.6	5.6	12.1	19.7	288 (^{67}Ga)
High Energy	4.32	62.8	6.6	13.8	22.0	176 (^{131}I)
Ultra-High Energy	3.4	75.0	6.0	10.4	~20.0	60 (^{18}F)

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

Measure Linearity

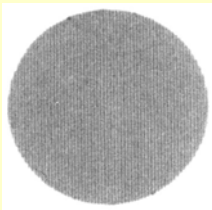
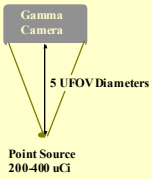
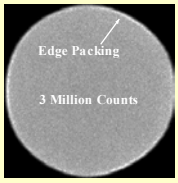


Image of PLES Phantom

Deviation from straight line of less than 0.5 mm for CFOV and 0.9 mm for UFOV

Measuring Intrinsic Uniformity

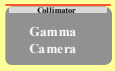


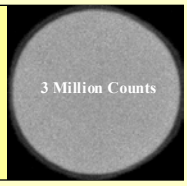


Flood Image
~ 1000 cts/cm^2 (±3% s.d.)

Measuring Extrinsic Uniformity

Disk Source
5-10 mCi of
^{57}Co or
^{99m}Tc





Quantitate Uniformity

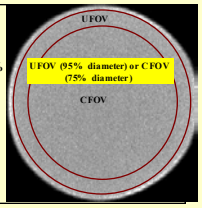
Integral Uniformity (IU)
Expect 2-3%

$$\frac{\text{Max. Pixel} - \text{Min. Pixel}}{\text{Max. Pixel} + \text{Min. Pixel}} \times 100\%$$

(4000 cts/cm^2 with 9-pt. Smoothing)

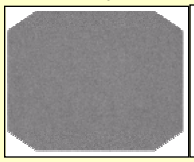
Differential Uniformity (DU) measures maximum uniformity change in FOV

Expect 1.5-2%

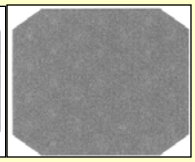


Energy Dependence of Uniformity

^{99m}Tc

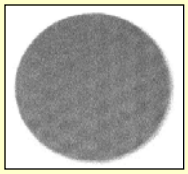


^{201}Tl

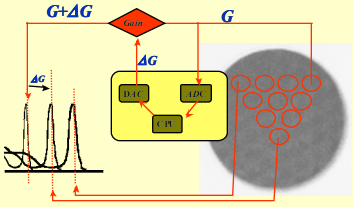


Non-Uniformity from Off-Peak Energy Window

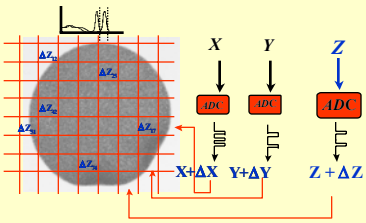
^{57}Co (122 keV) sheet source imaged with ^{99m}Tc (140 keV) photopeak window



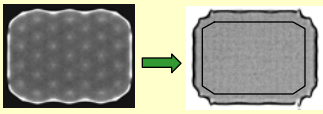
Automatic PMT Gain Control



Energy & Linearity Corrections



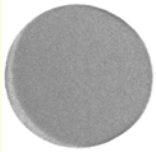
Computer Applied Corrections



- Digital corrections applied:
  - PMT Gain
  - Energy
  - Linearity
- Remaining non-uniformity removed by uniformity correction matrix

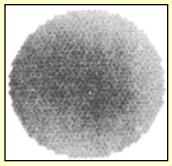
Non-uniformity From Shading by a Secondary Source

A second ^{99m}Tc source in the room or in the hot lab next door.

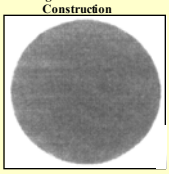


Collimator Structure Artifacts

Large Diameter Holes

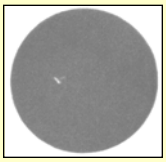


Irregular Lead Foil Construction

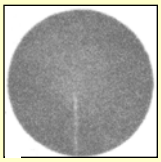


Collimator Damage

Crushed Lead Septa



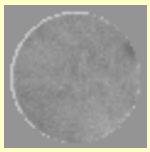
Lead Foil Separation



Uniformity Correction

High Count Flood Image

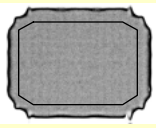
Flood Correction Matrix



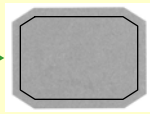
May be done intrinsically or extrinsically.

Intrinsic Uniformity Correction

IU = 4.2%



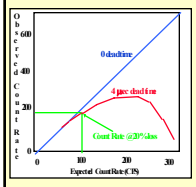
IU = 2.5%



- Scatter free point source for intrinsic flood
- 100+ million counts
- Energy dependent - new flood for each radioisotope

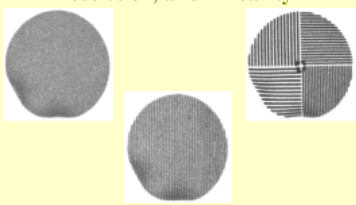
Uniformity Correction Masks Underlying Non-Uniformities!

Gamma Camera Dead Time Count Rate Capability

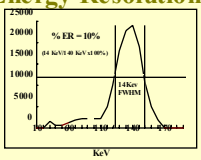


- The maximum achievable count rate is specified.
- Dead time measured with decaying source, attenuating plates, or by two-source method (AAPM Report No.9 p. 9-14).
- The observed count rate at 20% loss in sensitivity is specified.
- Patient count rates range from 1-10 KCPS.

Inter-Relationship of Uniformity, Resolution, and Linearity



Energy Resolution



- Energy resolution for ^{99m}Tc is 10% of the 140 keV photopeak. Acquisition window 20%.
- Energy resolution for ^{201}Tl it is greater than ~15% of the 70 keV photopeak. Acquisition window 30%.

Multiple Window Registration

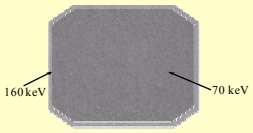
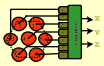


Image size may differ for differing photon energies. Flood images for two energies differ in size.

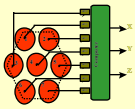
Digital Gamma Camera Improved Resolution



4 mm → 3 mm FWHM
(3/8" crystal, 3" PMT's)

4.5 mm → 3.5 mm FWHM
(5/8" crystal, 3" PMT's)

Digital Gamma Camera Improved Performance



Integral Uniformity UFOV:
4% → 3%

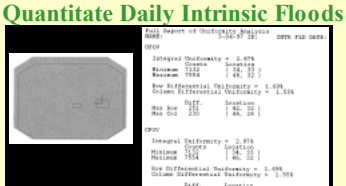
Energy Resolution:
10% → 9%

Absolute Linearity UFOV:
1.0 → 0.5 mm

Quality Control

- Uniformity - Each day of use, before imaging begins. Intrinsic flood image is preferred. Extrinsic of heavily used collimators as well. Flood images of 3-15 million counts.
- Resolution - Once per week with four-quadrant bar pattern (monthly for digital cameras, ACR weekly). Intrinsic resolution image is preferred. Images of 3-5 million counts
- Linearity - Once per week with PLES bar or orthogonal hole pattern (monthly for digital cameras, ACR weekly). Intrinsic resolution image is preferred. Images of 3-5 million counts.

Quantitate Daily Intrinsic Floods



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

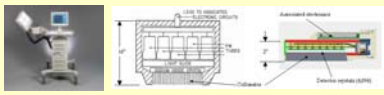
Daily ADAC FORTE 2

Date	Detector	Bkg count	Energy Peak	IU UFOV	IU CFOV	Coll check	Tech. CTS/SEC
2/3/03	1/2	3/8	140/139	2.74/2.79	2.74/2.44	✓	JK 44
2/4/03	1/2	3/5	140/139	2.49/2.52	2.49/2.50	✓	TC 48
2/5/03	1/2	4/7	140/139	2.95/2.96	2.95/2.86	✓	JK 50
2/6/03	1/2	4/7	140/139	2.35/2.17	2.35/2.40	✓	JK 50
2/7/03	1/2	4/6	140/139	3.28/3.57	3.28/3.21	✓	JK 50
2/7/03	redo			3.01/3.51	3.01/3.17		
2/10/03	1/2	5/8	140/139	2.97/2.83	2.97/2.14	✓	JK 50
2/11/03	1/2	3/5	140/139	1.52/1.57	1.52/1.5	✓	JK
2/12/03	1/2	4/7	140/139	1.52/1.77	1.52/1.66	✓	JK 51
2/13/03	1/2	4/5	139/139	2.73/3.06	2.73/2.01	✓	JK 47
2/14/03	1/2	4/5	139/139	2.79/3.30	2.79/2.96	✓	JK 50
2/17	1/2	6/9	139/140	2.74/2.41	2.74/2.10	✓	JK 49
2/18	1/2	5/5	139/139	2.19/2.36	2.19/2.02	✓	TC 48

Annual Measurements

- Energy resolution
- Multiple-window registration
- Count rate capability – peak count rate and dead time
- Sensitivity – counts/minute/uCi for a given collimator

Digirad Solid-State Imaging Detector



- 4096 3 mm^2 CsI(Tl) crystals and Si Photodiodes
- 3.1 mm intrinsic resolution
- 21 x 21 cm crystal area
- 15% energy resolution for Tc-99m
- Sensitivity greater than NaI(Tl) Anger camera

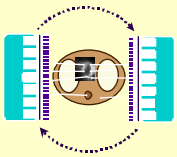
Gamma Medica MobileCAM

- 3136 2 mm^2 x 6 mm thick NaI(Tl) crystals with position sensitive PMT
- 2.0 mm intrinsic resolution
- 12.7 x 12.7 cm crystal area

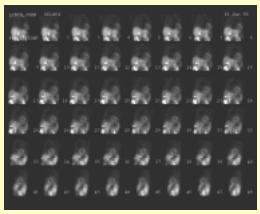
Gamma Medica LumGEM Breast Imager

- 5120 pixels (2.5 x 2.5 x 5 mm^3) Cadmium Zinc Telluride (CZT) solid-state detector array
- 2.5 mm intrinsic resolution
- 16 x 20 cm crystal area
- 6% energy resolution for Tc-99m

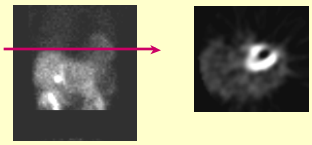
Rotating Gamma Camera SPECT



Projection Images of ^{99m}Tc-Sestamibi

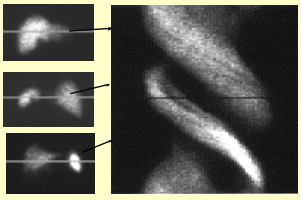


Transaxial Slices



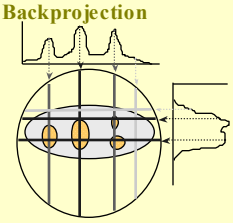
Each line across the image corresponds to one transaxial slice in the tomographic volume.

Sinogram from Projection Images of the Liver

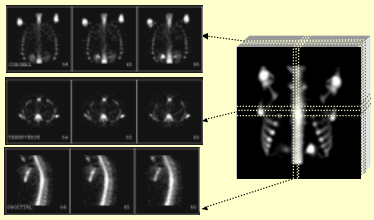


Tomographic Image Reconstruction by Backprojection

Counts in count density profiles at every camera angle are projected uniformly back into the patient volume along projection rays from whence they came.



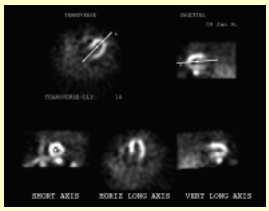
3-D Reconstruction



Myocardial SPECT

- Heart lies obliquely in the chest.
- Reconstruct tomographic image slices parallel and perpendicular to the long axis of the ventricles.

Oblique Cardiac Reconstruction



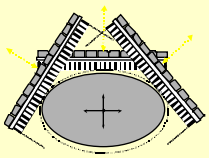
SPECT Resolution Based on Collimator (at 20 cm radius of rotation)

Collimator Type	Hole Diameter (mm)	Hole Length (mm)	FWHM at 0 cm (mm)**	FWHM at 10 cm (mm)**	FWHM at 20 cm (mm)**	Sensitivity (CPM/µCi)
Low Energy All Purpose	1.43	23.6	4.4	9.1	15.3	360 (^{99m}Tc)
Low Energy High Resolution	1.11	23.6	4.2	7.5	12.3	230 (^{99m}Tc)
Low Energy Ultra-High Resolution	1.08	35.6	4.2	5.9	8.6	100 (^{99m}Tc)
Medium Energy	3.02	40.6	5.6	12.1	19.7	288 (^{67}Ga)
High Energy	4.32	62.8	6.6	13.8	22.0	176 (^{131}I)
Ultra-High Energy	3.4	75.0	6.0	10.4	~20.0	60 (^{18}F)

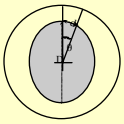
** Siemens Orbiter Gamma Camera System with intrinsic resolution of 3.9 mm FWHM

Non-Circular Motion SPECT

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



How Many Images to Acquire?



- Typically camera detectors rotate through 360 degrees.
- Stepping angle (θ) = 360 deg. / # stops
- Sampling distance (d) at the organ edge = θD/2
- For good resolution d must be small which implies small q and a large number of stops.

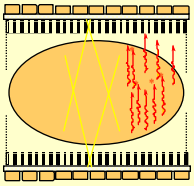
Low Resolution SPECT - 60 images at 6 degree steps

High Resolution SPECT - 120 images at 3 degree steps

360 vs. 180 Degree Acquisition Arc

- 360 degree acquisition arc balances resolution losses with depth.

360 degree acquisition arc balances photon attenuation losses.

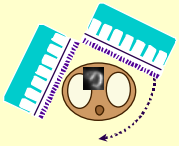


180 Degree Acquisition Arc for Heart

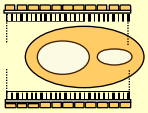
Heart sits anterior in the chest.

Heart not visible in posterior projections.

Dual detectors set at 90 degree angle most efficient.



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

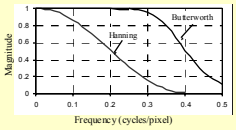
How Many Counts in a SPECT Study?

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 Smoothing Filters



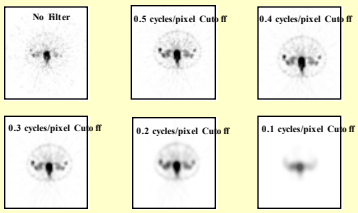
Butterworth Filter

$$B(f) = \frac{1}{1 + (f/f_{cutoff})^{order}}$$

Hanning Filter

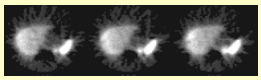
$$H(f) = \tfrac{1}{2}[1 + \cos(\pi f/f_{cutoff})]$$

Smoothing Filters -Butterworth Filter

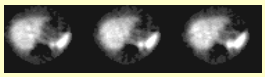


Attenuation in the abdomen

No Attenuation Correction



With Attenuation Correction

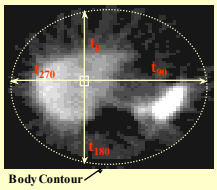


Chang Attenuation Correction Method

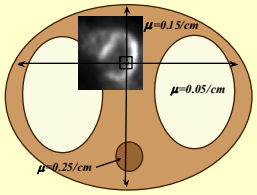
$$C = C_0 e^{-\mu t}$$

μ - linear attenuation coefficient in tissue. Assume uniform tissue density *(for 140 keV, μ=0.15/cm)*

t - depth in mm

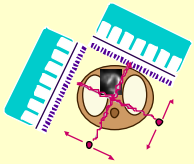


Attenuation Correction in the Thorax



Chang attenuation correction method invalid in the thorax due to the varying tissue densities .

Measured Attenuation Correction

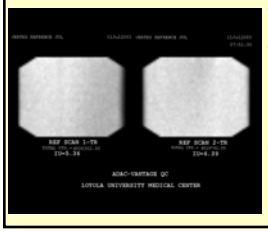


- Perform transmission imaging just like X-ray CT
- Line source of ^{153}Gd ($T_{1/2}$ *242 days, photon energies of 97 & 104 keV*) scans across the camera FOV at every camera stop, or multiple parallel line sources across field-of-view.
- Dual Isotope windows allows for simultaneous emission and transmission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

Measured Linear Attenuation Map

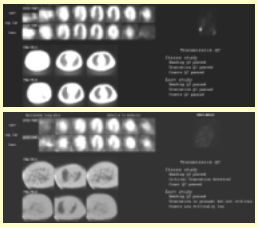
- Measured linear attenuation coefficients used instead of uniform coefficients in Chang attenuation correction method.
- Attenuation map is segmented to fixed attenuation coefficients for soft tissue to reduce noise.

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.

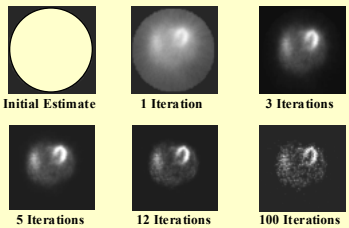
Transmission Scan Patient QC



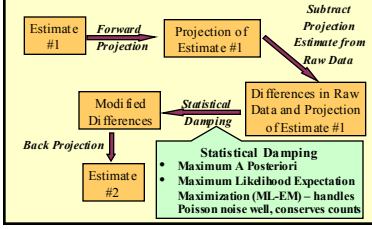
Look for:

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

Iterative Reconstruction



Method of Iterative Reconstruction

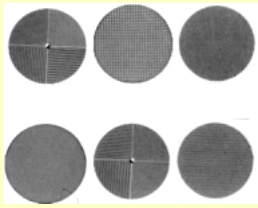


OSEM – Accelerated EM

- Acceleration of EM using ordered subsets. As many as 8 subsets of the projection date are used.
- Iterative updates are made for each subset. One full iteration is complete after all 8 subsets have been completed.
- Corrections for attenuation, scatter, and resolution losses can be incorporated into the iterative reconstruction algorithms

SPECT Quality Control

SPECT demands that the gamma camera operate at optimum performance.



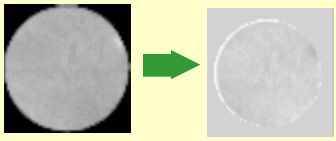
Bullseye Ring Artifact

Concentric rings of alternating high and low count densities appear in the transaxial images due to insufficient gamma camera uniformity.

Uniformity Correction By Computer

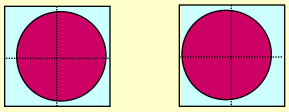
High Count Flood Image

Flood Correction Matrix



30-100 million count flood images, 10 times daily flood requirements

Center-of-Rotation

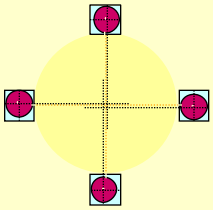


Anterior Image

Posterior Image

The gamma camera image must be centered in the computer image matrix, otherwise errors in backprojection occur.

Center-of-Rotation Error

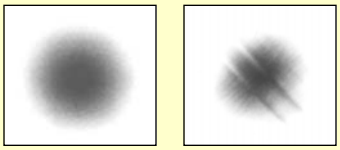


- COR error is propagated as offset during backprojection
- COR study acquired weekly, monthly, or bi-annually.

Collimator Hole Angulation

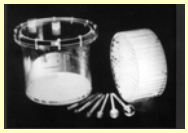
Holes Are Paralld

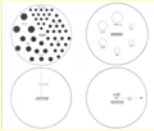
Non-Parallel Holes



Images obtained by imaging a point source at a distance of 10 feet.

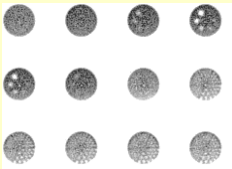
Monthly SPECT Phantom Imaging





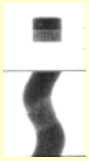
Cold Rods: 25, 19, 16, 13, 11, 10 mm
Cold Spheres: 38, 32, 25, 19,16,13 mm

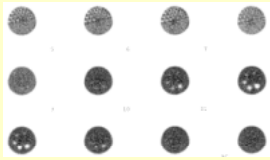
Monthly SPECT Phantom Images



- **Acquire SPECT phantom studies with 2-3 time counts obtained clinically.**
- **Reconstruct at highest resolution filter.**
- **Look for bullseye artifacts. If present, new intrinsic correction flood must be acquired.**
- **Look for consist transaxial resolution. If resolution loss, acquire new COR corrections.**

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.