Nuclear Medicine Physics and Testing

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Conflicts of Interest

- Nuclear Medicine and PET physics reviewer for the ACR Accreditation program

Learning Objectives

- Be familiar with the tests recommended for routine quality assurance, annual physics testing, and acceptance tests of gamma cameras for planar imaging.
- Be familiar with the tests recommended for routine quality assurance, annual physics testing, and acceptance tests of SPECT systems.
- Be familiar with the tests of a SPECT/CT system that include the CT images for SPECT reconstructions.
- Become knowledgeable of items to be included in annual acceptance testing reports including CT dosimetry and PACS monitor measurements.

Introduction

- This presentation is based on the recommendations of the TG177 Report – now in process of approval.
- Compiled by Nuclear Medicine experts including James R. Halama, Daryl Graham, Beth A. Harkness, S. Cheenu Kappadath, Mark T. Madsen, Richard J. Massoth, James A. Patton, Sharon L. White, Lawrence E. Williams, and Wesley W. Wooten.
- Specifies performance tests to be made on gamma cameras, SPECT and hybrid SPECT/CT systems for acceptance testing, annual physics surveys, and routine QA.
- A manual detailing the performance test procedures under widely varying conditions
- Primary reference is "*Performance measurements of gamma cameras: National Electrical Manufacturers Association (NEMA) Standards Publication, NU 1-2012*"

Preparatory Steps for Successful Testing

- Identify types of exams performed– planar, wholebody, SPECT, SPECT/CT
- Identify the radioisotopes used and corresponding collimators
- System calibrations
- Test equipment needed
- Locate manufacturer manuals

Radioisotopes to Test

- ^{99m}Tc
- ^{57}Co – needed for extrinsic tests
- At least one other radionuclide from the following: ^{201}Tl, ^{123}I, ^{67}Ga, ^{131}I, and ^{111}In. Choice depends on clinic use
- An additional radionuclide is not needed if only ^{99m}Tc is used

Detector & System Calibrations

- Completed prior to testing
- Uniformity for ^{99m}Tc and other radionuclides
  - Most new systems have uniformity calibration for ^{99m}Tc only. The calibration is used for all other energy windows selected
  - Uniformity calibration for ^{57}Co is not routinely performed
- Center-of-rotation and multi-head alignment for SPECT
- SPECT/CT alignment

Manufacturer Manuals

- Describe procedures for detector calibrations
- Provide performance specifications
- Describe QA procedures:
  - What calibrations are performed by the user and frequency
  - Routine tests and test frequency
  - All must be included and documented in camera QA protocol

Test materials and Equipment

- Sites should provide:
  - Radioisotopes to be used and dose calibrator (required)
  - Sheet source for extrinsic uniformity
  - Syringes and vials
  - Quadrant bar-phantom of appropriate dimensions
  - SPECT Phantom
- Physicist should provide:
  - Capillary tubes for line sources
  - Flask or dish to be used for sensitivity measurements
  - Attenuating Cu plates for count rate characteristic measurements

Gamma Camera Tests

- Physical Inspections
- Planar Imaging
- SPECT Imaging
- Hybrid SPECT/CT

Physical Inspection & Shielding

- Check condition of camera system
- Identify and note condition of collimators in clinical use
- Assess detector shielding *qualitatively*
  - Acceptance test - use 1 mCi ^{99m}Tc in syringe and move source slowly (top and sides) while observing count rate
  - Annual survey – visually examine for possible damage to shielding
- Assess adequate room and operator shielding at acceptance testing, particularly for SPECT/CT. Note assessment in report.

Monitors Used for Image Processing

- Test monitors in the camera room that a technologist uses to review and process images – measured annually
- Display SMPTE or TG18QC testing pattern using processing software or through the operating system
  - Identify the 5% and 95% luminance patches
  - Measure maximum and minimum luminance's
  - Measure luminance uniformity
  - Note spatial resolution and linearity with bar pattern patches

Monitors Used for Image Interpretation

- Evaluate monitors located in the "vicinity" of the gamma camera; evaluated annually
- May be evaluated by another physicist or other service. Note date of evaluation and test results
- Display requirements of monitors for NM not published. TG177 report recommens maximum luminance > 120 cd/m^2, minimum < 2 cd/m^2, and non-uniformity <20%

Gamma Camera Planar Tests

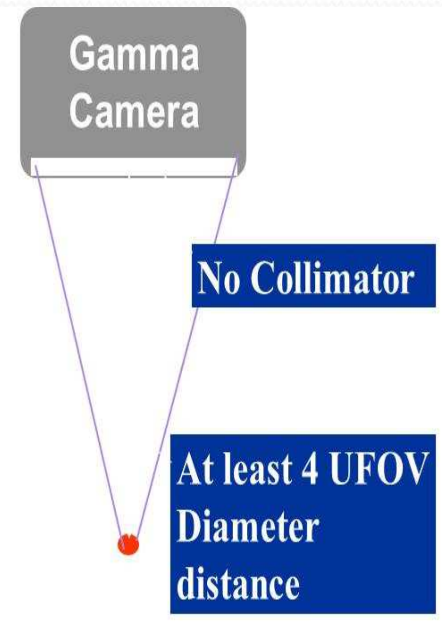
- Uniformity, spatial resolution & linearity, energy resolution, sensitivity, count rate characteristic, multiple-window spatial registration, wholebody
- Acceptance and annual physics surveys
- Details the performance test procedures under widely varying conditions.
- Refer to **IAEA Quality Control Atlas** for Scintillation Camera Systems International Atomic for example test images

Intrinsic Flood-Field Uniformity

- Measurement of each detector uniformity without collimator and point source
- UFOV mask may be absent so long as performance criteria are met
- Assess visually and quantitatively using NEMA IU & DU definitions
- Acceptance testing – ^{99m}Tc and at least one other radionuclide, unless ^{99m}Tc is only used isotope
- Annual survey – ^{99m} Tc and optionally one other radionuclide

Measurement Notes:

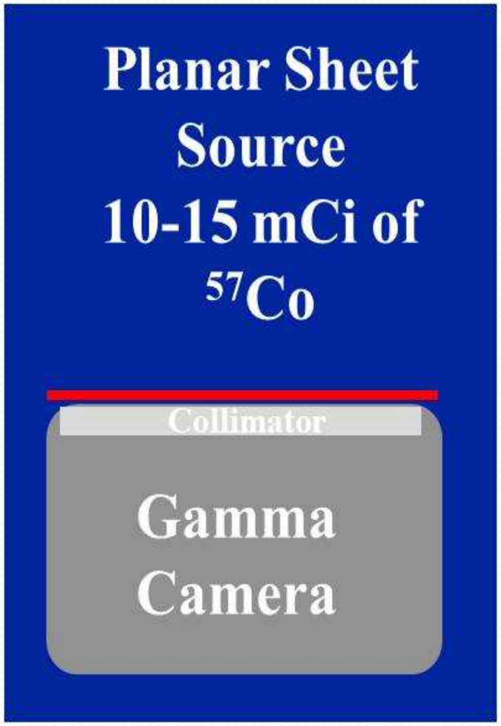
- Point source of spherical volume < 0.3 ml
- Position directly over detector at a distance of at least 4*UFOV. Shorter distance may need additional software correction
- Adjust activity to achieve 20-40 Kcps
- How many counts?
  - Depends on detector size and scales by area
  - 30 million for large FOV detectors
  - 10 million if uniformity criteria can be met



Note: count rate at edge is < 2% lower than center at 4 UFOV

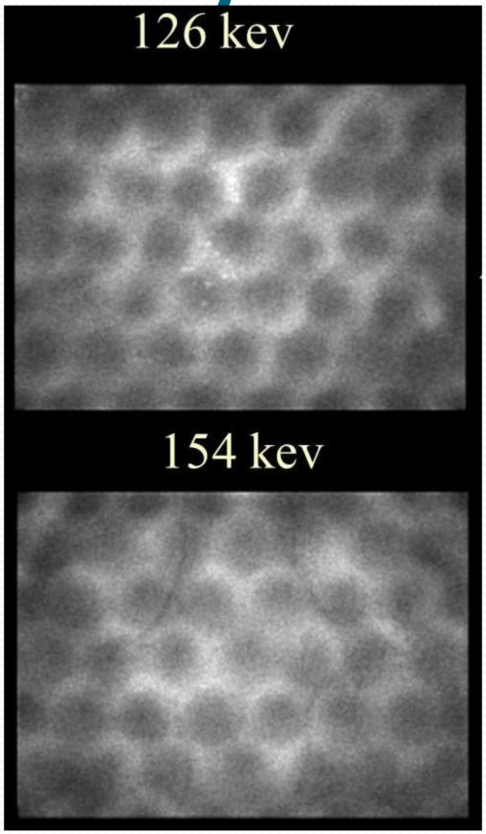
Extrinsic Flood-Field Uniformity

- Check uniformity for collimators used clinically
- Both acceptance and annual survey
- ^{57}Co sheet source is preferred with activity level for < 40 Kcps
- How many counts? Scales with size. For large FOV, acquire at least 10 million counts
- Quantitative analysis is optional



Intrinsic Off-Peak Uniformity

- Tests for crystal hydration & other detector problems
- Both acceptance and annual surveys
- Use ^{99m}Tc point source and acquire flood images 126 & 154 keV and energy window 20%
- Visually evaluate images:
  - Multiple hot spots indicate crystal hydration
  - Atypical PMT pattern is due to possible PMT decoupling or other calibration deficiency

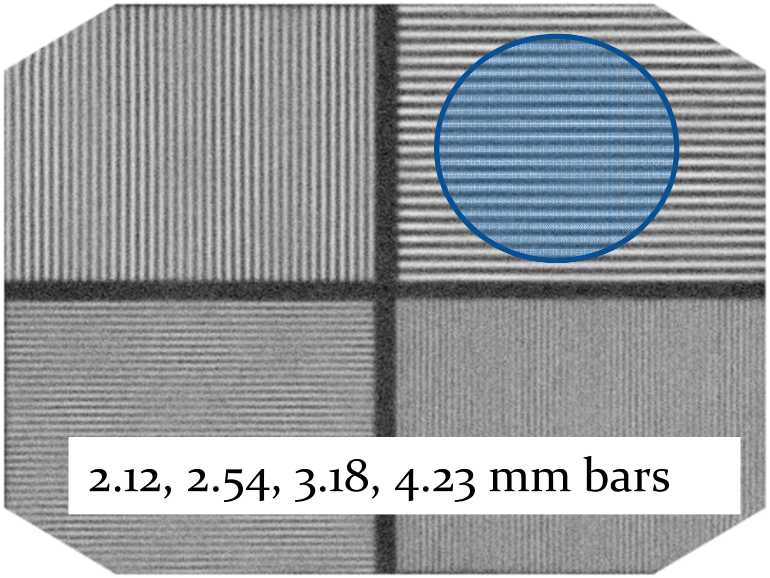


Intrinsic Spatial Resolution & Linearity

- Acceptance tests –quadrant bar phantom for ^{99m}Tc; NEMA slit phantom is optional
- Annual survey – quadrant bar phantom for ^{99m}Tc
- Quantify FWHM using Hander method on bar phantom images
- Slits & bars used to evaluate linearity. Visually analyzed

Hander Method

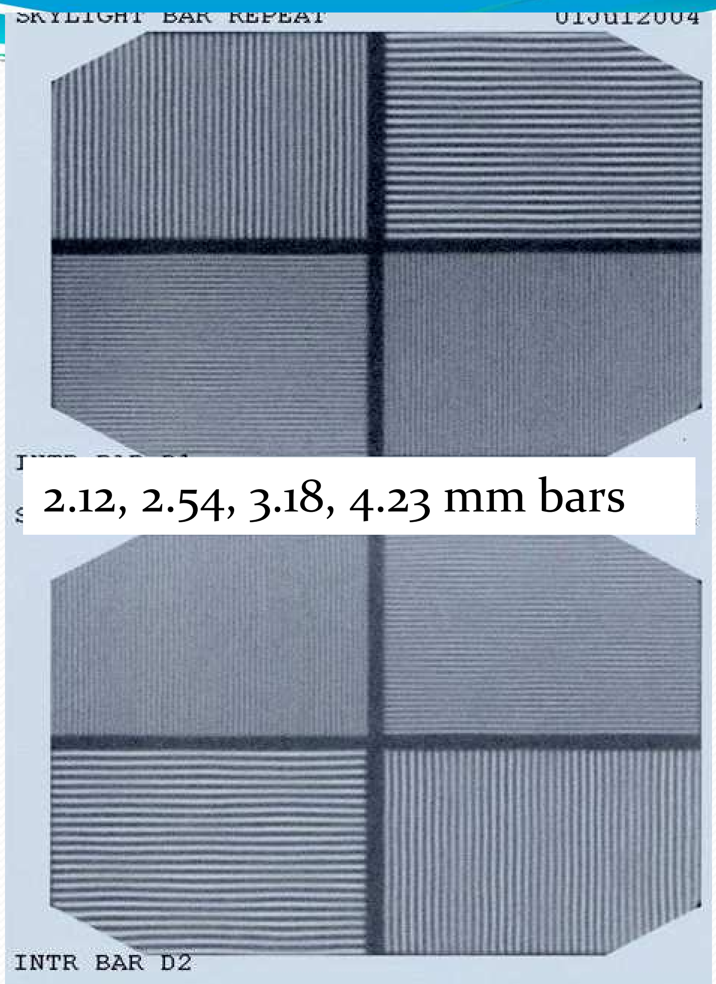
- The FWHM is calculated as follows:
  - $MTF = [2(\sigma_{ROI}^2 - \mu_{ROI} - \sigma_{nu}^2)]^{1/2} / \mu_{ROI}$
  - $FWHM = 1.058 w_{ROI} [\ln(1/MTF)]^{1/2}$
  - σ_{ROI} & μ_{ROI} from circular ROI, w_{ROI} is bar size, σ_{nu} and is for flood image non-uniformity (assume zero)



Choose quadrant with bars just < expected FWHM

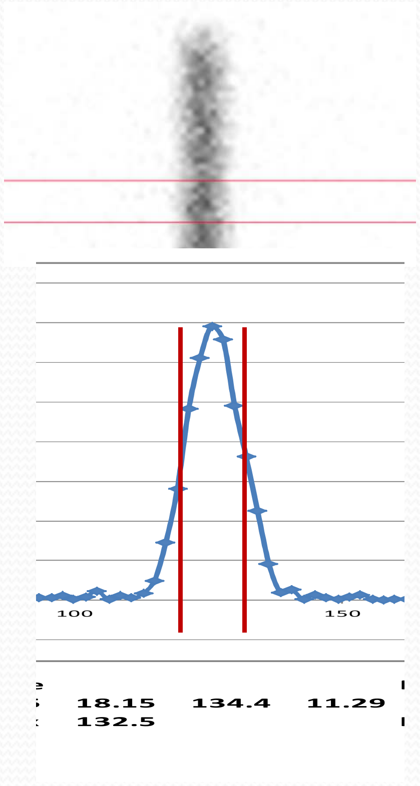
Linearity Evaluation

- Visually inspect quadrant bar phantom for non-linearities
- The results may be reported as:
  - no observable non-linearity
  - just noticeable and may be less than 1 mm
  - significant (fail) and may be greater than 1 mm.



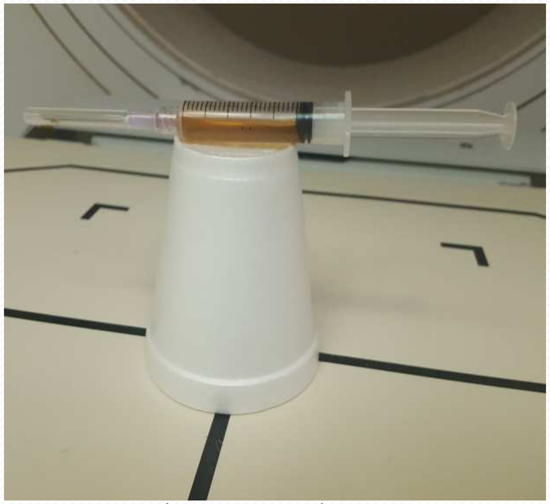
Extrinsic Spatial Resolution

- Measures system spatial resolution with an installed clinical collimator
- Acceptance test:
  - measure FWHM for ^{99m}Tc with a line source at a distance of 10 cm, and
  - ^{57}Co flood source and quadrant bar phantom with one low energy collimator
- Annual survey - with ^{57}Co flood source and quadrant bar phantom with collimator used at acceptance testing



Extrinsic Planar Sensitivity

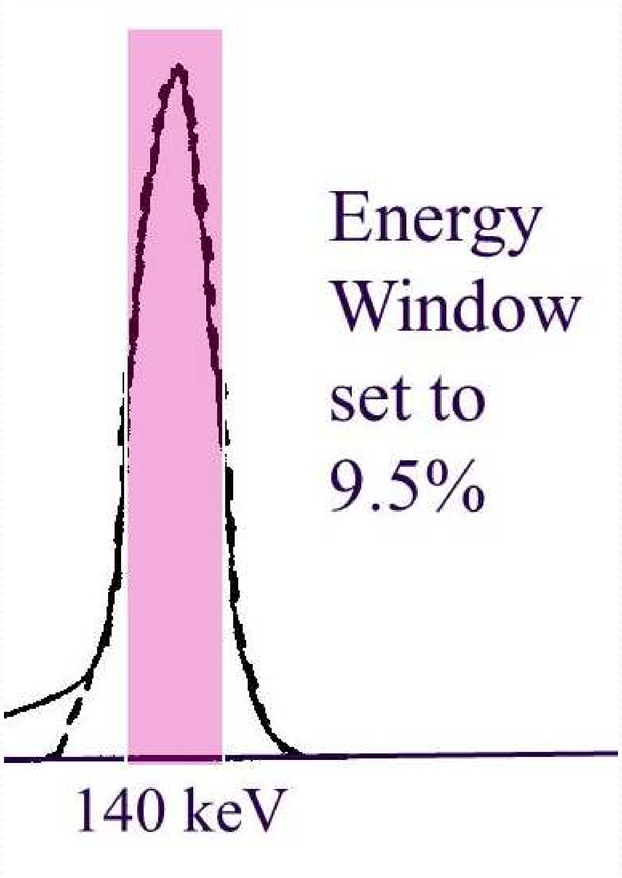
- Detector sensitivity measured in CPM/uCi. Multiple detectors to be within 5% differences
- Measured for ^{99m}Tc and one low energy collimator for both acceptance test and annual survey
- The sensitivity source configuration may be a Petri dish, culture flask, or syringe with a source/liquid thickness less than 3 mm



- 3 ml in 5 ml syringe
- Decay correct to 1 min.

Energy Resolution

- Measured for ^{99m}Tc only
- Acceptance testing
  - quantitatively measured with a stored energy spectrum
  - measure keV/channel by measuring distance between ^{99m}Tc and one other radionuclide peak (^{57}Co)
- Annual survey – may quantitative measurement or by visual inspection of photopeak width at half-max

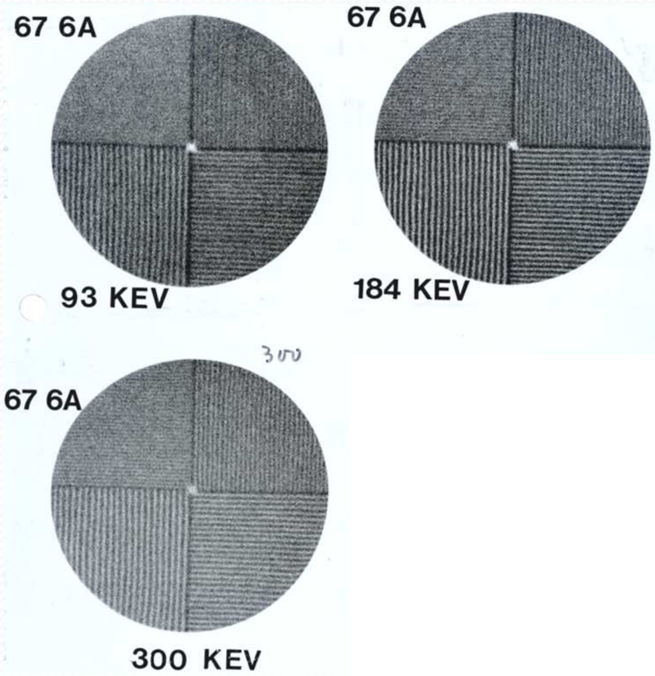


Count Rate Performance

- Measure intrinsically with ^{99m}Tc
- Acceptance testing:
  - Measure maximum peak count rate
  - Optionally measure full count rate characteristic using either decay method, or attenuating Cu plates
  - Or optimally use two-source method to measure dead-time
- Annual survey:
  - Measure maximum peak count rate (in air with point source in syringe)
  - Optionally measure dead-time with two-source method

Multiple-Energy Window Spatial Registration

- Optional for cameras that use have digital signal processing
- Should be tested for non-digital signal processing systems
- Isotopes that may be used are ^{201}Tl, ^{67}Ga or ^{111}In



Measure and compare distances between bars at each energy

Whole-Body Scanning Systems

- Not all camera systems designed to perform whole-body scanning
- Optional –performed at acceptance testing
- Measure spatial resolution by scanning over a line-source of ^{99m}Tc
- Measure uniformity by scanning a ^{57}Co sheet source

SPECT

- Tomographic spatial resolution – measured from SPECT acquisition of a line source
- Image quality – test for artifacts, spatial resolution and contrast. Measured from SPECT acquisition of the Jaszczak phantom
- Center-of-rotation/multiple head registration (COR/MHR) calibration and QC - expected to be performed prior to testing.
- Tests performed for both acceptance testing and annual survey

Tomographic Spatial Resolution

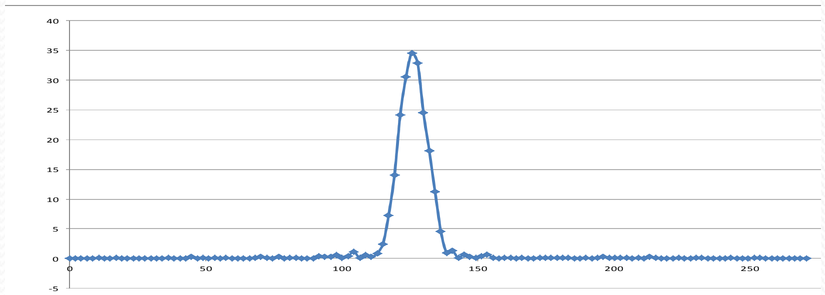
- Acquisition of ^{99m}Tc line source at a 20 cm AOR
- Measure FWHM of PSF from reconstructed slices with FBP in both axial and tangential directions
- Measure FWHM of LSF for planar acquisition of line source at 20 cm distance
- Compare tomographic and planar spatial resolution. Should be less than 10% difference

SPECT Spatial Resolution Measurement

- Fill 12 cm capillary tube with ^{99m}Tc ~ 2 mCi/ml
- Center the capillary tube parallel to and on the AOR, and set the radius-of-rotation to 20 cm
- Acquire 120-128 projection images with a high resolution matrix (128x128 with zoom 2)
- Reconstruct SPECT cross-sections using FBP
- Acquire planar stationary image of the capillary tube for each detector at 20 cm
- Draw line profiles across the SPECT and planar images, and measure the FWHM of the LSF across the images of the capillary tube

FWHM of LSF Measurements

Planar Image



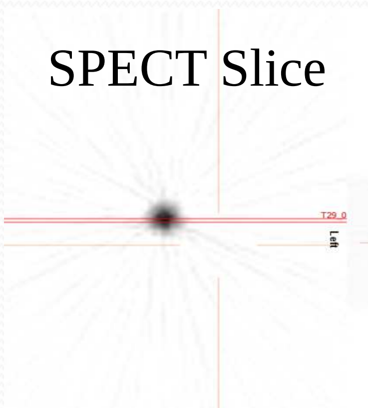
Low Side
119.45 14 121.6 24.15
Half Max 120.1

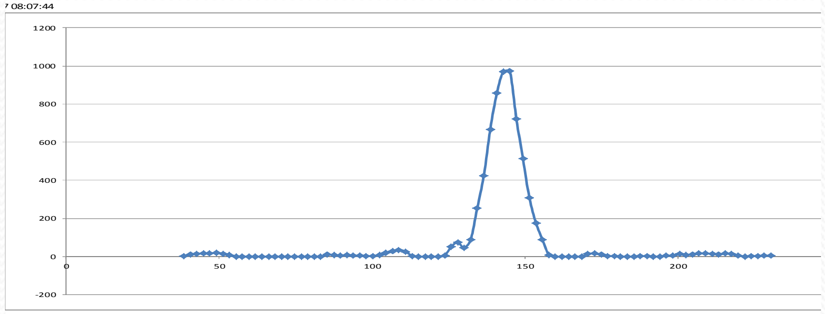
High Side
132.25 18.15 134.4 11.29
Half Max 132.5

Peak
125.85 34.57
Half Peak 17.29

FWHM 12.38 mm

SPECT Slice





Low Side
136.5 424 138.6 668
Half Max 137

High Side
149.3 514 151.4 308
Half Max 149.6

Peak
143 971
Half Peak 485.5

FWHM 12.56 mm

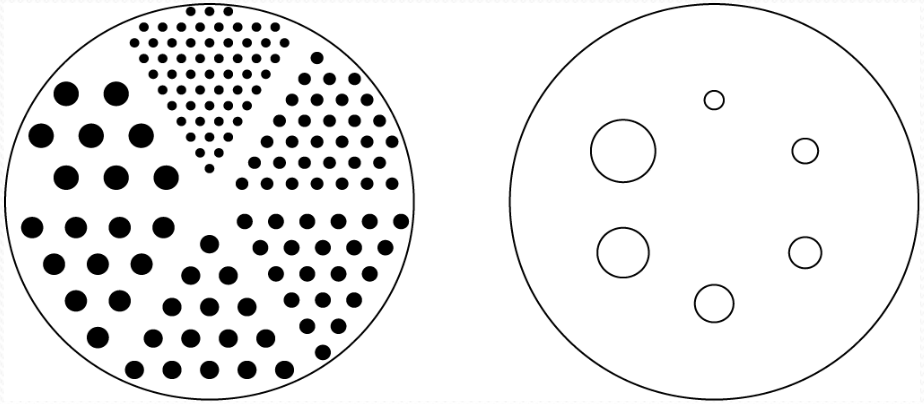
Planar FWHM: 12.4 mm

SPECT FWHM: 12.6 mm

SPECT Image Quality

- Use ACR Accreditation protocol for acquisition and reconstruction with Chang's method for attenuation correction of the Deluxe Model Jaszczak phantom
- Spatial resolution - smallest rod sector visualized – at least 11.1 mm rods should be seen
- Contrast detectability – identify the smallest sphere visualized, at least 15.9 mm sphere. Calculate the contrast of the largest sphere
- Uniformity – evaluate slices for artifact. Characterize concentric ring artifact magnitude whether $\geq$ noise

Jaszczak SPECT Phantom



Jaszczak Deluxe (Data Spectrum Corporation; SPECT.com):

- **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**

Small (Mini) for small FOV systems available

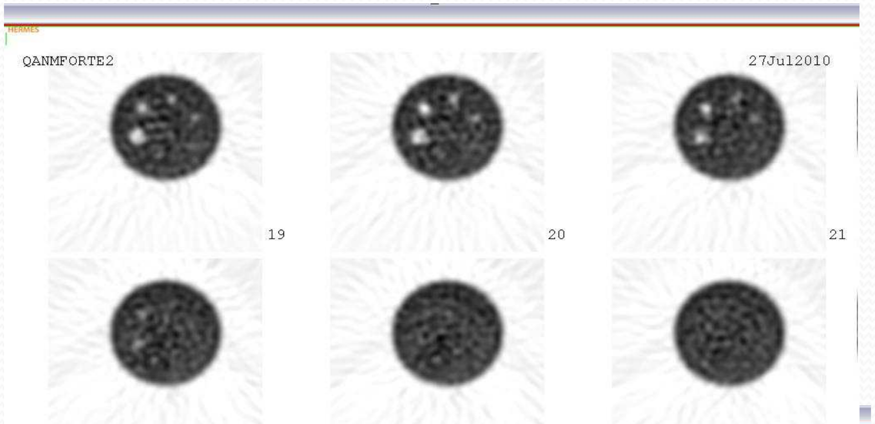
^{99m}Tc SPECT & LEHR Collimator

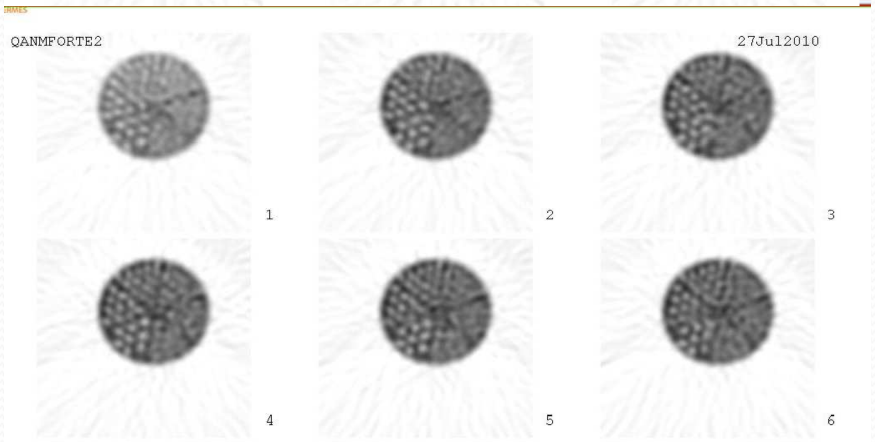
Jaszczak Deluxe Phantom

- Radius-of-Rotation 22 cm (less is better)
- Chang attenuation correction required with μ=0.12/cm
- 6 mm/slice

ACR Phantom Satisfactory Criteria:

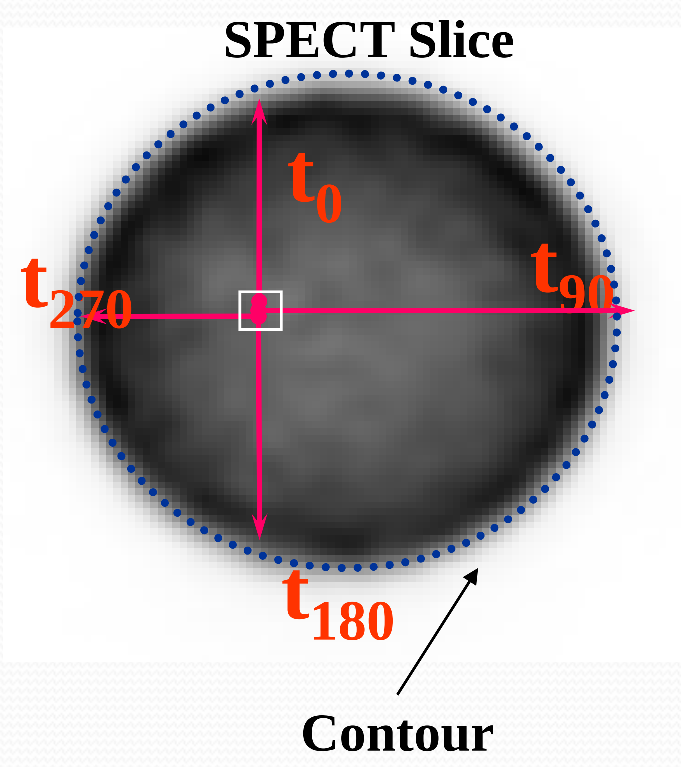
- 19.1 mm sphere observed with high contrast
- 11.1 mm rods visible



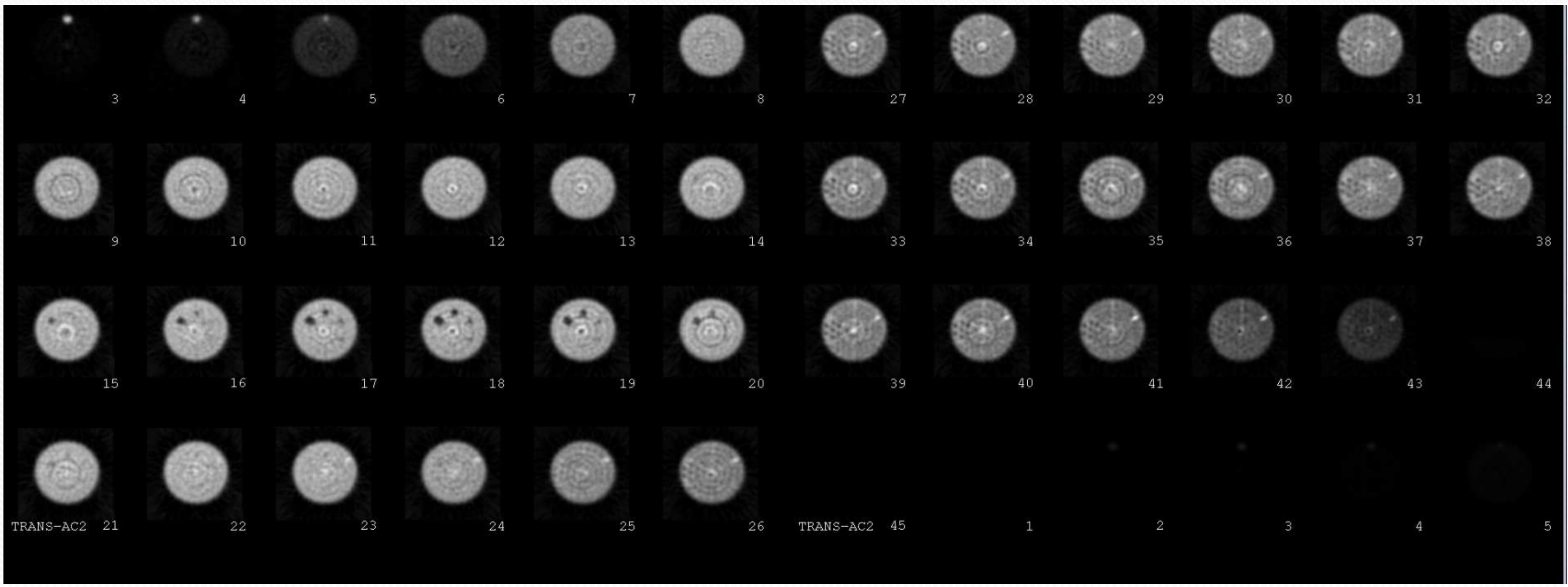


Chang Attenuation Correction Method

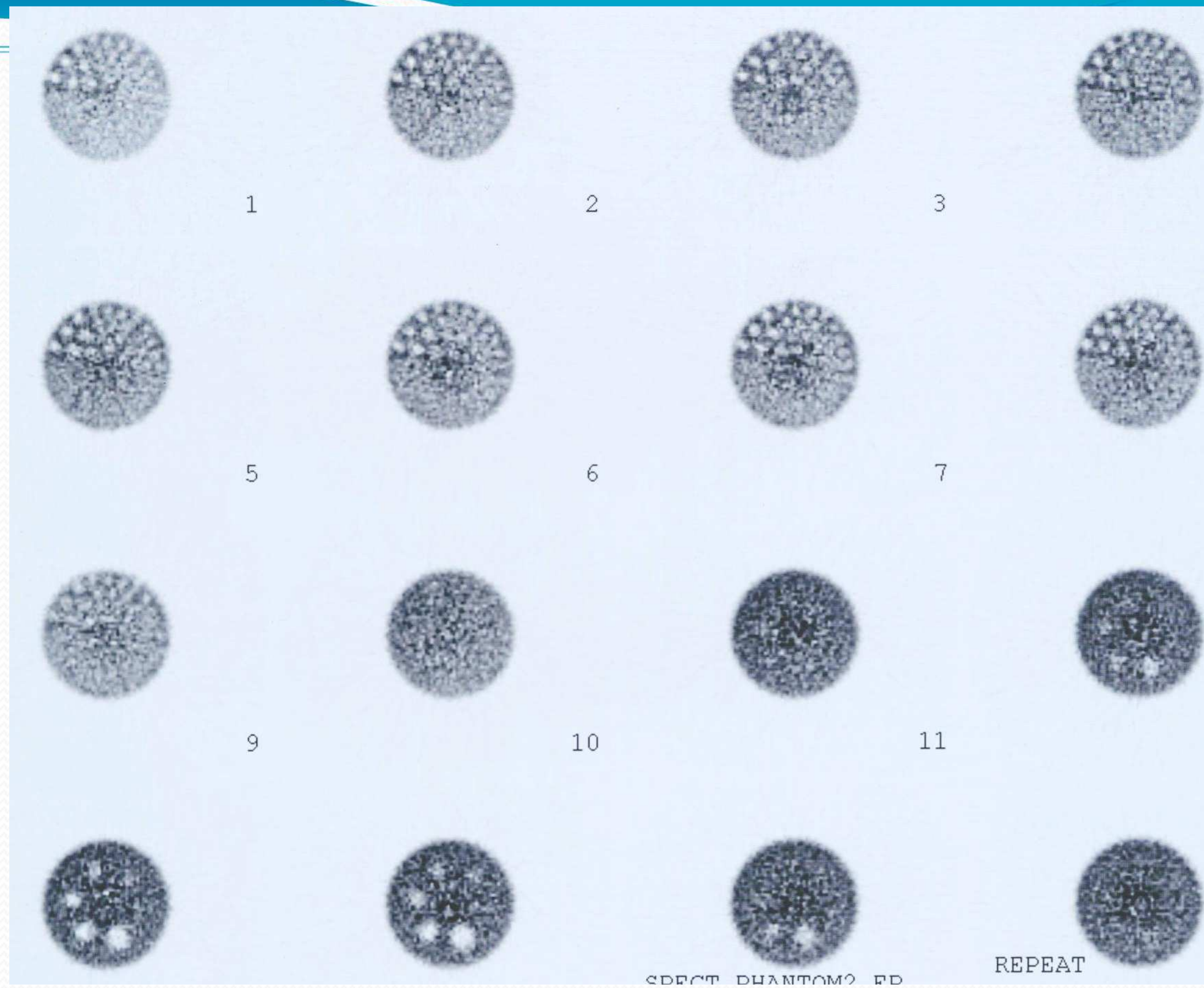
- Attenuation is calculated based on source depth and pre-assigned linear attenuation coefficient.
- Contour drawn to identify the external boundary of the object.
- Linear attenuation coefficient is for soft tissue and is assumed to be constant in the entire cross-section *(for 140 keV, μ=0.12/cm in presence of scatter)*
- Distance (t) is the average depth for all acquisition angles.
- Correction is applied to all reconstructed slices.



SPECT Phantom Uniformity – Significant Ring Artifact!



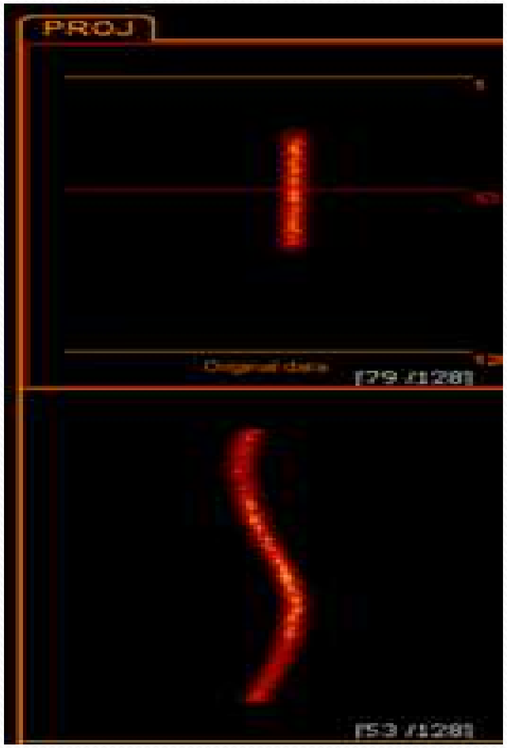
SPECT Phantom Marginal Ring Artifacts



Evaluation for COR/MHR Accuracy

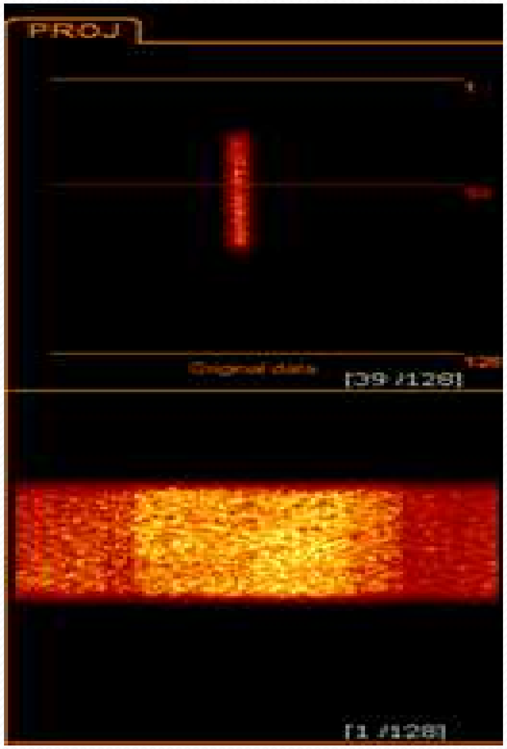
- Tomographic spatial resolution is within specification
- Sinogram and cyclogram of line source and phantom slices show no artifact

Evaluate Projection Images for COR and MHR Errors



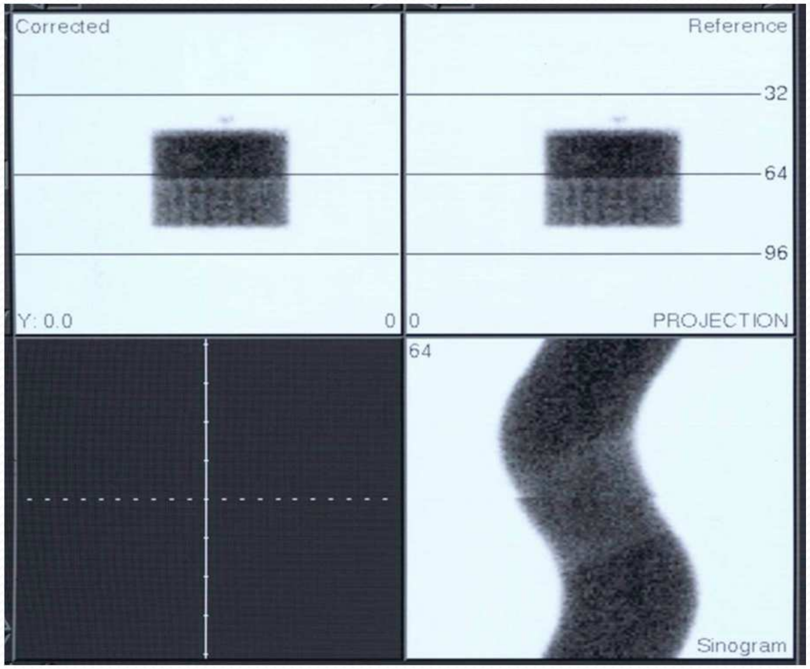
Left:
Sinogram of the line source projections. No discontinuity observed between the two detector heads.

Right: Linogram/Cyclogram of the line source projections. No discontinuity observed between the two detector heads.



MHR Mis-Alignment in X

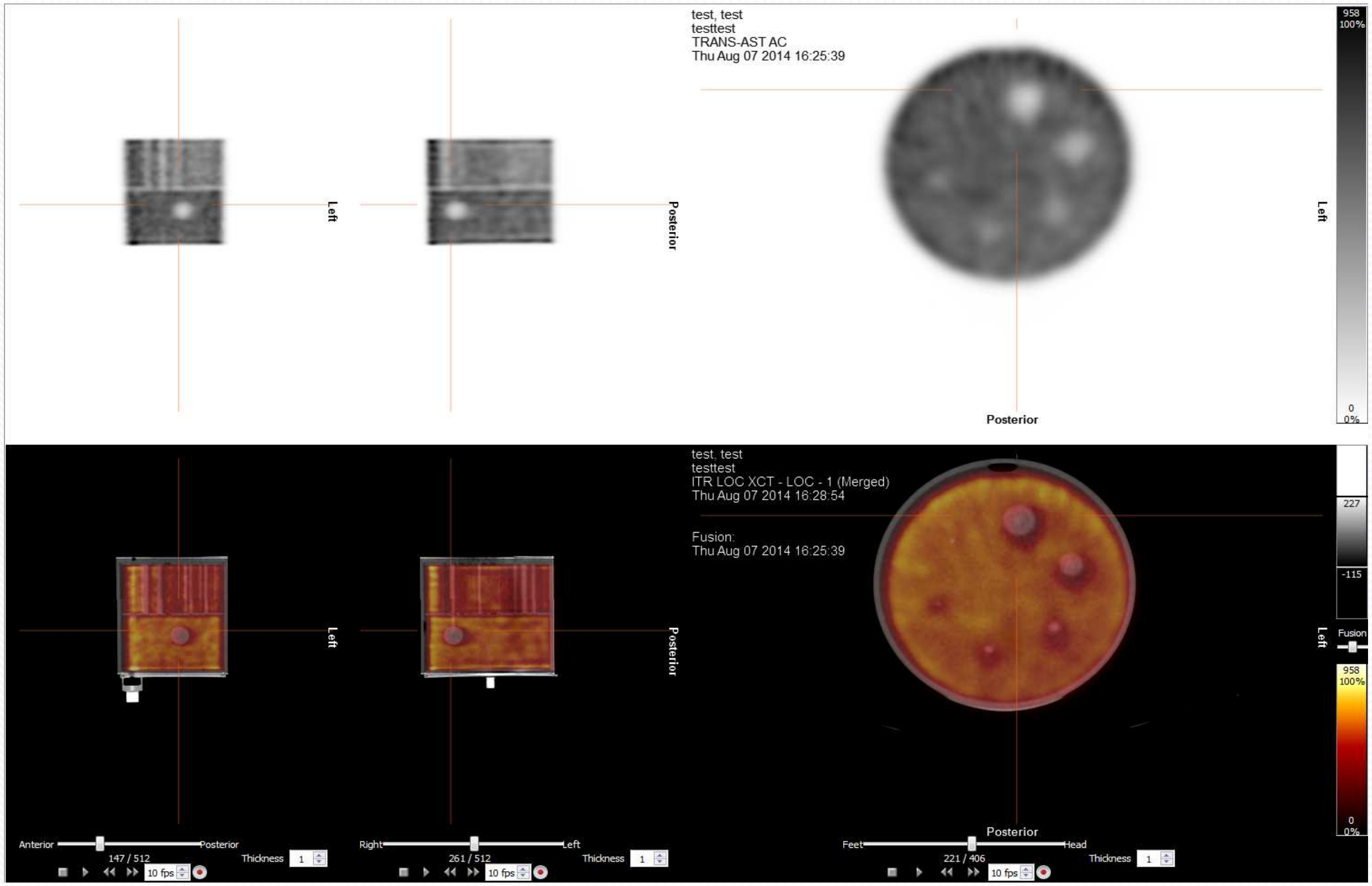
Top detector misaligned with bottom detector, may lead to distortion and resolution loss in reconstructed images.



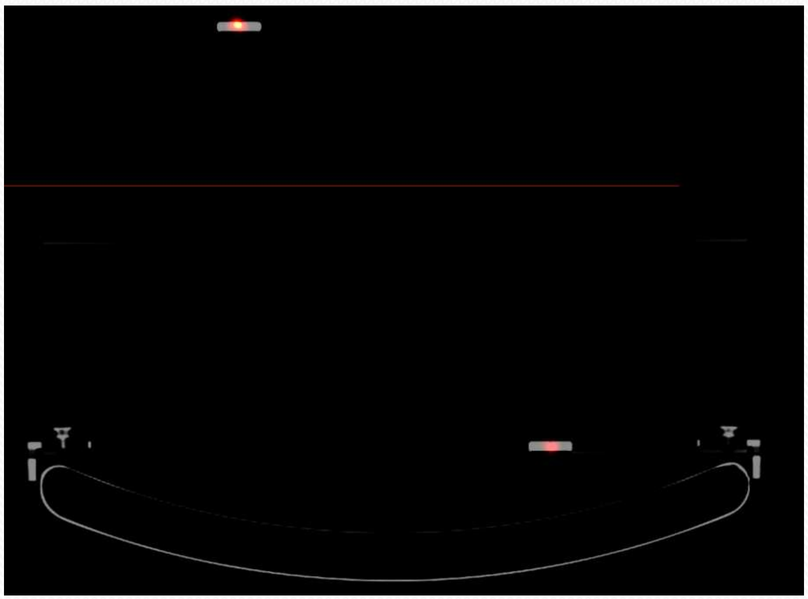
Hybrid SPECT/CT

- Test gamma detectors for planar imaging performance
- Tomographic spatial resolution - test the SPECT as done for SPECT only systems with line source
- Image quality – acquire Jaszczak phantom with same protocol as for SPECT only. Acquire CT of the phantom. Reconstruct using CT for attenuation correction
- SPECT and CT alignment – perform manufacturer alignment test procedure, or evaluate alignment of CT with Jaszczak slices
- Performed for both acceptance testing and annual surveys

SPECT/CT Phantom Fusion



SPECT/CT Alignment



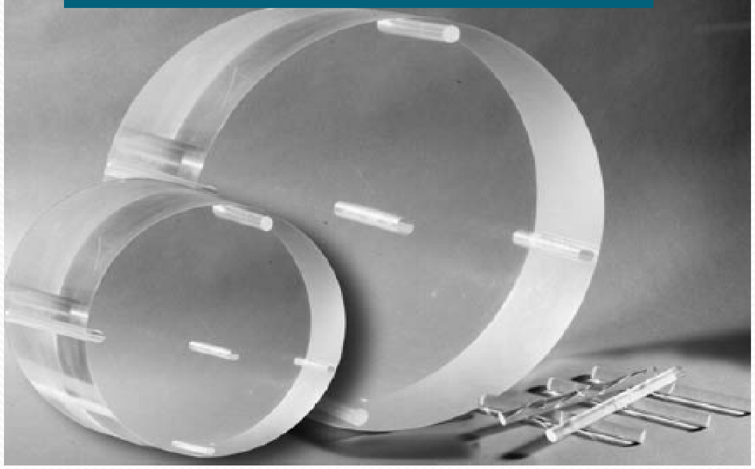
- SPECT & CT alignment procedures may be performed with the manufacturer phantom.
- ^{57}Co point sources can be imaged with whose location seen on both the SPECT and CT scans.
- Alignment should be to within 2 mm.
- Follow recommended test frequency by the manufacturer.
- Report results of the SPECT & CT alignment in annual physics survey.

CT Image Quality and Dose Assessment

- Testing of the CT component of the hybrid system may done separately by a CT trained QMP. Is necessary if the CT is used for diagnostic imaging.
- Recommend the following ACR *CT Quality Control Manual*
- Measure $CTDI_{vol}$ – may be required by state regulations. Report dose for body SPECT/CT study, and for any adult and pediatric protocols used diagnostically.
- May include CT image quality and dose assessment in acceptance testing and annual survey reports

SPECT/CT - CT Dose

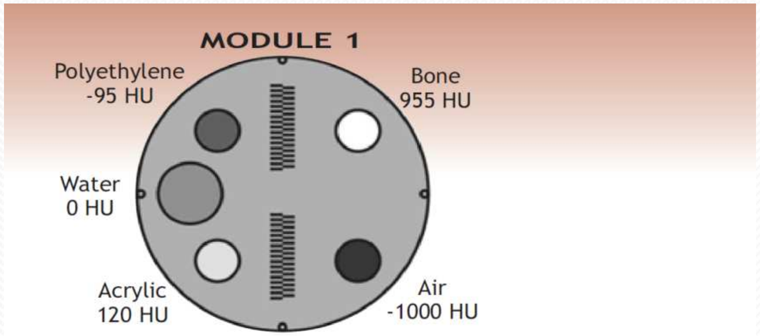
$CTDI_w$ measured for head and body sections



- Use standard methods to measure CT dose but with protocols used for SPECT.
- A challenge to measure on flat panel 14 cm x-ray detector of Philips Brightview.
- Typical doses of the CT ~1/10 to 1/3 of diagnostic CT. Note also doses for diagnostic CT scans done on unit.
- For annual physics survey, may report CT dose measurements on the unit made by another qualified medical physicist.

SPECT/CT - CT Image Quality

ACR CT Phantom may be used for evaluation



- Daily Perform HU accuracy and noise for water and evaluate for artifacts.
- Assess CT contrast, noise, spatial resolution monthly
  - Of importance is CT # accuracy. CT#'s are translated to SPECT linear attenuation coefficients.
- For annual physics survey report on HU accuracy, CT contrast, noise, spatial resolution. May be made by another qualified medical physicist.

How Long Does it Take?

Tests		Acceptance Minutes		Annual Minutes	
Physical Inspection			60		30
Planar			250		145
	Uniformity (intrinsic & extrinsic floods)	120		60	
	Off-peak floods	30		30	
	Spatial resolution (bars & line sources)	40		20	
	Energy resolution	20		10	
	count rate	30		15	
	sensitivity	10		10	
SPECT			75		75
	Spatial resolution (line source)	30		30	
	SPECT Phantom	45		45	
SPECT/CT			50		20
	Spatial resolution (same as SPECT only)	0		0	
	SPECT Phantom (same as SPECT + CT scan)	5		5	
	SPECT & CT spatial alignment (manufacturer)	30		0	
	CT Dose & Image quality documentation	15		15	
	Total Minutes		435		270
	Total Hours		7.25		4.50

Conclusions

- Provided a comprehensive review of the testing of gamma camera and SPECT systems.
- NEMA documents were used a guideline, but tests reduced and simplified to reduce time for performance measurements.
- Hybrid SPECT/CT is tested as a gamma camera, but with CT for attenuation correction and for image registration. Additional registration test needed.
- Evaluation of the CT component may be completed separately. Reports of this testing may be included in reports for nuclear medicine testing.