Large field-of-view pixelated gamma cameras

Non-Anger large field-of-view gamma camera detector and collimator characteristics and system calibration, commissioning and annual performance evaluation

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System Description - GE Discovery NMCT 670 CZT

SPECT

- Two large FOV (51 x 39 cm) CZT detectors
  - 130 CZT modules, each is a 16 x 16 pixel array
  - Intrinsic spatial resolution: 2.46 mm
  - Non removable Wide Energy High Resolution (WEHR) collimator
  - Recommended isotopes: ^{99m}Tc, ^{201}Tl, ^{123}I, ^{133}Xe, ^{177}Lu

CT

- 16 slice Optima CT 540
- 70 cm aperture

System Description - GE Discovery NMCT 670 CZT

NM & CT Consoles

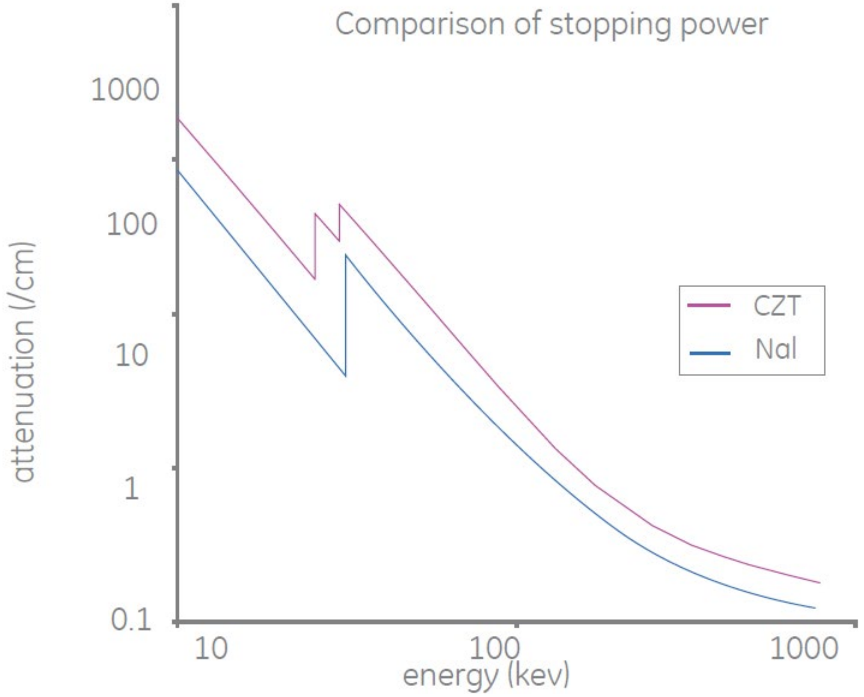
- Interface for exam scheduling
- NM & CT scan acquisition
- CT reconstruction and scan QC
- Utilities for routine quality control, calibrations and performance tests

Xeleris workstation

- Provides image viewing, processing & analysis apps
- Volumetrix MI for SPECT and SPECT/CT processing
- Q.Metrix for quantitative SPECT statistics
- Other specialized image processing & analysis apps

Cadmium Zinc Telluride

- Room temperature direct conversion semiconductor
- Higher density than NaI(Tl)
  - 5.8 g/cm^3 vs. 3.67 g/cm^3
- Slightly lower effective Z than NaI(Tl)
  - 50 vs. 56
- Higher attenuation coefficient for typical energies of interest in SPECT



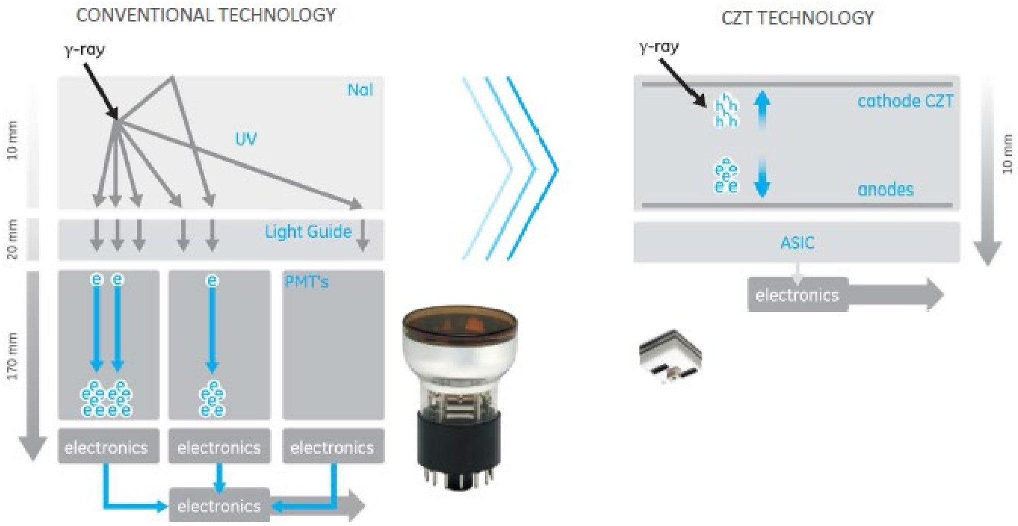
CZT vs. NaI(Tl) Technology

NaI(Tl)

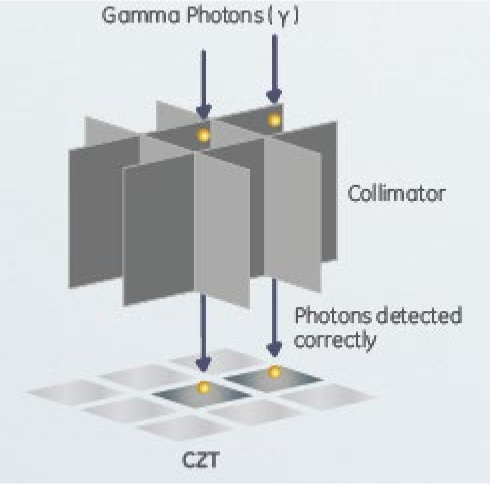
- Incident gamma rays deposit their energy in the scintillator, creating light photons.
- The light photons are converted into electrical pulses by a PMT array.
- Anger logic is then used to determine the origin of the light photons from the scintillator crystal.

CZT

- Incident gamma rays deposit their energy in the pixel crystal lattice generating pairs of charge carriers.
- An applied electric field is used to collect the charge carriers to produce a current pulse
- Since the current pulse comes from a single pixel, its position is known



Registered Collimator and Pixelated Detector

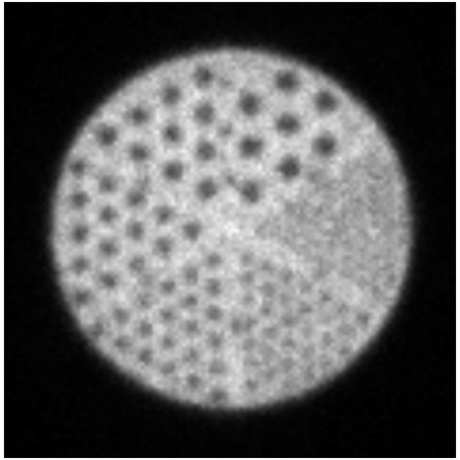


- Each collimator opening is registered to a single pixel
- Intrinsic spatial resolution is determined by the discrete pixel spacing of the individual detector elements, in this case 2.46 mm
- Eliminates photon scatter between pixels
  - Since there is no scintillator, there is no photon or light scatter within the detector

Registered Collimator and Pixelated Detector

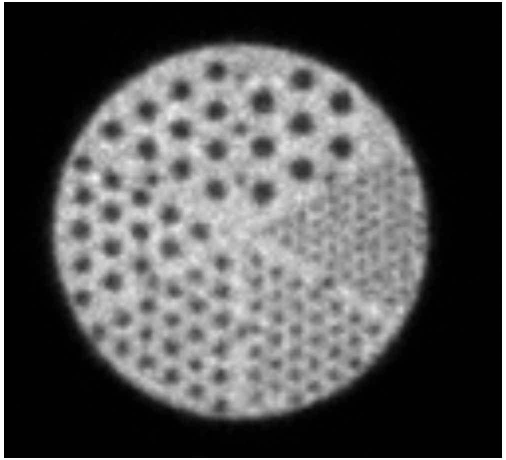
Spatial Resolution NaI

- Intrinsic Spatial Resolution: 3.8 mm
- System Spatial Resolution: 7.4 mm @ 100mm with LEHR collimator



Spatial Resolution CZT

- Intrinsic Spatial Resolution: 2.46 mm
- System Spatial Resolution: 6.3 mm @ 100mm with WEHR collimator



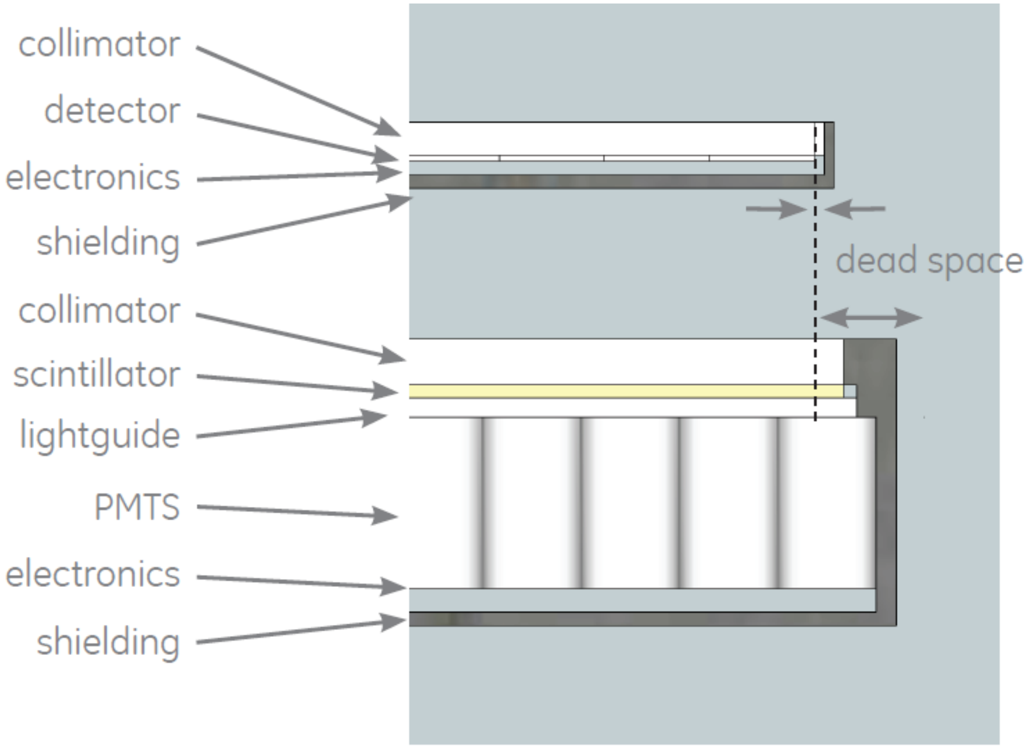
Dead Space

In a conventional camera, the position of events beyond the center of the last (edge) PMT is difficult to resolve.

- Dead space: 7.5cm

In a CZT camera, the pixels extend to the edge of the detector with no loss of image quality

- Dead space: 2.5cm

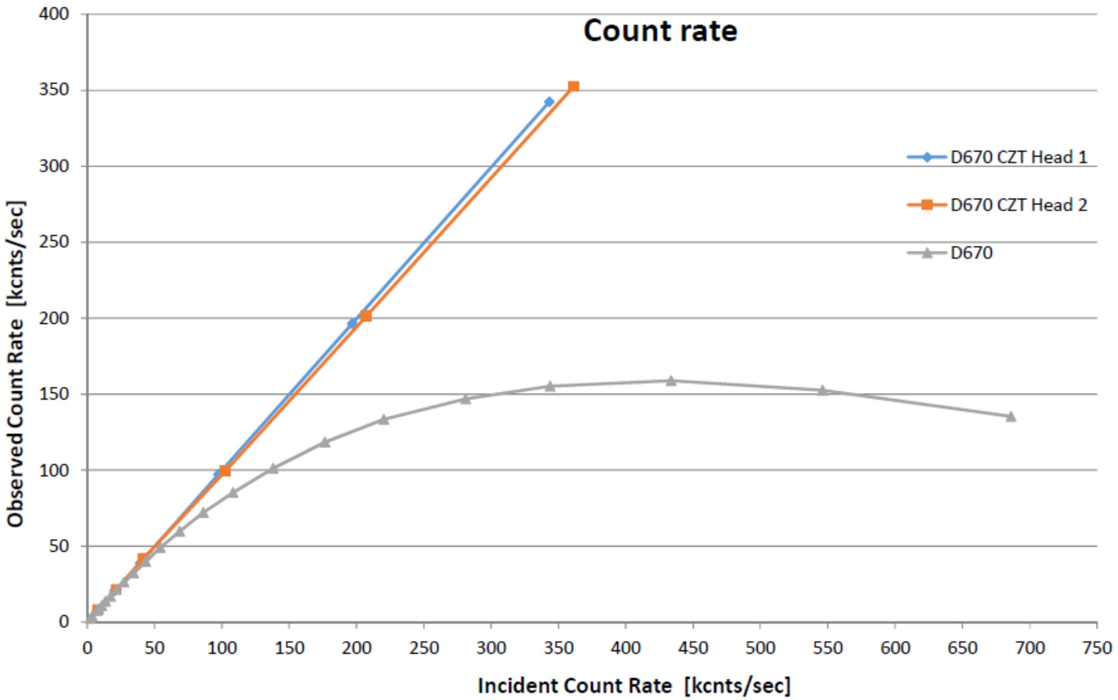


Count Rate Performance

CZT has no dead time or detector saturation

Count rate loss with a 20% window

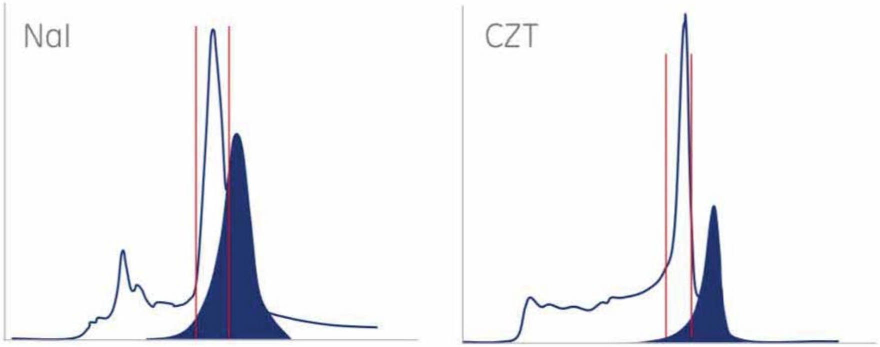
- *CZT: <1% loss @ ≥ 330 kcps*
- NaI: 20% loss @ ≥ 250 kcps
- Maintains quantitative accuracy for high count rate tracers



Energy Resolution

Intrinsic Energy Resolution
FWHM ^{99m}Tc @ 20 kcps

- CZT ≤ 6.3%
- NaI ≤ 9.5%
- Better energy resolution allows a narrower energy window, reducing the fraction of scattered events in the imaging window
- Better discrimination between energy peaks enables simultaneous dual isotope imaging

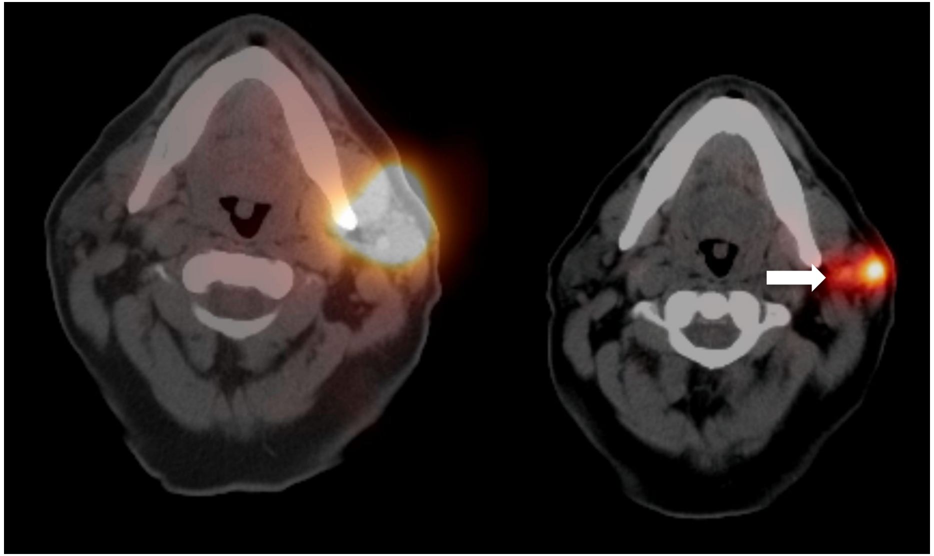


Overlay of ^{99m}Tc and ^{123}I spectra, showing greater crosstalk between the two peaks for the NaI detector with its poorer energy resolution and wider energy window.

CZT vs. NaI(Tl) Lymphoseek

Both SPECT/CT fusion images on the right are from a Lymphoscintigraphy study imaged successively a conventional NaI SPECT/CT system and a CZT system

- The sentinel node was not seen in the image on the left from the conventional camera due to blooming from high background activity at the injection site
- In the image on the right, acquired on the CZT camera, the sentinel lymph node can be seen (white arrow)



Commissioning & Acceptance

- Evaluate the installation and physical condition of camera and accessories
- Perform necessary system calibrations
  - Calibrations for isotopes that will be used
  - Including calibrations for isotopes with scatter windows
- Perform acceptance tests to establish baseline performance
  - NM Performance
  - CT Performance
- Perform an area survey if needed
  - New or revised room construction
  - Installation of a SPECT/CT in a SPECT room

Commissioning & Acceptance

Evaluate Physical Condition

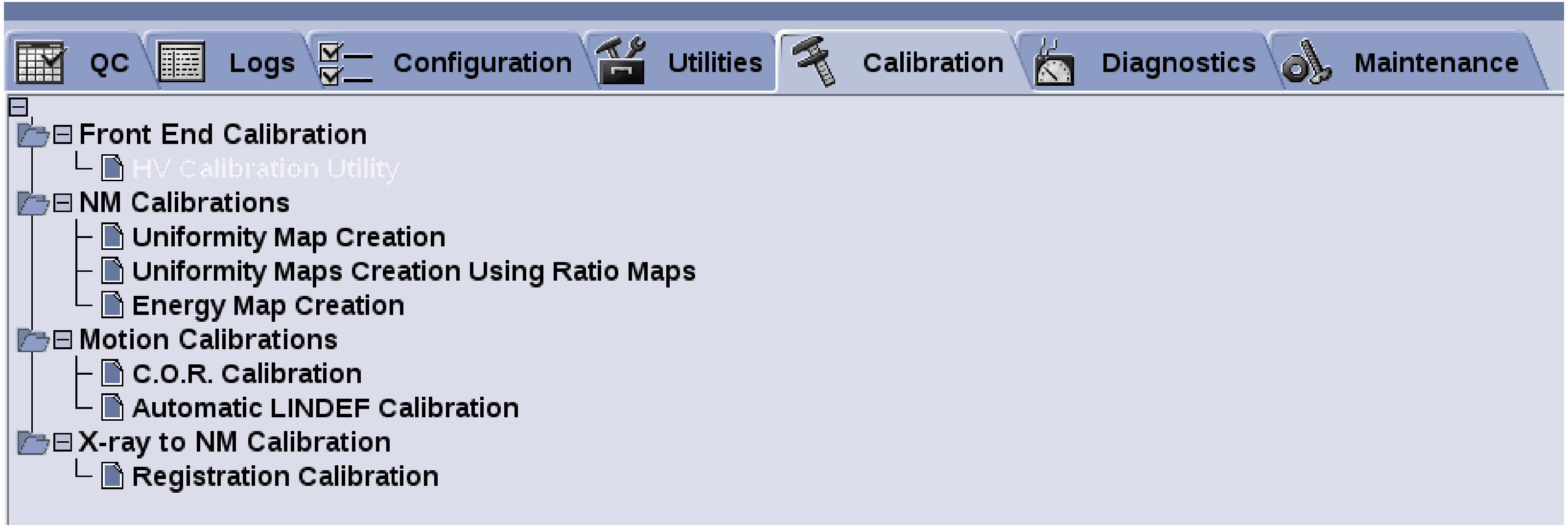
- Examine the camera system for the following:
  - Dents, scratches, loose covers and other mechanical defects
  - Smooth detector and table motions without noise or erratic motion
- Examine room conditions
- Examine the condition of all computers and displays connected to the camera system
  - Note the software versions and note any operational problems
- Locate and test the emergency stop switches.
- Locate and test collision detection devices on the collimator face and the gantry

Commissioning & Acceptance

- NM Calibrations performed during commissioning
  - Bad Pixel List Updates (Periodic QC)
  - Extrinsic Uniformity Calibrations
  - Planar Sensitivity Calibrations
- Note: System has non-removable WEHR registered collimators
  - Precludes intrinsic calibrations and tests.
  - A collimator cart, decoy collimators, and a torque wrench are provided for service use.

Important Note!

- Administrator login is required in order to access the QC, calibration, and performance tests.



Periodic QC

- Periodic QC is analogous to Periodic Re-Tuning of a NaI(TI) system
- Periodic QC is also part of the map creation process
- Periodic QC is used to improve CZT-based detector tuning to correct out-of-spec daily QC results or as preventive maintenance and consists of the following steps:

Calibrations Backup	Energy Acquisition
Background Acquisition	Energy Map Update
Noisy Pixels List Update	Bad Pixels List Update
Source Positioning	Image Quality Processing

Periodic QC

Calibrations Backup

- Backs up existing calibrations just in case…

Background Acquisition and Noisy Pixels List Update

- Identifies noisy pixels from open energy window acquisition with no source

Bad Pixels Check Report

Status: Failed

Overview: Detectors 1, 2 out of acceptance limitSummary out of acceptance limit

Administrative Information

Camera: Discovery NM/CT 670 CZT

IP address: 192.168.251.1...

Date: 11/08/2015 17:05:17

User name:

Summary | Detector 1 | Detector 2

Parameter Name	Value	Acceptance Criteria
Total number of bad pixels	146	<=1200.0
Too many new bad pixels found - list is not saved	66414	<=0.0

Periodic QC

Source Positioning

- Using the persistence image, verify that the source is positioned properly

Energy Acquisition and Energy Map Update

- Corrects energy peak shifts for each pixel based upon open energy window acquisition with sheet or flood source present
- For every pixel in the detectors, the energy calibration algorithm converts the peak position measured on each pixel to the real energy peak (in keV).
- An Energy Map is created for each detector, where the final interpolated Energy Map contains gain and offset factors for each pixel

Bad Pixels List Update

- Based upon Energy Acquisition

Periodic QC

Bad Pixels List Update

Number of Bad Pixels clusters bigger than 1 pixel	7	<=130.0
Maximal cluster size of Bad Pixels	2	<=3.0
Number of Bad Pixels	68	<=600.0
Number of New Bad Pixels	154	<=40.0

Too Many Bad Pixels can occur:

- At the end of Daily QC processing
- During Noisy Pixels Calibration
- During Bad Pixels List Update
- At end of Periodic QC

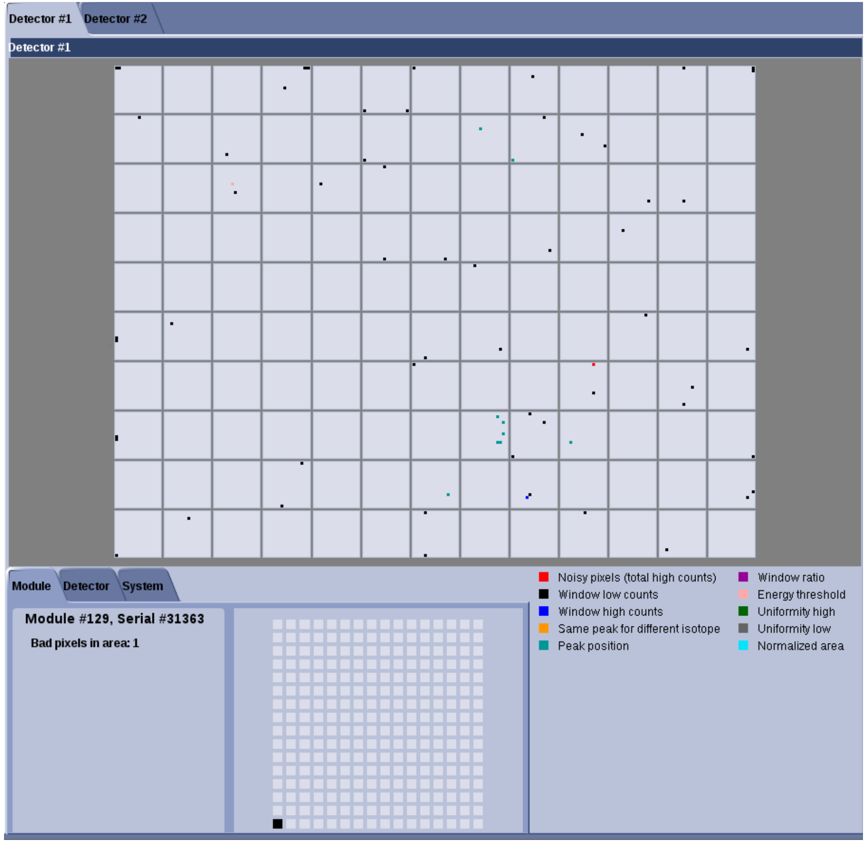
If this happens:

- Verify that no source is in the vicinity during Noisy Pixels Calibration
- Verify that the source is positioned correctly for all other tests
- *Repeat the test*
- <u>If the failure persists, call service.</u>

Periodic QC

Bad Pixel Report

- Shows map of bad pixels
  - Bad pixels are color coded
- Selecting a detector module shows the module details
  - Module ID and serial number
  - Number of bad pixels
  - Bad pixel locations within the array
  - The bad pixel color codes are listed at the bottom of the screen



Periodic QC

Bad Pixel Definitions

From NM800 & NM600 Series Calibrations, Map Creation & System Tests Manual

Bad pixels creation criteria	Explanation	Identified in the following procedures
Noisy pixels (total high count)	Noisy pixels are pixels that acquired more than 40 counts on background acquisition (no radiation source) in an open window during 180 seconds.	• Modules Screening • **Noisy pixels list update**
Window low\high count	Low\high raw counts (no energy correction) in energy window, where energy window is PP± 30[bins]	• Single energy map creation for Co57&Tc99m • **Energy update (PQC, Extrinsic Uniformity map creation using ratio)**
Peak position (PP)	Raw peak position (before energy correction) is out of spec.	• Single energy map creation for Co57&Tc99m • **Energy update (PQC, Extrinsic Uniformity map creation using ratio)**
Same peak for different isotopes	Low difference between PP of two isotopes (before energy correction).	• Interpolated energy map creation
Window ratio	Low ratio between raw count (no energy correction in E window and raw counts in open window.	• PQC with Tc99m (in energy map update)
Energy threshold	High energy threshold.	• Interpolated energy map creation • **Energy update (PQC, Extrinsic Uniformity map creation using ratio)**
Normalized area	Based on Co57 energy acquisition	• Interpolated energy map creation • **Energy update (PQC, Extrinsic Uniformity map creation using ratio)**
Uniformity low\high	Pixels with relatively higher or lower counts (after uniformity correction) than other pixels in the detector.	• Intrinsic calibration QC • **Periodic QC (image verification)** • **Daily QC** • **QC after extrinsic uniformity map creation**

Periodic QC

Image Quality Processing

- Acquisition: 16,250 K counts
- Checks the following parameters

Energy Peak	141.024 Kev	>=139.0 and <=142.0
FWHM	5.985 %	<=6.5
Uniformity	4.21 %	<=6.5
Noise Status	1	>=1.0 and <=1.0
Number of bad pixels	76	<=600.0
Number of bad pixels clusters bigger than 1 pixel	9	<=130.0
Maximal cluster size of bad pixels	3	<=3.0

Examples of Corrections Acquisition Images

Figure 5 Acquisition Before Corrections

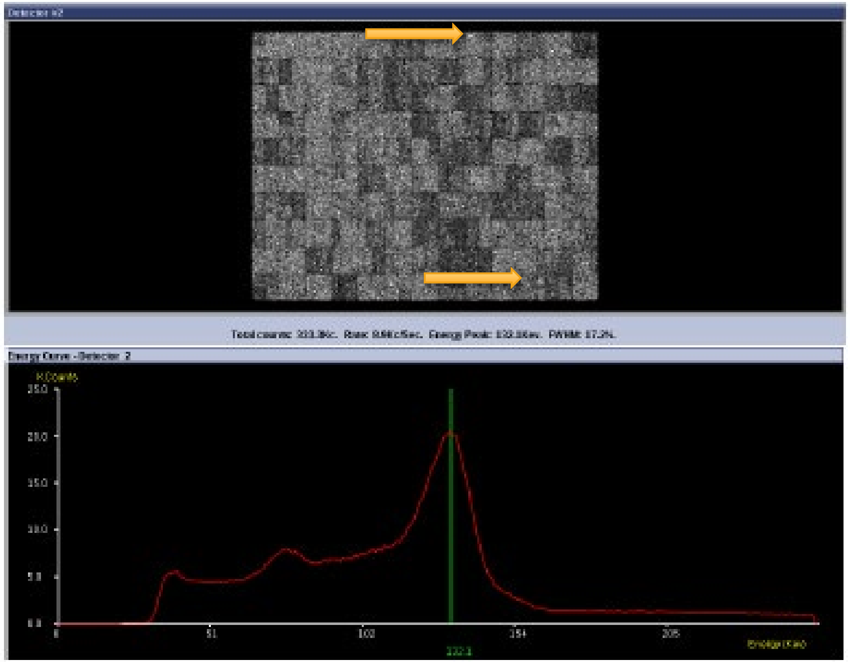
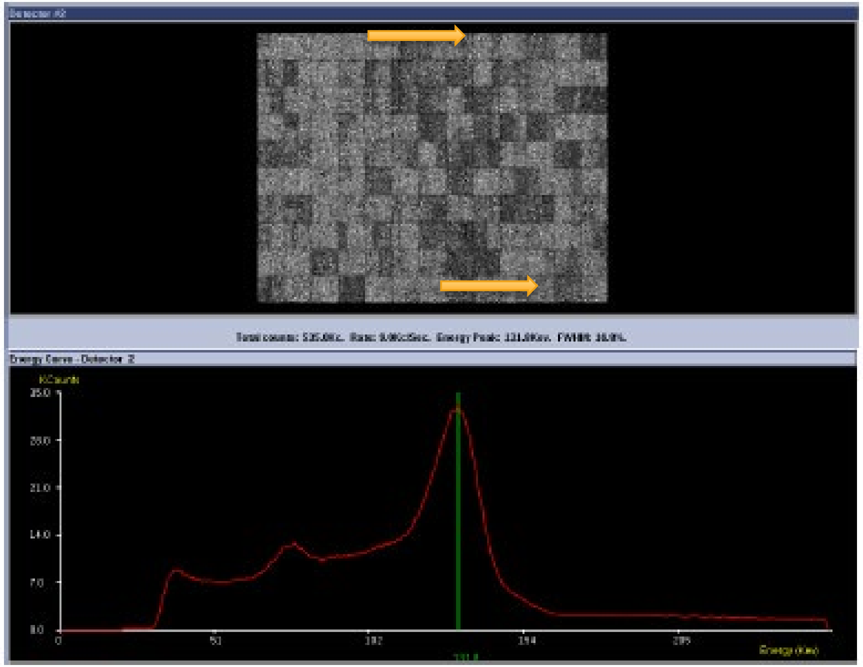


Figure 6 Acquisition After Bad Pixels Correction



From NM800 & NM600 Series Calibrations, Map Creation & System Tests Manual

Examples of Corrections Acquisition Images

Figure 7 Acquisition After Bad Pixels and Energy Corrections

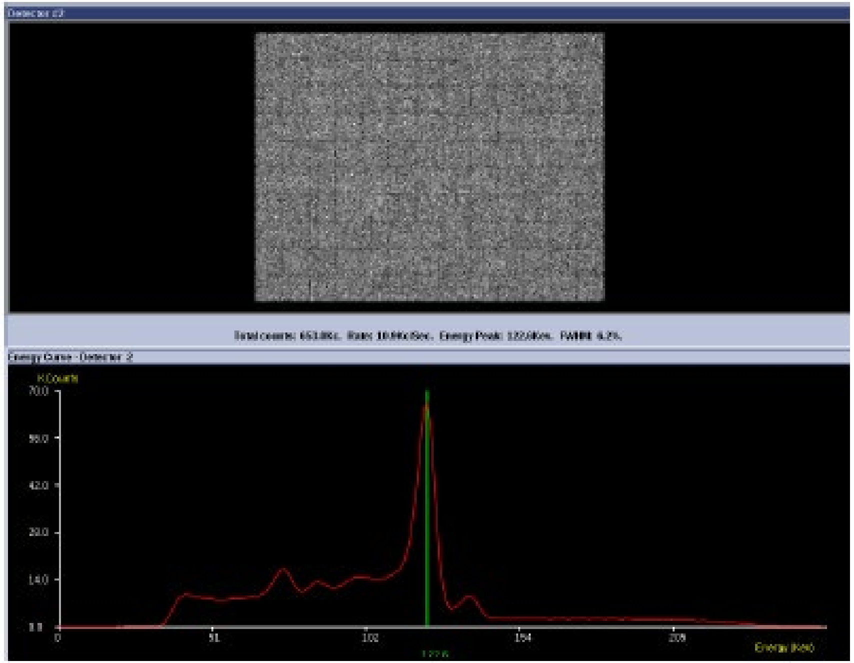
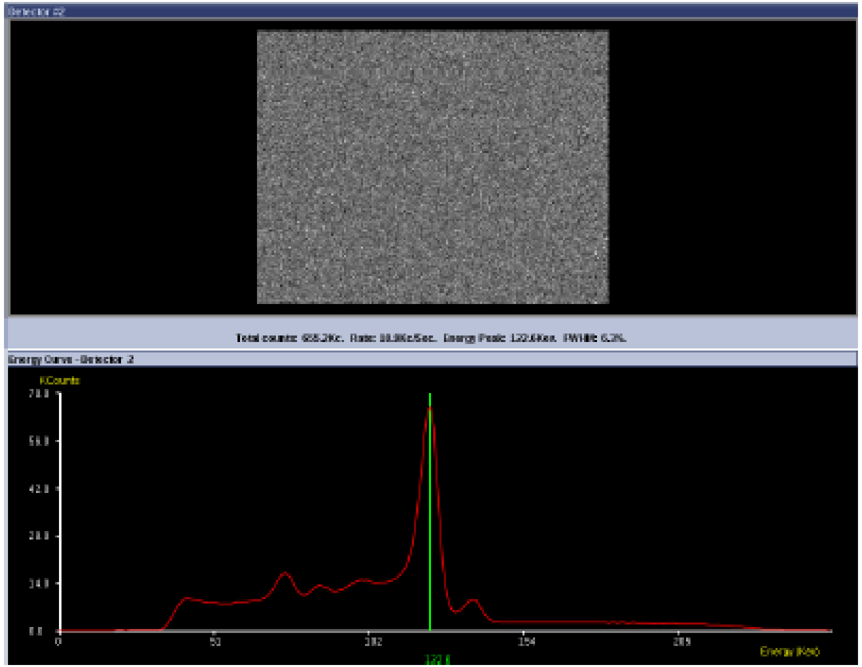
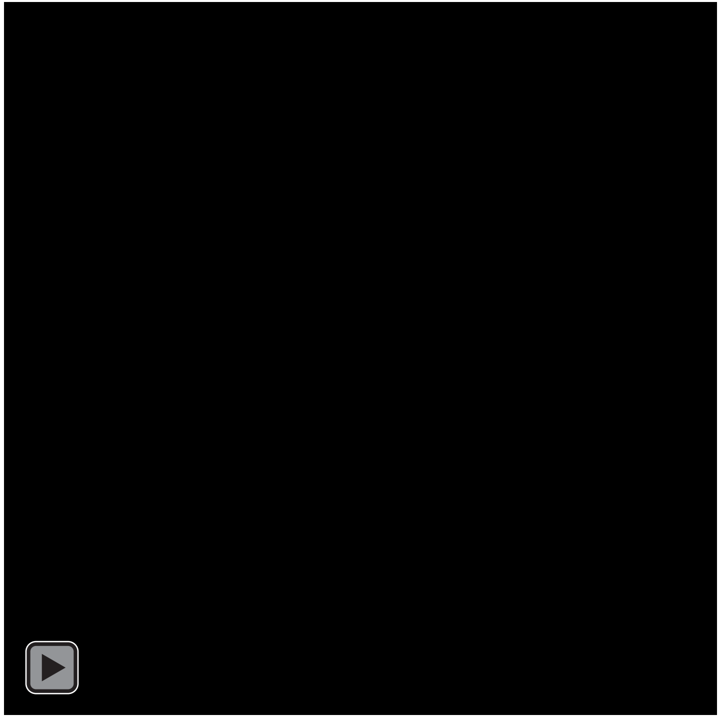


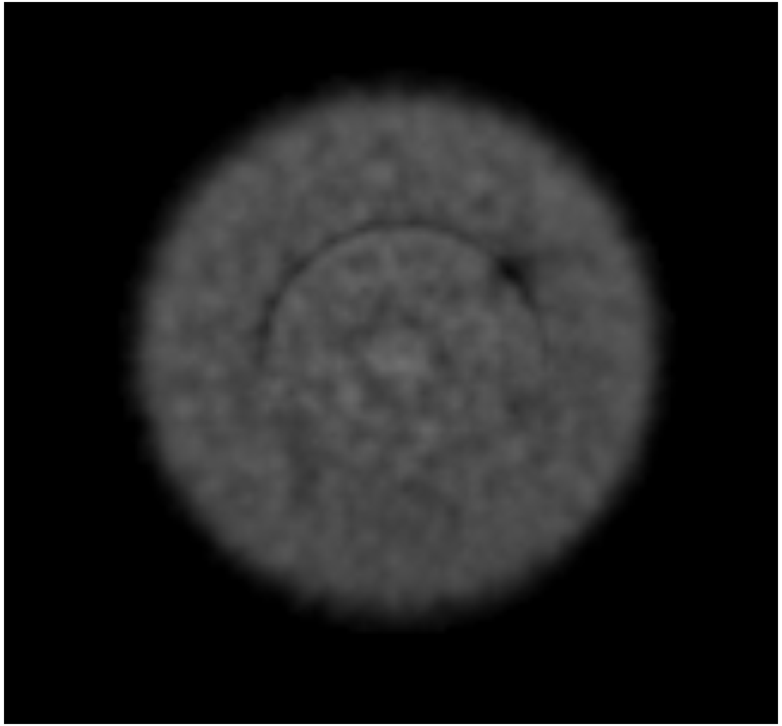
Figure 8 Acquisition After Bad Pixels, Energy and Uniformity Corrections



From NM800 & NM600 Series Calibrations, Map Creation & System Tests Manual

Uncorrected Bad Pixel Results





Factory Calibrations

The image quality of the D670 CZT depends on the following system-stored calibrations, that are initially performed at the factory:

- Energy Calibration - a single interpolated map for all isotopes for all pixel
- Uniformity Calibration - for Tc99m, Tl201 and Co57
- A Bad Pixels List is created for each CZT detector

The following procedures might be performed while servicing the system, either during preventive maintenance or after modules replacement/swap:

- Periodic QC, including Bad Pixels List update and Energy Map update
- Uniformity Calibration, including Bad Pixels List update, Energy Map update and Uniformity Maps creation
- Uniformity evaluation using the Uniformity Test tool

Uniformity Map Creation

Uniformity maps contains weighting factors for each pixel that are applied to correct image uniformity for different isotopes

A prerequisite to uniformity map creation is performing Periodic QC

There are two map creation methods:

- Extrinsic uniformity maps (recommended)
  - Requires a fillable flood source
- Uniformity maps based on ratio maps
  - For sites where ^{99m}Tc fillable flood is not available
  - Based on factory ratio maps, Tc99m/Co57, Tc99m/Tl201, etc.

Extrinsic Uniformity maps

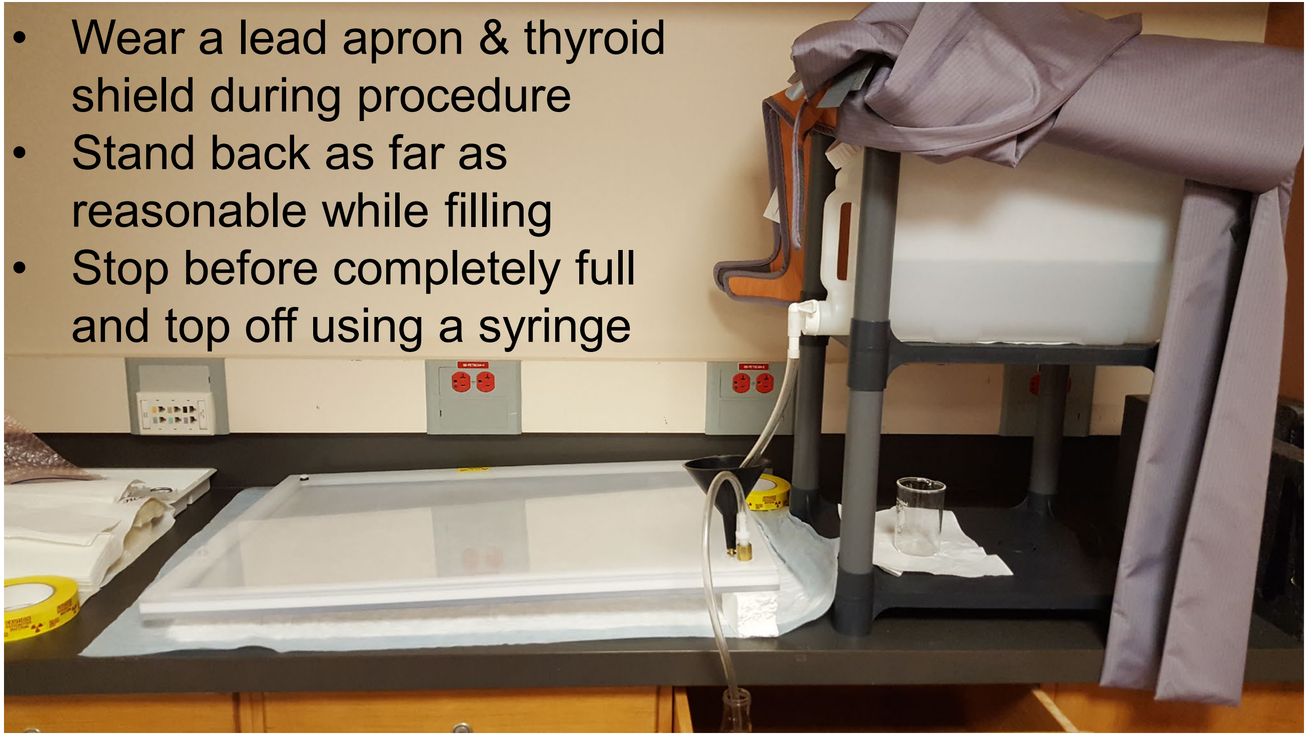
Using the built in Uniformity Maps Creation tool, acquire uniformity maps with the same energy windows that are used clinically, ^{99m}Tc 15% and 20%

- Recommended number of counts for Jaszczak phantom tests is 400 million counts
- Recommended number of counts for clinical scans at least 130 million counts
- Rate up to 300 kcps with a windowed energy peak

Flood Source Filling

Pre mix ^{99m}Tc with water and a few drops of dish washing soap in a 2.5 gallon carboy

- Wear a lead apron & thyroid shield during procedure
- Stand back as far as reasonable while filling
- Stop before completely full and top off using a syringe



Uniformity Maps Based on Ratio Maps

Performed using the Uniformity Map Creation Using Ratio Maps Utility which supports multiple map creation based on the "single" uniformity map concept

Applicable for isotopes ^{99m}Tc, ^{201}Tl and ^{57}Co.

1. Prior to uniformity map creation, perform Periodic QC
2. Acquire a new ^{57}Co extrinsic uniformity map using ^{57}Co flood.
3. Create new uniformity maps based on new ^{57}Co extrinsic uniformity map and factory extrinsic ratio maps

Uniformity maps based on ratio maps

The Uniformity Map Creation Using Ratio Maps Utility creates the following uniformity maps:

Map Type	Isotope	Energy session	Based on	Map Name (xhead #-1 or 2)
Extrinsic +/-10% window	Tc99m	Tc99m	Extrinsic Co57 flood acq. & Ratio map	map.x.s.Tc99m_20 WEHR45
Extrinsic +/-7.5% window	Tc99m	Tc99m_15	Extrinsic Co57 flood acq. & Ratio map	map.x.s.Tc99m_15 WEHR45
Extrinsic +/-10% window	Tl201	Tl201	Extrinsic Co57 flood acq. & Ratio map	map.x.s.Tl201 WEHR45

Planar Sensitivity Calibration

Camera Sensitivity is needed for Quantitative SPECT

Two built in methods for measuring camera sensitivity

- Guided Workflow - auto calculates sensitivity
- Manual - user calculates sensitivity and manually enters it into the system

Planar Sensitivity Calibration Workflow

- From NM Calibrations, select Camera Sensitivity
- Select the Energy Session, Collimator, and Guided Workflow
  - Correction weight is needed for energy sessions with scatter windows
- A background test is performed with no sources present
- The source for the sensitivity acquisition is set up
  - An absorbent pad is placed on the lower detector, a 10 cm spacer is placed on the pad and flat plastic dish is placed on the spacer.
  - The flat plastic dish is filled with 60cc of water, then 2 – 3 mCi of ^{99m}Tc is evenly dispersed in the water
  - The initial and residual activity in the ^{99m}Tc syringe is recorded

Planar Sensitivity Results

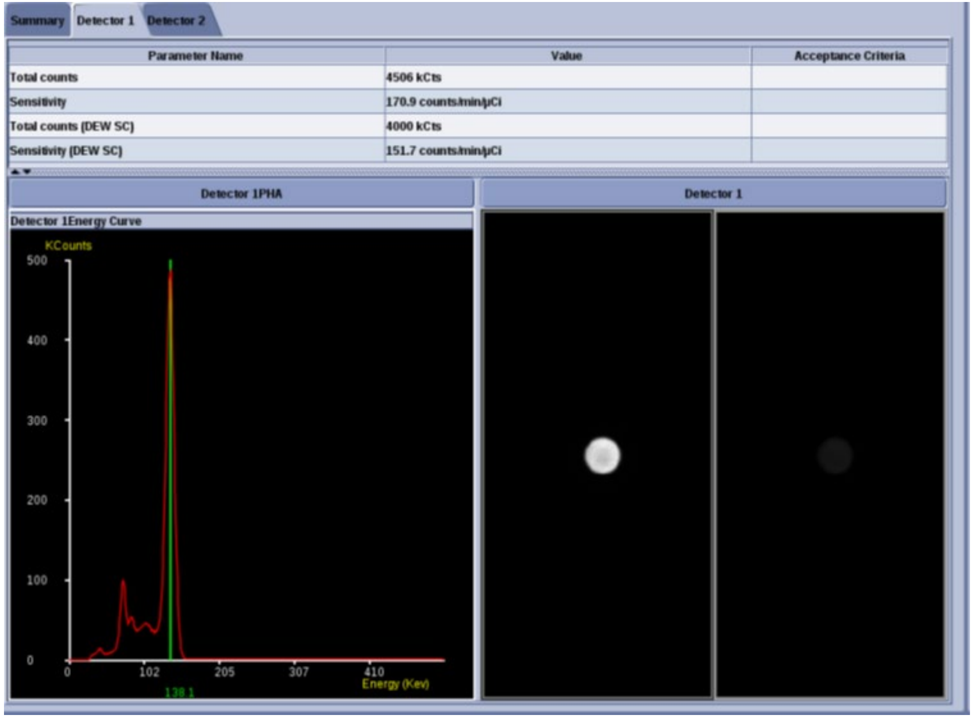
- Enter the initial and residual ^{99m}Tc activities into the user interface and continue the Guided Workflow acquisition
- When the acquisition is complete, the system calculates sensitivity and displays the Sensitivity Report

Parameter Name	Value	Acceptance Criteria
Energy Session	Tc99m SC[140.5 and 120]	
Collimator	LEHR	
Crystal thickness	3/8	
Actual Activity	5.3 milliCi	
Acquired on	06/23/2016 09:38:54	
Current Measurement		
* Camera Sensitivity No scatter correction (SC)	172.2 counts/min/µCi	
* Camera Sensitivity DEW scatter correction	152.5 counts/min/µCi	
* Difference between two detectors	1.5 %	<=5.0
Previous Measurement		

Planar Sensitivity Results

In addition to the summary sensitivity results, the results for each detector are shown

- Detector PHA
- Acquired images for the isotope and scatter windows
- Calculated sensitivities for the isotope and scatter windows
- From this screen, clicking on Save Sensitivity saves the results in the database



Acceptance Testing

Establishes baseline performance for NM & CT

- NM - Follow applicable ACR Quality Control requirements
  - Can’t do intrinsic NM measurements due to non removable collimator
  - Can’t do NM count rate tests because of high count rate capabilities
    - Error message displayed at rates > 350kcps
  - Planar resolution and linearity tests not necessary
    - According to NEMA NU 1-2018, for discrete pixel detectors with non-removable collimators, the measurement and analysis of intrinsic spatial resolution as defined for single crystal cameras is not directly applicable. For these systems, the discrete pixel size (pitch) shall be reported.
- CT - Not used for diagnostic CT, ACR requirements do not apply
  - Use GE CT QC Phantom and follow GE QC protocols

NM Acceptance Testing

Evaluate System Uniformity for ^{57}Co and ^{99m}Tc energy windows.

- Use the built in Uniformity Test tool (in Performance Tests)
  - Default stops at 60 million counts on each detector
  - Calculates integral, x & y differential for both UFOV & CFOV
  - Includes pass/fail results vs. GE specs
- Use ~20 mCi ^{57}Co sheet source or ~40 mCi ^{99m}Tc fillable flood
- *It's a good idea to run periodic QC first*

Parameter Name	Value	Acceptance Criteria
CFOV Integral Uniformity	1.969608872 %	<=4.0
CFOV X-Diff Uniformity	1.404110191 %	<=2.0
CFOV Y-Diff Uniformity	1.326162715 %	<=2.0
UFOV Integral Uniformity	1.969608872 %	<=5.0
UFOV X-Diff Uniformity	1.404110191 %	<=3.0
UFOV Y-Diff Uniformity	1.492206768 %	<=3.0

NM Acceptance Testing

Sensitivity

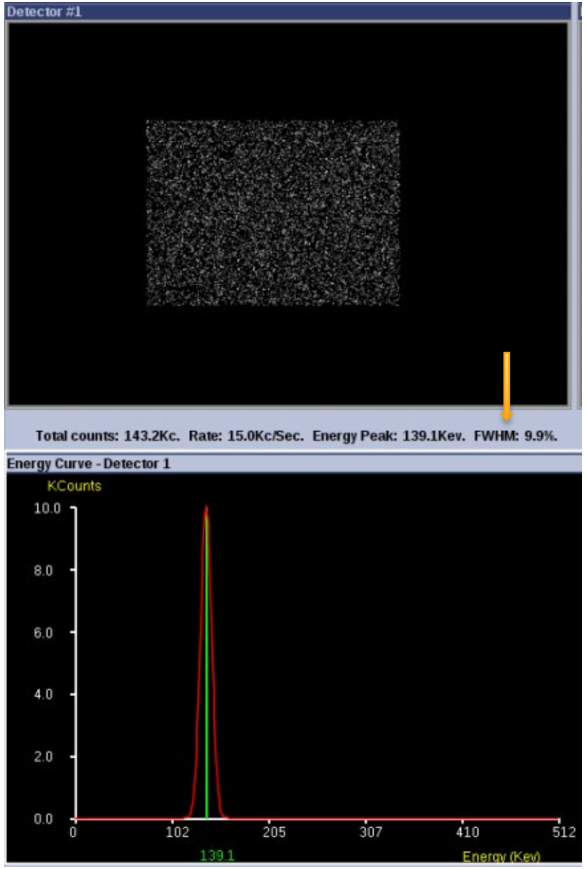
- Use values from sensitivity calibration for ^{99m}Tc energy windows

Energy Resolution

- Record ^{57}Co and ^{99m}Tc energy resolution FWHM values from their respective uniformity acquisitions (yellow arrow)

Spatial Resolution

- ACR Planar Resolution with ACR Phantom



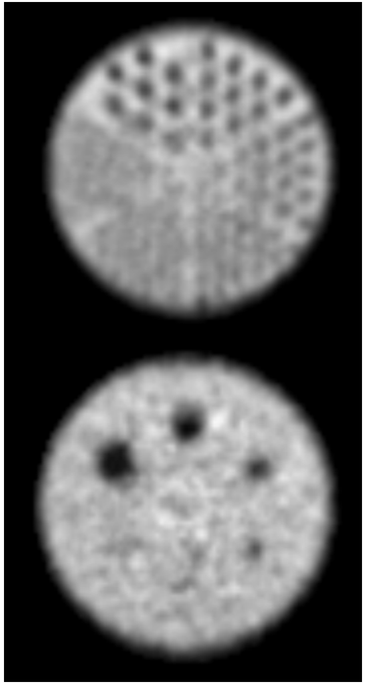
NM Acceptance Testing

SPECT Performance

- Follow instructions in NM 600 Series Cameras, Infinia, Ventri, & Millennium ACR SPECT Phantom Acquisition & Processing Tips
- Acquire with ^{99m}Tc 15% and 20% energy windows
- Acquire attenuation correction CT
- Reconstruct with and without CTAC using Volumetrix MI
- Produce ACR Phantom images for ACR submission

Monitor Evaluation

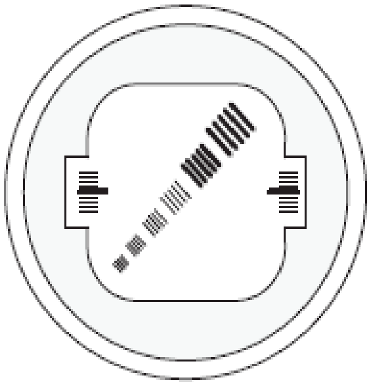
- Review SMPTE pattern on Xeleris monitor following the guidance in the 2017 ACR CT Quality Control Manual



CT Acceptance Testing

For CT image quality evaluation, use the GE CT QC phantom and built in QC protocols to measure:

- CT number accuracy
- High contrast resolution
- Low contrast resolution
- CT number uniformity
- Slice thickness accuracy
- Alignment light accuracy



Perform dosimetry measurements with CTDI Phantom

- Use CT Generic Scan for dosimetry measurements
- Displayed CTDI from brain & body CTAC Low Dose protocols

Image acquisition display

- Review SMPTE pattern on CT Monitor per 2017 ACR CT Quality Control Manual

Annual Physics Survey

NM follows applicable ACR Quality Control requirements

- Intrinsic uniformity and count rate performance are excluded

- Perform extrinsic uniformity test for ^{57}Co and ^{99m}Tc (15% window)
  - *Do periodic QC first*
- Record energy resolution for ^{99m}Tc after uniformity acquisition
- Measure sensitivity for ^{99m}Tc 15% energy session
  - Perform sensitivity calibration as at commissioning / acceptance
- Spatial Resolution
  - ACR Planar Resolution with test with Jaszczak Phantom

Annual Physics Survey

- SPECT Performance with Jaszczak Phantom
  - Acquire with only ^{99m}Tc 15% energy window
  - Reconstruct FBP with Butterworth filter and Chang's AC
  - Produce ACR Phantom images ACR renewal (if needed)
- Monitor Evaluation of Xeleris monitor
  - SMPTE Pattern
- Review of technologist NM QC
  - Daily, monthly, etc.
- Dose Calibrator & Uptake Probe QC

Annual Physics Survey

CT Annual Survey is the same as CT Acceptance Testing

- CT Image QC
  - GE QC phantom and monthly QC protocol
- Dosimetry
  - CTDI Phantom
- Image acquisition display
  - SMPTE pattern
- Review of technologist QC
  - Daily, weekly, etc.

Annual Physics Survey

- If everything passes, we'll be back next year…
- In the event deficiencies are identified during the annual survey, the responsible field service personnel are notified
  - Work with field service personnel to resolve deficiencies
  - Follow up surveys to verify that corrective action was effective

References

- CZT Technology: Fundamentals and Applications White Paper, GE Healthcare
- Discovery NM/CT 670 CZT, Breakthrough SPECT Technology, GE Healthcare
- NEMA NU 1-2018, Standard for Performance Measurements of Gamma Cameras
- NM800 & NM600 Series Nuclear Medicine Imaging Systems Quality Control Operation Guide, GE Technical Publications, Direction 5791051-1EN, Rev. 1
- NM800 & NM600 Series Nuclear Medicine Imaging Systems Calibrations, Map Creation & System Tests Manual, GE Technical Publications, Direction 5718532-1EN, Rev. 8
- NM 600 Series Cameras, Infinia, Ventri, & Millennium ACR SPECT Phantom Acquisition & Processing Tips, TiP Applications Training Material, DOC1797094 Rev 1
- Improved Sentinel Node Localization in Patients with Newly Diagnosed Melanoma Utilizing a Fully Digital CZT SPECT/CT System Versus a Conventional NaI SPECT/CT System, Leonard Zimmermann, Patrick Wojtylak and Arash Kardan Journal of Nuclear Medicine May 2020, 61 (supplement 1) 328