Basic Principles of Gamma Camera Imaging and Quality Control

Sharon L. White, PhD

University of Alabama at Birmingham

July 16, 2015

UAB MEDICINE

Knowledge that will change your world

Disclosures

No financial disclosures.

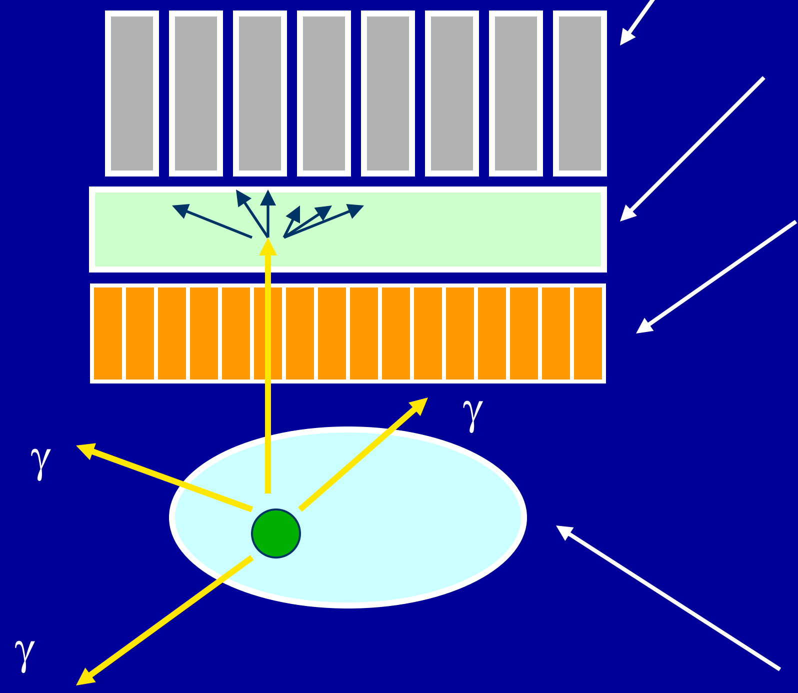
Gamma camera images and photographs of equipment are for illustrating concepts and not intended to advertise or endorse any particular manufacturer or vendor.

Learning Objectives

1. Understand basics of operation of conventional gamma cameras.
2. List performance characteristics of gamma cameras and features affecting performance.
3. List basic gamma camera calibrations and how they affect performance.
4. List QC tests for gamma cameras required by accrediting organizations.
5. Describe how to perform basic QC tests and assess acceptable performance.

Gamma Cameras –Dual Head

Gamma Camera Operation



Array of Photomultiplier Tubes (PMTs):
Localizes the position where the gamma ray interacts in the crystal

Sodium Iodide crystal:
A gamma ray from the patient interacts and produces visible light photons

Collimator:
Forms a projection image by allowing only gamma rays traveling in certain directions to reach crystal (for a parallel hole collimator, gamma rays approximately perpendicular to crystal pass through).

Gamma rays emitted from patient

Conventional Gamma Cameras

- Two detectors (heads) most common, although single head and triple head cameras are used
- Each head has single large NaI (sodium iodide) crystal, up to 40 cm X 60 cm. Typical crystal thickness: 3/8 or 5/8 inch
- Array of photomultiplier tubes, typically ~ 50 per head

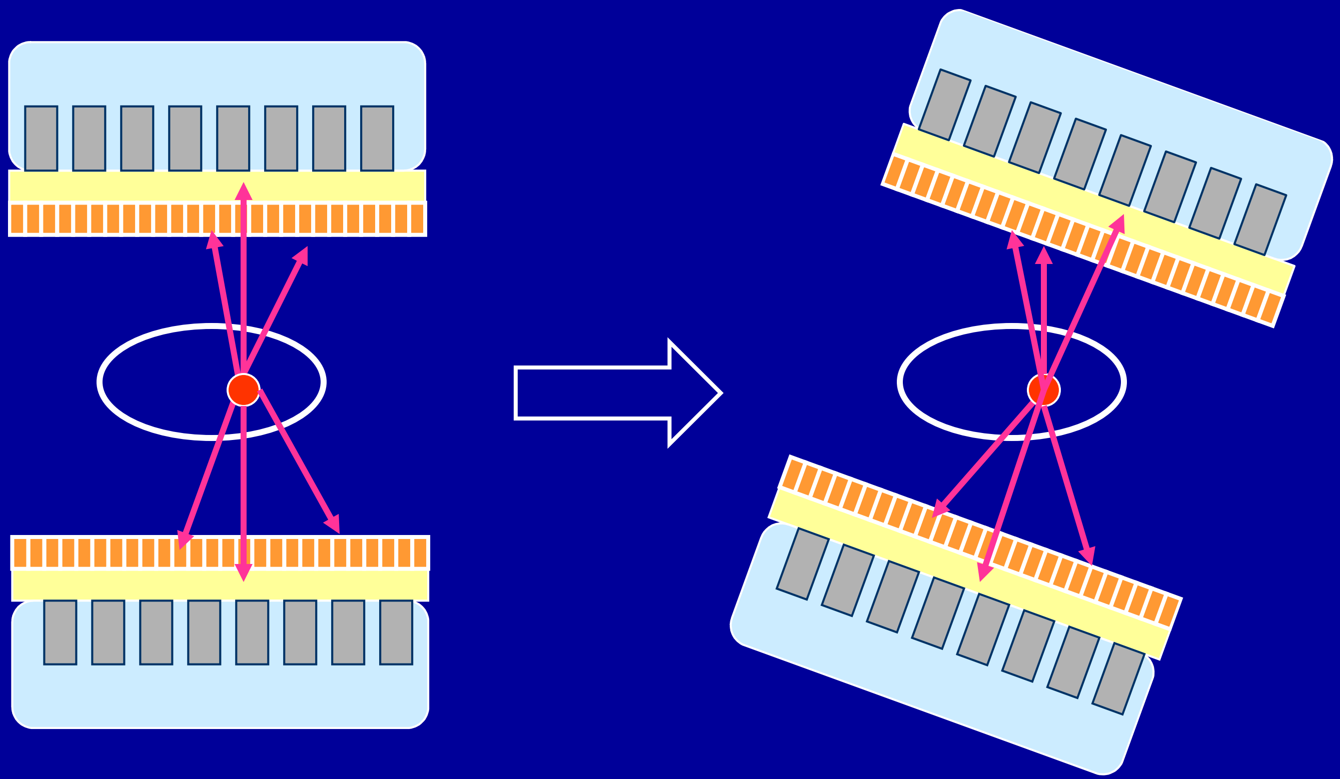
Position Determination

- The point where the gamma ray hits the crystal is determined by a weighted average of the signals from the group of PMTs receiving light from that event.
- The collimator localizes the origin of the gamma ray as somewhere along a specific line through the patient, since only gamma rays traveling parallel to the holes will go through. (Except for occasional septal penetration.)

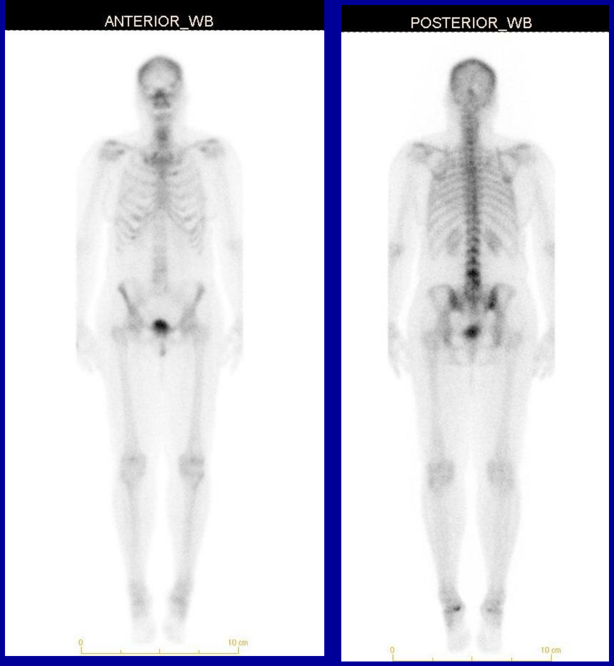
Types of Imaging

- Static Planar
- Dynamic Planar
- Whole body
- Tomographic (SPECT)
- Not all gamma cameras do all types of imaging – some do only planar, or only SPECT.

SPECT Operation

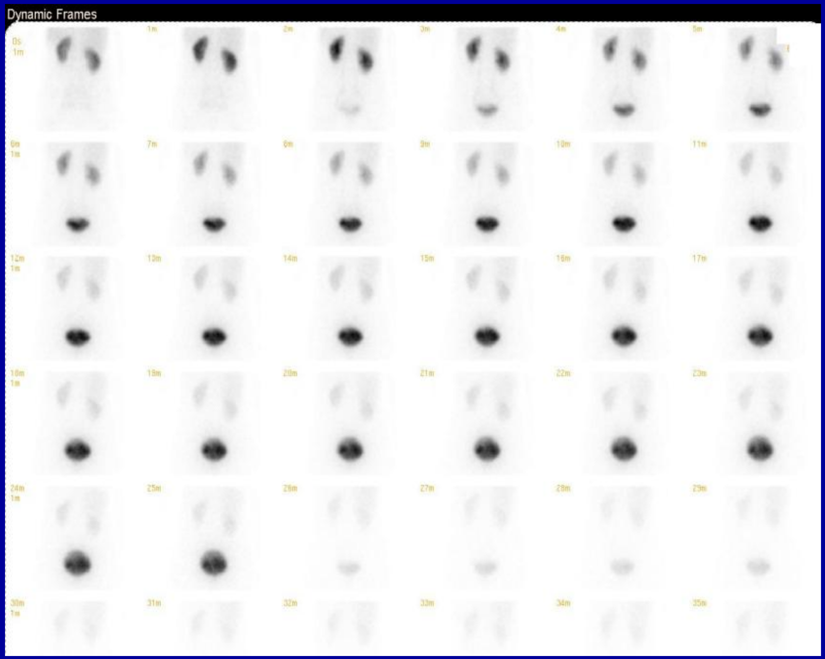


Camera heads rotate around patient, acquiring a set of projection images that are reconstructed into slices

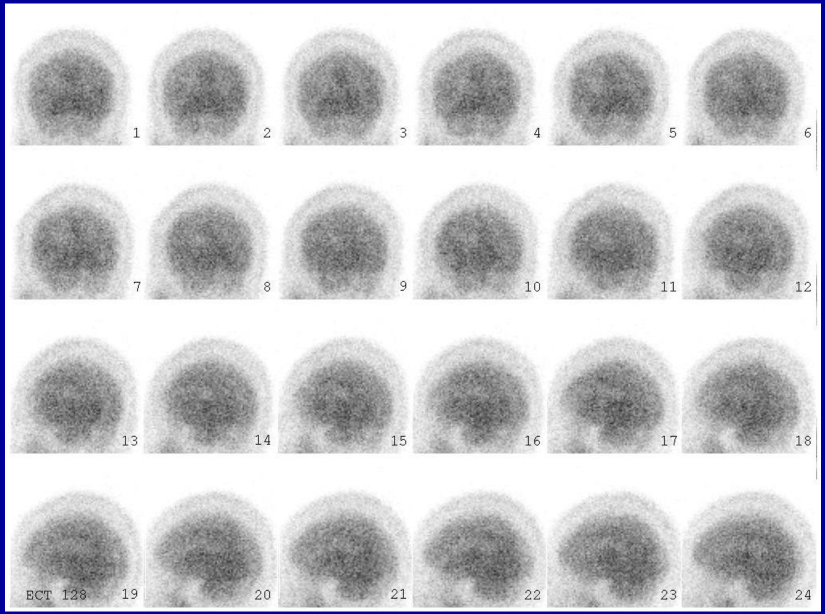


Whole Body Bone Scan

Static Planar



Dynamic



SPECT projection images

Performance Characteristics

- Spatial Resolution
- Efficiency/Sensitivity
- Energy resolution

UAB MEDICINE
Knowledge that will change your world

Spatial Resolution

- Intrinsic resolution (R_{int}) refers to how well the crystal and PMT system localize an interaction in the crystal. Affected by crystal thickness, gamma ray energy, scatter in crystal.
- Collimator resolution (R_{coll}) refers to how well the collimator localizes the gamma ray source in the patient, affected by hole diameter and length, distance from collimator to patient.
- System resolution (R_{sys}) is a combination of intrinsic and collimator resolution:

$$R_{sys} = \sqrt{R_{int}^2 + R_{coll}^2}$$

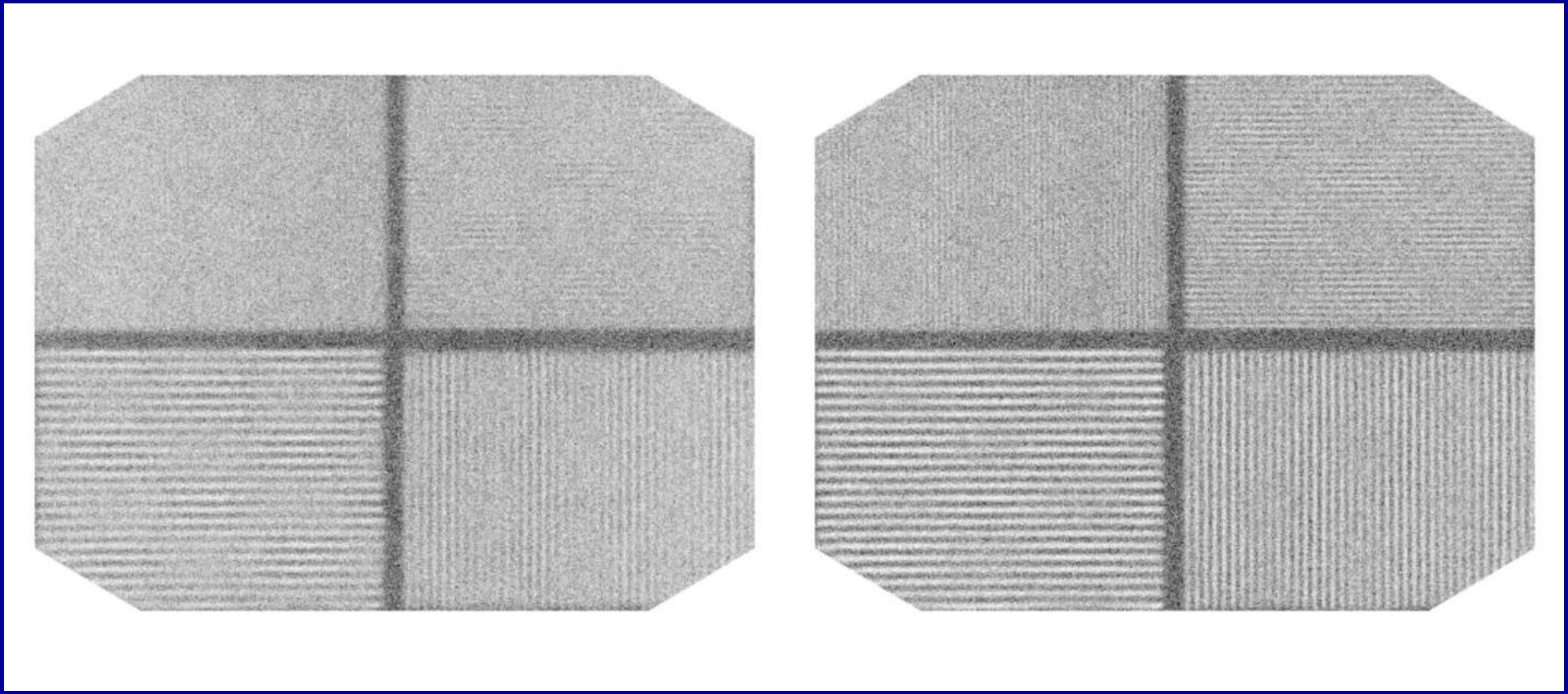
Intrinsic Spatial Resolution

- Affected by statistical fluctuations in number of light photons produced by scintillator.
- More light photons improves statistics, causing less significant fluctuation in signal size and more accurate positioning
- Intrinsic spatial resolution improves with increasing gamma ray energy, up to ~ 250 keV.
- At higher energies scatter in the crystal becomes more significant. Scatter can cause mispositioned events, degrading resolution.

Intrinsic Spatial Resolution

- A thinner crystal has better intrinsic resolution than a thicker one – less spreading of light and multiple scatter events less likely to be detected.
- Typical intrinsic resolution is 3.5 to 4.5 mm, depending on crystal thickness
- Crystal thickness a tradeoff between spatial resolution and efficiency – thinner crystals have worse efficiency than thicker ones.

Bar pattern using Thallium, one peak at a time



Lower energy peak only, 69 keV

Upper energy peak only, 167 keV – Better resolution at higher energy

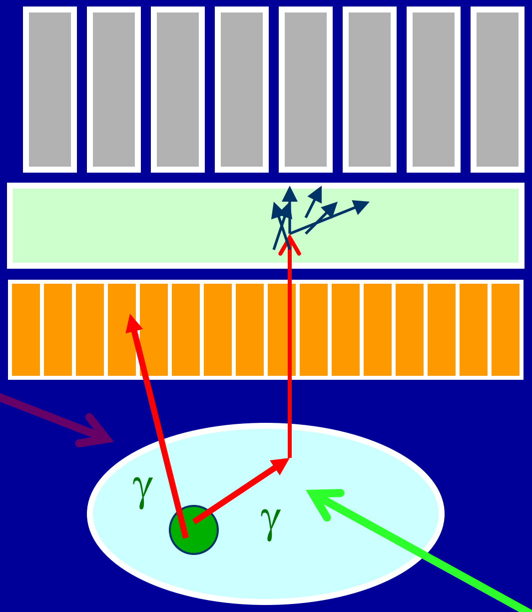
- Parallel hole collimators used most commonly
- Different collimators available for different energy radionuclides – medium energy for ^{111}In and ^{67}Ga, high energy for ^{131}I
- Different choices available for favoring high resolution vs. high sensitivity
- Parallel hole collimator produces image same size as object – no magnification or minification.

Collimators and Scatter

- Gamma rays undergoing Compton scatter in the patient can pass through collimator holes as well as unscattered ones.
- A scattered photon has lower energy than the initial photon. Scattered photons in the image are reduced by energy discrimination, although some scattered photons are still included when their energy loss is small enough that they are inside the allowed energy window.

Scatter in Patients

A scattered or non-scattered gamma may be emitted at such an angle to be absorbed by septa and not enter crystal

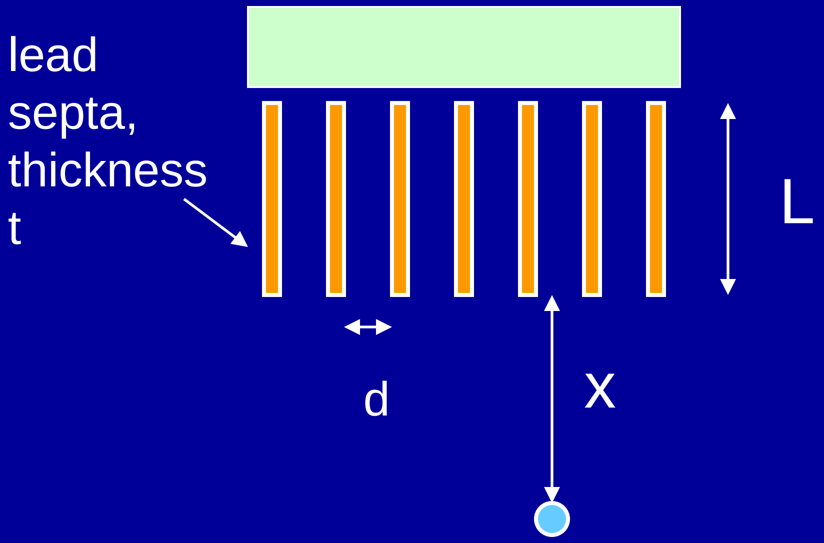


Scattered photon may be accepted as good event if energy within window. Results in mis-positioned event

If scattered photon energy sufficiently low, it will be rejected by energy discrimination – it will be outside energy window.

Scatter in patient. Scattered photon passes through collimator hole

Parallel Hole Collimator Resolution

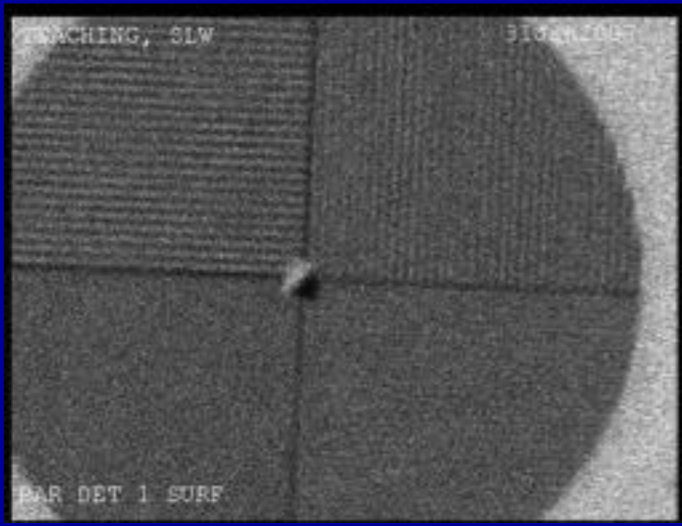


d = hole diameter
L = hole length
X = distance from collimator
to source

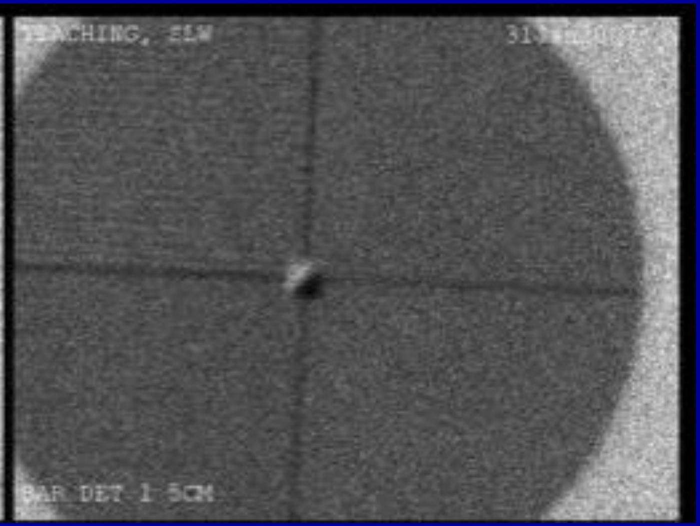
Collimator Resolution

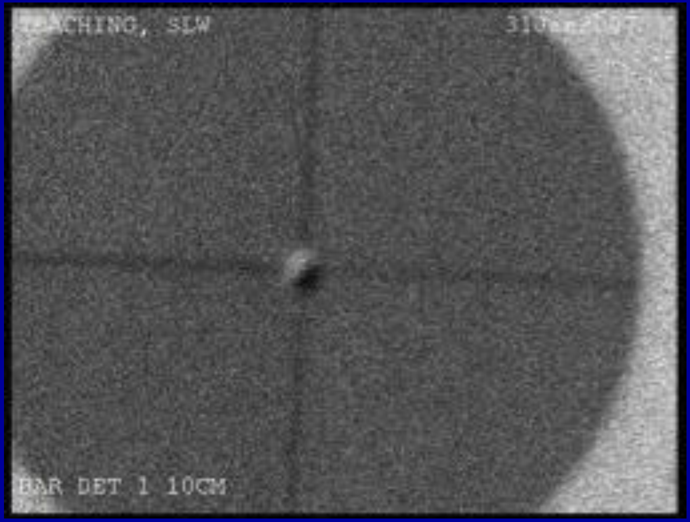
$$R_{coll} \approx \frac{d}{L}(L + x)$$

At collimator surface



5 cm from surface





10 cm from surface

Collimator resolution gets worse as source moves away from collimator surface. Important to position patient as close as possible to collimator

Collimator Specifications

Type	Hole Diameter (mm)	Septal Thickness (mm)	Hole Length (mm)	Coll. Res. At 10 cm (mm)	System Res at 10 cm (mm) 9.5 mm crystal
LEGP	1.40	0.180	24.7	8.0	8.8
LEHR	1.40	0.152	32.8	6.3	7.4
MEGP	2.95	1.143	48.0	10.7	11.3
HEGP	3.81	1.727	60.0	12.0	12.5
HEHR	3.06	1.95	60.0	9.6	10.4

Other collimator types

- Pinhole – forms magnified view of small object, such as thyroid. Image is inverted.
- Diverging – produces minified image, for imaging large object (e.g. lungs) on smaller detector area. No longer common.
- Converging – produces non-inverted, magnified view of small object. Not commonly used.
- Fanbeam – hybrid of parallel hole and converging, sometimes used in brain SPECT

Efficiency or Sensitivity

- Refers to fraction of emitted gamma rays detected and used to form image
- Efficiency has intrinsic component based on the thickness of the crystal and the attenuation coefficient of the scintillation material (how likely that a gamma ray is absorbed and detected rather than just pass through)
- Thicker crystal will have higher efficiency, at a cost of decreased spatial resolution.

Efficiency or Sensitivity

- System efficiency is a combination of intrinsic efficiency and collimator efficiency.
- Collimator efficiency related to diameter and length of holes, and thickness of septa.
- Tradeoff between collimator spatial resolution and efficiency.

Efficiency or Sensitivity

- Parallel hole collimator efficiency proportional to:

$$\left(\frac{d}{L}\right)^2 \times \frac{d^2}{(d+t)^2}$$

d=hole diameter
L=hole length
t=septal thickness

System Sensitivity

- System sensitivity relatively low, <≈ .02 %, due to necessity of absorptive collimation.
- System sensitivity usually specified in cpm/μCi at 10 cm for a specific radionuclide.
- Typical values on the order of 150-170 cpm/μCi for Tc-99m for a low energy high resolution collimator.

Energy Resolution

- Good energy resolution important :
  - scatter rejection
  - separating multiple photopeaks
- Depends significantly on statistical fluctuations in events in the imaging chain, such as number of light photons produced in scintillator, and number of photoelectrons produced in PMT photocathode, although other factors contribute

- Defined as FWHM of photopeak divided by photopeak energy, expressed as percentage
- Since it is energy dependent, for a gamma camera usually specified for Tc-99m, typically 9-10% for conventional gamma cameras.

Image Acquisition Options

- Matrix size (examples are 64 X 64, 128 X 128, 256 X 256, 512 X 512)
- Zoom factor (field of view)
- Combination of matrix size and zoom factor determines pixel size. Pixel size affects resolution and noise in image, as well as slice thickness in SPECT
- Total counts and imaging time

Image Acquisition Options

- The following slides shows the effect of different image acquisition options, such as matrix size, zoom factor and total counts.
- Planar images of four quadrant bar pattern and SPECT phantom standing on end are used to illustrate these options.

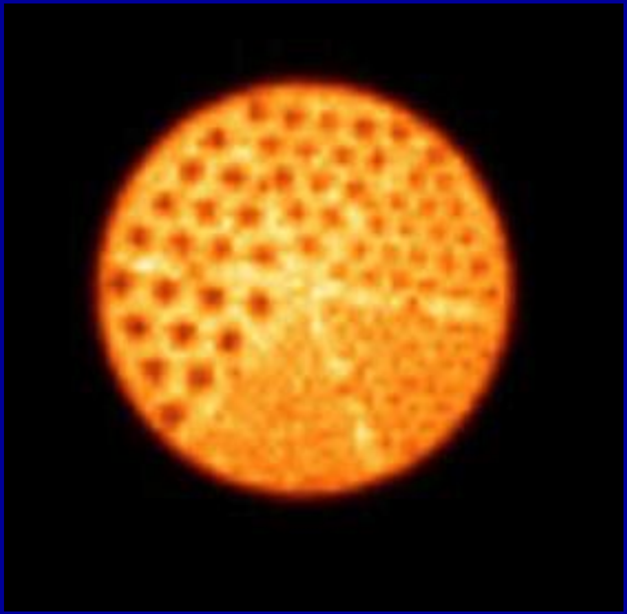
SPECT Phantom

- Jaszczak Phantom for SPECT quality control.
- Approved by ACR for SPECT ACR accreditation images
- Standing on end, used for evaluation of planar spatial resolution with scatter – rod sizes: 12.7, 11.1, 9.5, 7.9, 6.4 and 4.8 mm

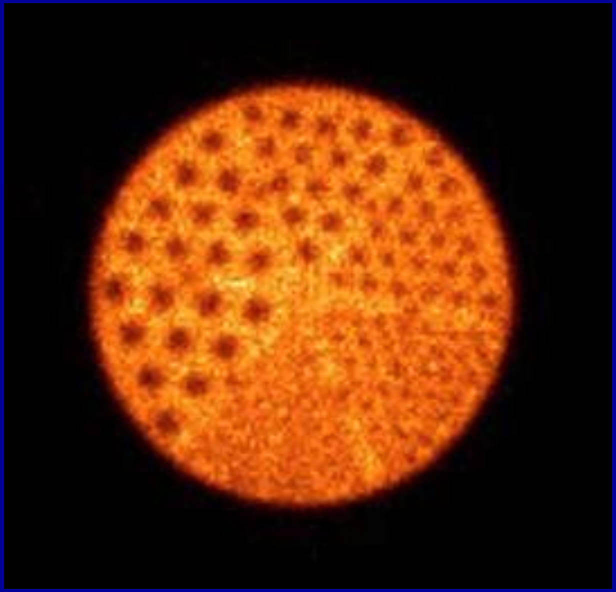
Image Acquisition Options

- The following slides shows the effect of matrix size options ranging from 64 X 64 to 512 X 512
- Total counts the same in each – 500K for SPECT phantom and 5 M for bar pattern

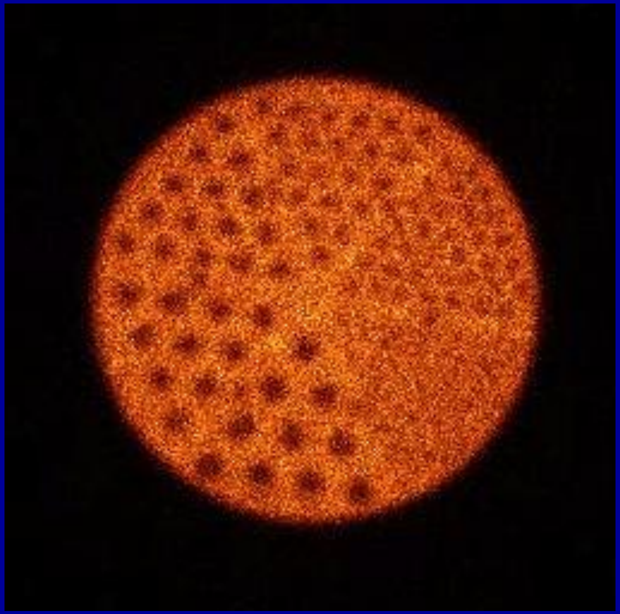
64 X 64



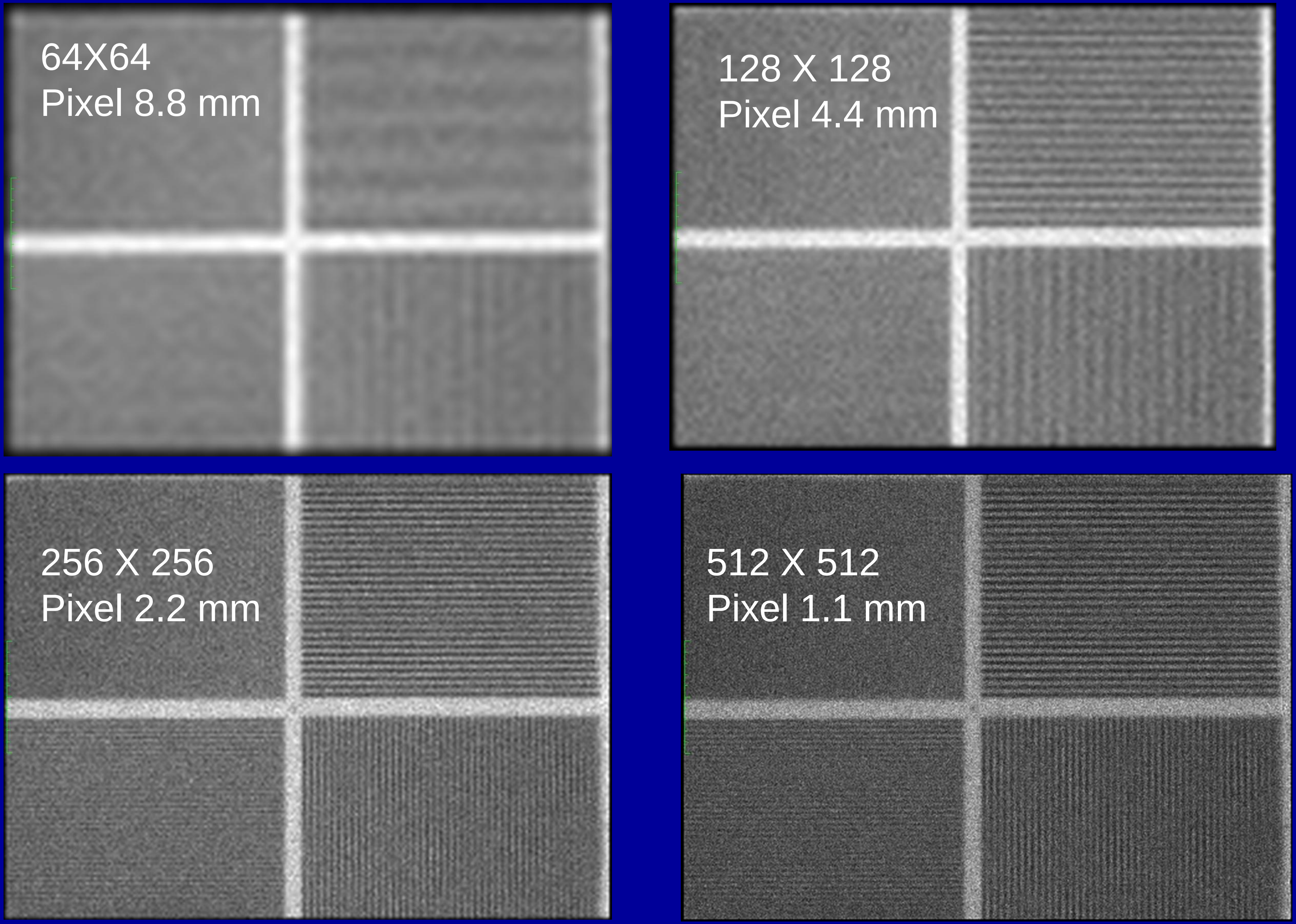
128 X 128



256 X 256



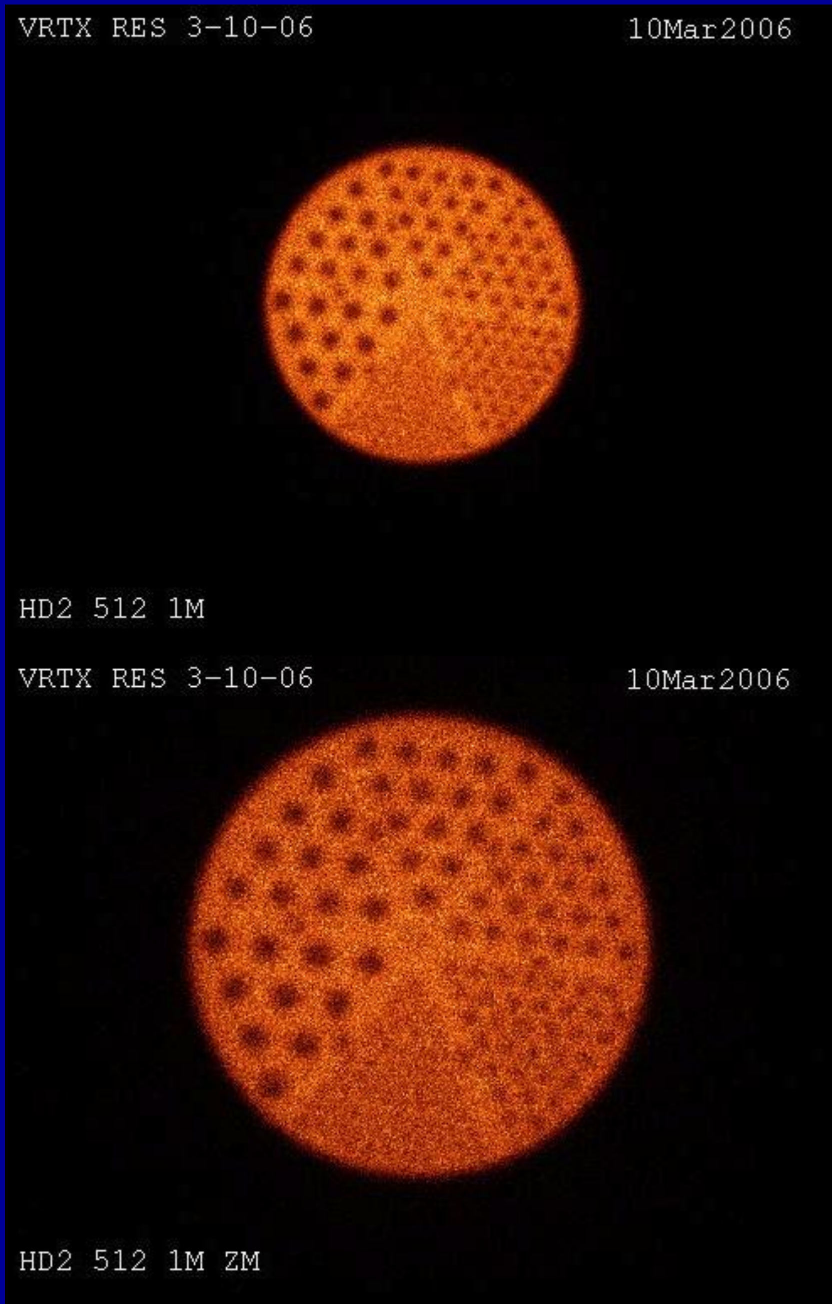
512 X 512



Bar spacings 2.0, 2.5, 3.0, 3.5 mm

Image Acquisition Options

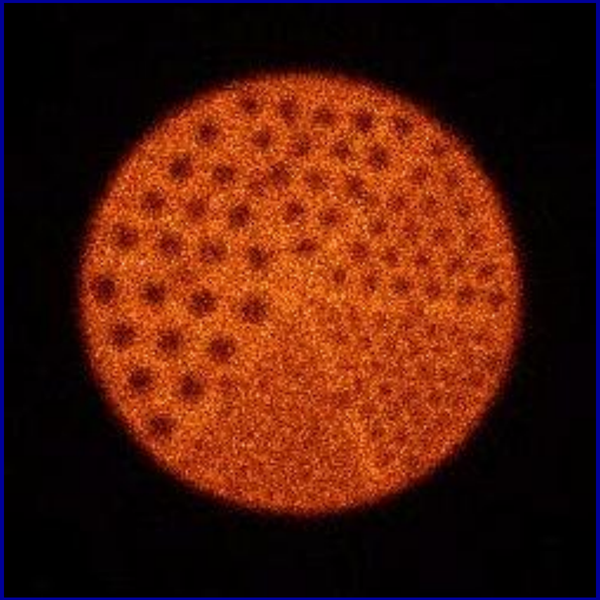
- The following slide shows zoom options.
- Matrix size 512 X 512 on each, but smaller field of view used with Zoom 1.46 on second one, resulting in smaller pixel size.



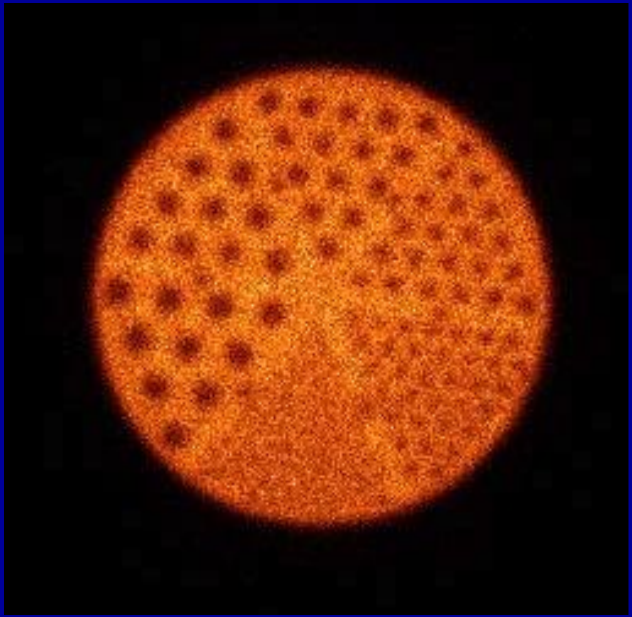
512 X 512 matrix,
1 M counts

512 X 512 matrix,
Zoom 1.46, 1 M counts

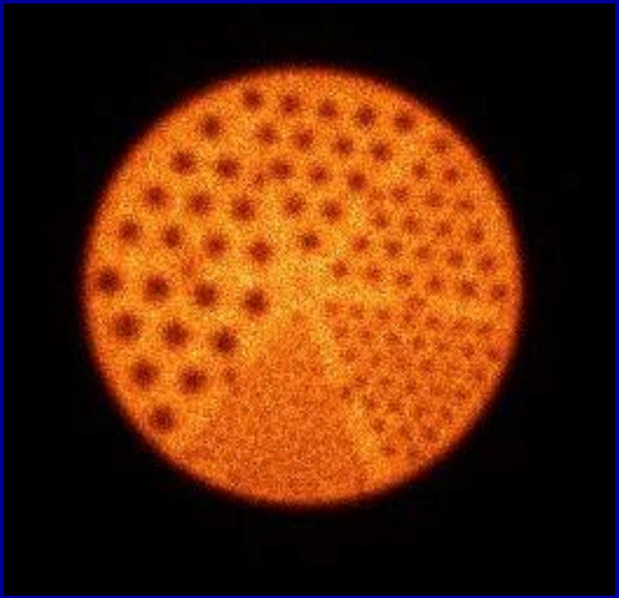
- The following slides show three images with the same matrix size, 512 X 512
- Total counts different in each
- Counts per pixel higher with higher total counts, causing images to be less noisy, affecting visibility of rods or bars.



500K

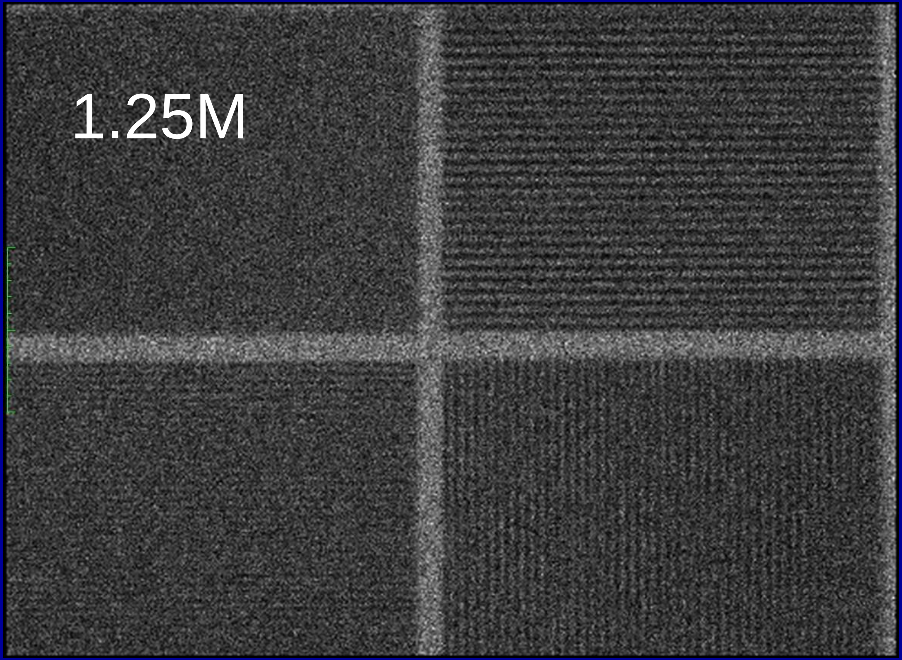


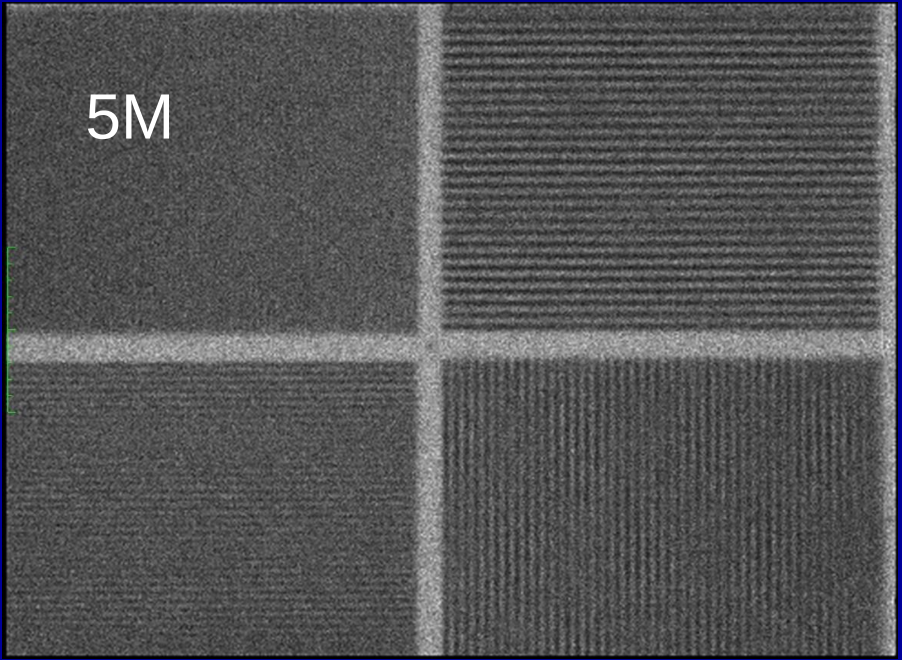
1M

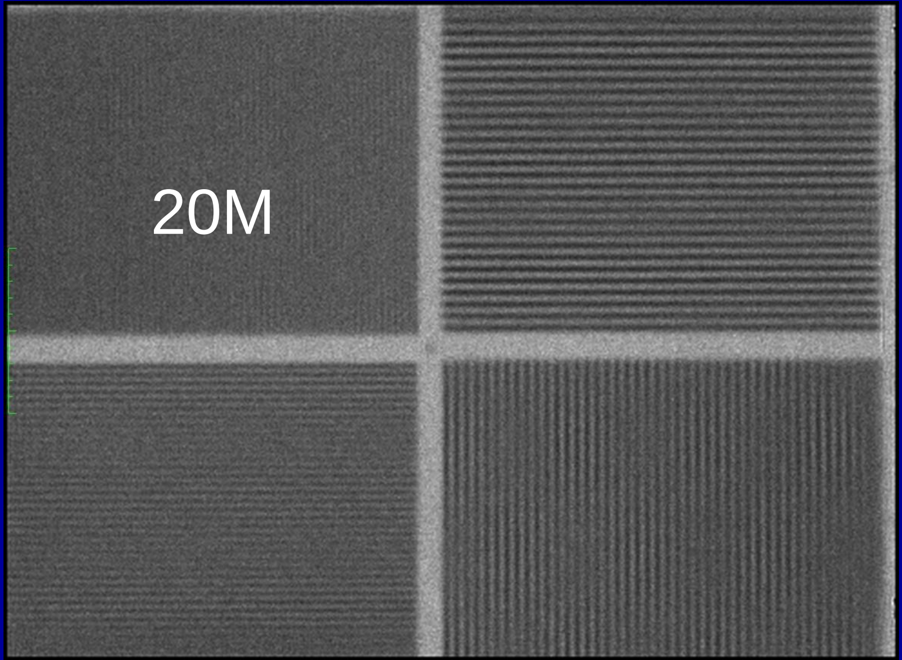


2M

All 512 X 512 Matrix
Total counts varies







512 X 512 matrix
Total counts varies
From 1.25 M to 20 M

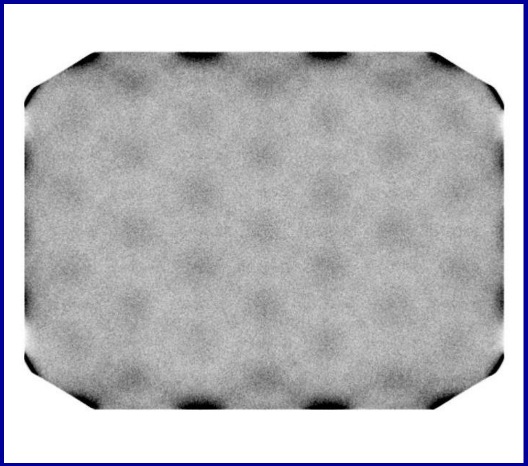
Gamma Camera Calibrations

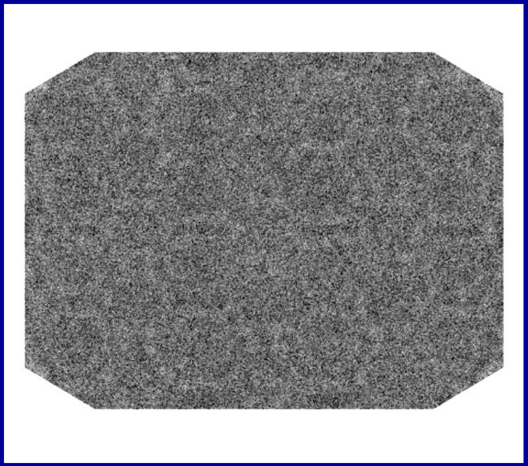
- PMT gains must be balanced
- Correction Tables:
  - Energy
  - Linearity
  - Uniformity (Flood)
- Center of Rotation (COR) offset calibration for SPECT-capable cameras.

- Energy correction table corrects for variations in measured energy across the detector
- Linearity table corrects for non-uniform light collection efficiency across face of photomultiplier tubes, which causes straight lines to appear wavy without correction
- Flood table corrects for remaining non-uniformities

Effects of Correction Tables

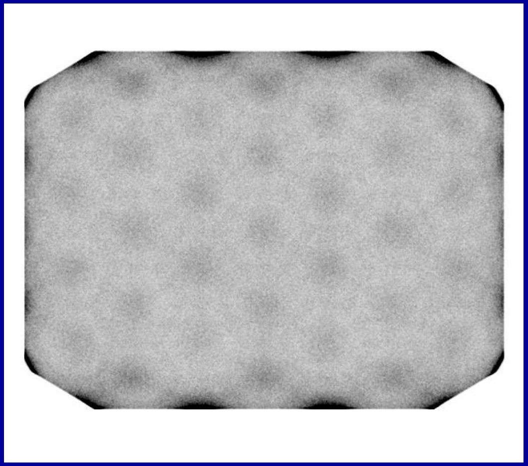
No corrections

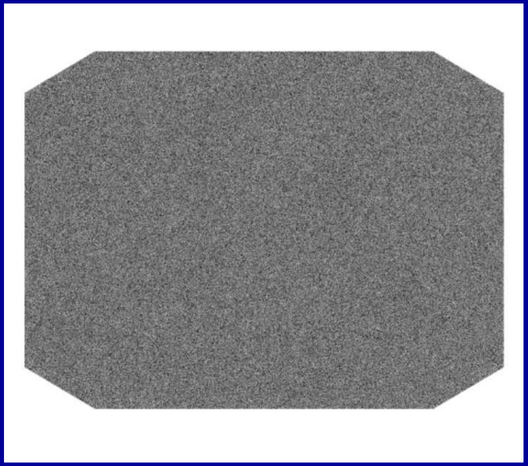




Energy And Linearity

Energy only





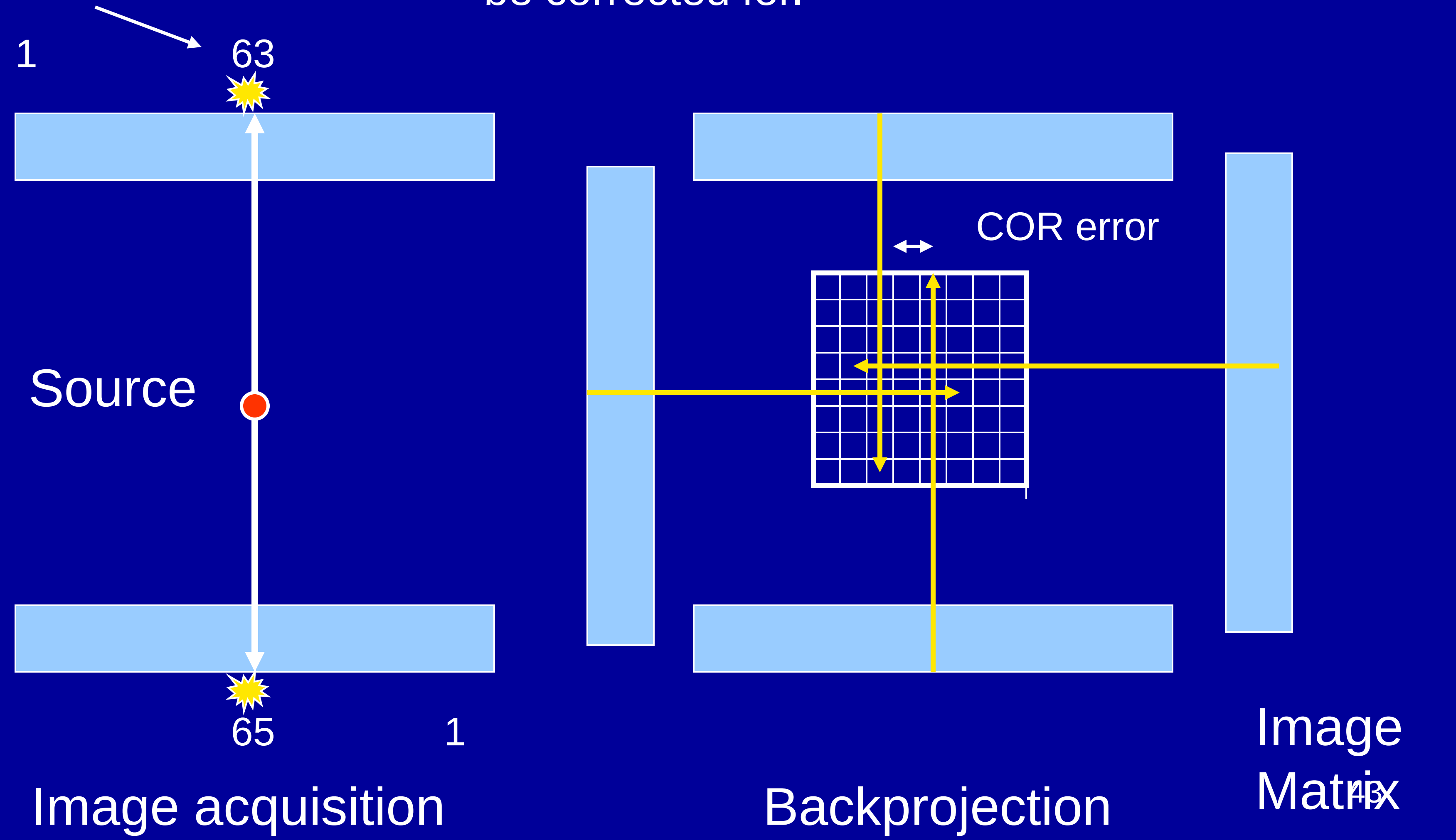
Energy, Linearity, Uniformity (all corrections)

^{99m}Tc Intrinsic Flood Images

Center of Rotation

Pixel number
recording signal
128x128 matrix

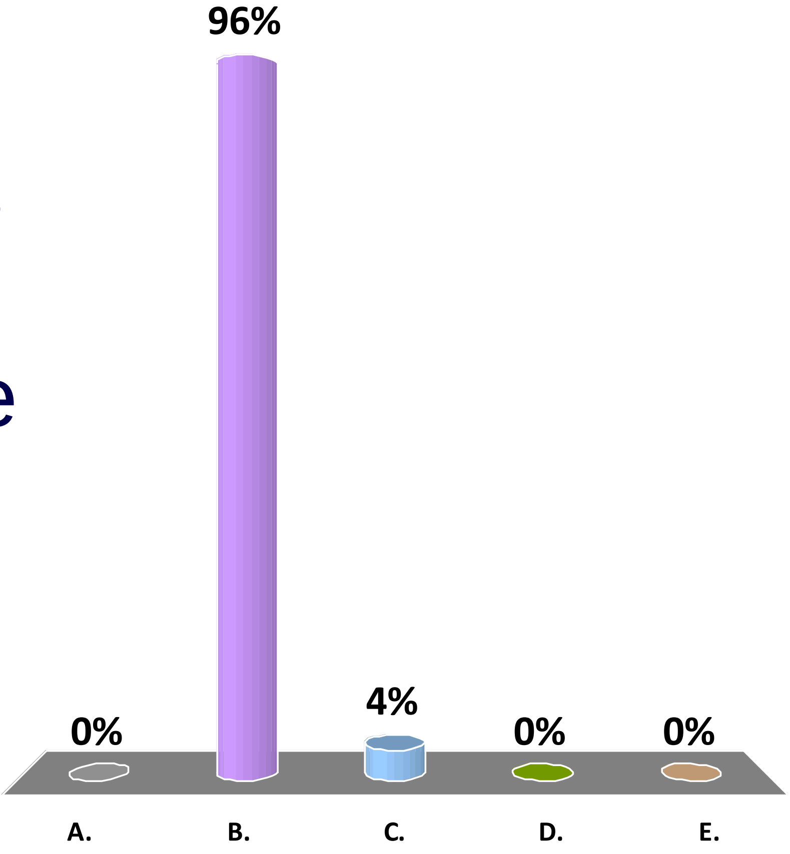
Offsets between physical center of rotation and center of image matrix must be corrected for.



SAMS Question

What is the primary function of a collimator in a gamma camera?

A. Protect the crystal
B. Define direction of incoming gamma rays entering crystal
C. Substantially eliminate scatter
D. Reduce count rate to prevent dead time
E. Shield the electronics



What is the primary function of a collimator in a gamma camera

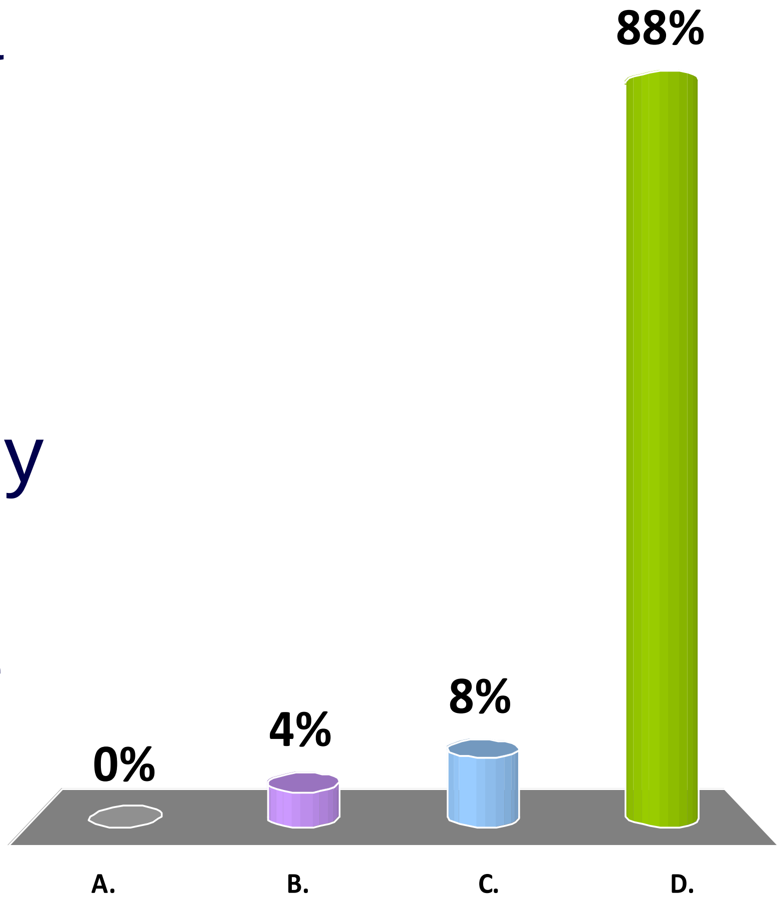
A. Protect the crystal
B. Define direction of incoming gamma rays entering crystal
C. Substantially eliminate scatter
D. Reduce count rate to prevent dead time
E. Shield the electronics

Reference: The Essential Physics of Medical Imaging, JT Bushberg, JA Seibert, EM Leidholdt Jr, JM Boone, 3rd edition, 2012, 680-681.

SAMS Question

Which would improve spatial resolution in gamma camera images?

A. Choose a camera with a thicker crystal
B. Use a 64X64 matrix rather than 256X256
C. Image with lowest energy gamma rays available
D. Position patient as close as possible to collimator face



Which would improve spatial resolution in gamma camera images?

A. Choose a camera with a thicker crystal

B. Use 64 X 64 matrix rather than 256 X 256

C. Image with lowest energy gamma ray available

D. Position patient as close to collimator face as possible

Reference: The Essential Physics of Medical Imaging, JT Bushberg, JA Seibert, EM Leidholdt Jr, JM Boone, 3rd edition, 2012, 686-691.

Physics in Nuclear Medicine, SR Cherry, JA Sorenson, ME Phelps, 4th edition, 2012,365-366.

- Routine QC tests are performed daily and weekly, typically by technologists
- Physicists should perform annual assessments.
- Accrediting bodies provide standards for annual tests

Joint Commission Requirements

- Effective July 1, 2015, at least annually, assess:
  - Image uniformity/system uniformity
  - High contrast resolution/system spatial resolution
  - Sensitivity
  - Energy Resolution
  - Count Rate Performance
  - Artifact evaluation

American College of Radiology Accreditation

- At least annually:
  - Intrinsic uniformity
  - System uniformity
  - Intrinsic or System spatial resolution
  - Relative sensitivity
  - Energy Resolution
  - Count Rate Parameters
  - System performance for SPECT: tomographic uniformity, contrast and spatial resolution

Intersocietal Accreditation Commission (IAC) Recommendations

- Guidelines for annual tests include:
  - Overall system performance may be evaluated with a fillable phantom with cold inserts of different sizes and visually inspect resulting images
  - Collimator integrity, comparing intrinsic and extrinsic floods, should be performed as well as visual inspection of collimators

Routine QC - Uniformity

- Uniformity must be checked every day that gamma camera is used, before the first patient
- Uniformity (flood) image may be acquired with collimator on for system (extrinsic) uniformity or collimator off for intrinsic uniformity
- 5 million counts adequate for daily QC for large FOV camera, use 256 X 256 or 512 x 512 matrix (manufacturer may have specific recommendations)

System Uniformity

With collimator on, use planar sheet source:

^{57}Co sheet source
10-15 mCi when new
122 keV γ
Half life 270 days

Water filled sheet source
Add 10-15 mCi ^{99m}Tc
140 keV γ
Half life 6 hours

Intrinsic Uniformity

- General method – use ~ 500 μCi ^{99m}Tc point source, placed at a distance of five times the length of the camera field of view
- Some cameras have a special source holder and vendor specific procedure which allows the source to be closer

UAB MEDICINE

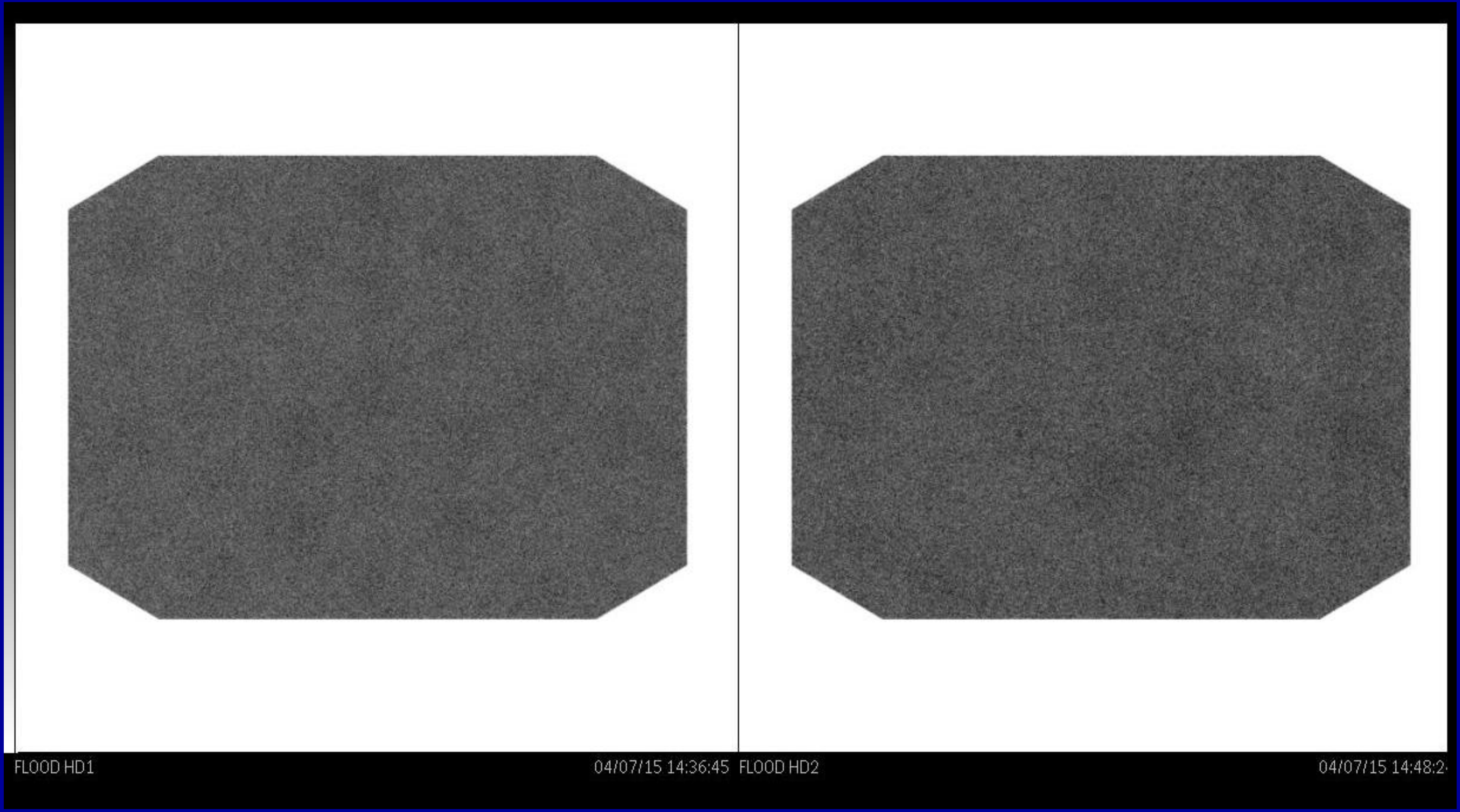
Knowledge that will change your world

Uniformity- Annual Testing

- Acquire intrinsic uniformity images with Tc-99m at low and high count rates – often the daily QC is only done with Co-57.
- Low count rate, typically 20-40 kcps, high count rate, 65-80 kcps, but refer to manufacturer's recommendations.
- The high count rate acquisition provides assessment of camera's function at higher count rates – modern cameras should still have good uniformity.

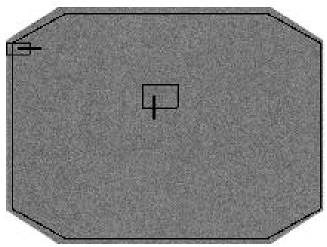
Good uniformity images

Poor uniformity



Uniformity - Quantification

QC 1 13 09 ARGUS



FLOOD

UFOV

CFOV

Full Report of Uniformity Analysis

NAME: QC 1 13 09 ARGUS ID: DK DATE: 13Jan2009

UFOV

Integral Uniformity = 4.49%

	Counts	Location
Minimum	2331	(6, 18)
Maximum	2550	(30, 26)

Row Differential Uniformity = 3.28%

Column Differential Uniformity = 2.41%

	Diff.	Location
Max Row	158	(6, 18)
Max Col	120	(29, 26)

CFOV

Integral Uniformity = 3.70%

	Counts	Location
Minimum	2368	(31, 44)
Maximum	2550	(30, 26)

Row Differential Uniformity = 2.81%

Column Differential Uniformity = 2.41%

	Diff.	Location
Max Row	138	(26, 27)
Max Col	120	(29, 26)

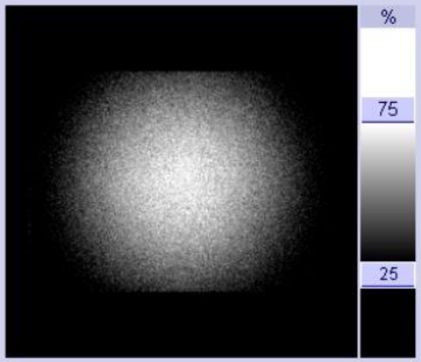
Integral Uniformity should be < 5% for 5M count extrinsic flood for camera following NEMA method for calculation. Refer to vendor specifications.

Series Description: Daily Intrinsic Flood10/11/06
Series Time: 1:23:41 PM

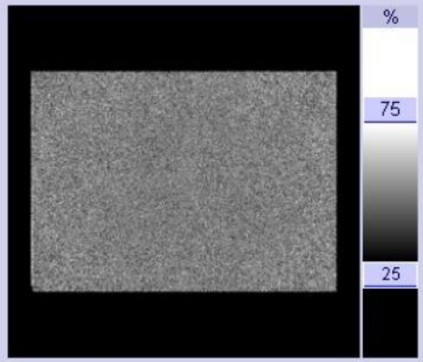
Intrinsic Verification

Patient ACR-UNIFORMITY

Detector 1



Acquired Flood



Curvature Corrected Flood

Study: QC

Series: Daily Intrinsic Flood10/11/06

Uniformity

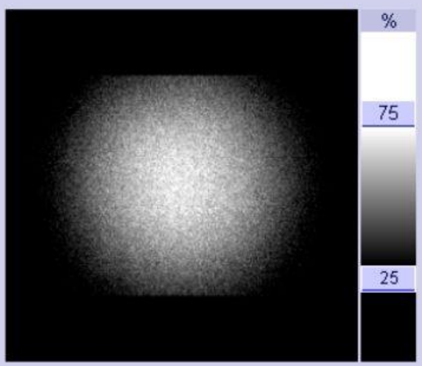
	Central FOV	Useful FOV
Integral:	2.14 %	2.61 %
Differential:	1.42 %	1.78 %

255

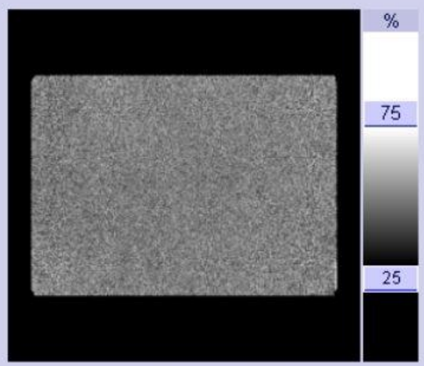
128

0

Detector 2



Acquired Flood



Curvature Corrected Flood

Study: QC

Series: Daily Intrinsic Flood10/11/06

Uniformity

	Central FOV	Useful FOV
Integral:	2.17 %	2.62 %
Differential:	1.77 %	1.77 %

Image QC Report

Status: Passed

Overview: Image QC completed successfully

Administrative Information

Camera: D630

Date: 08/05/2014 02:15:33

IP address: 127.0.0.2

User name: Administrator

Image QC Report | Background Test (Two Detectors) Report

Detector1

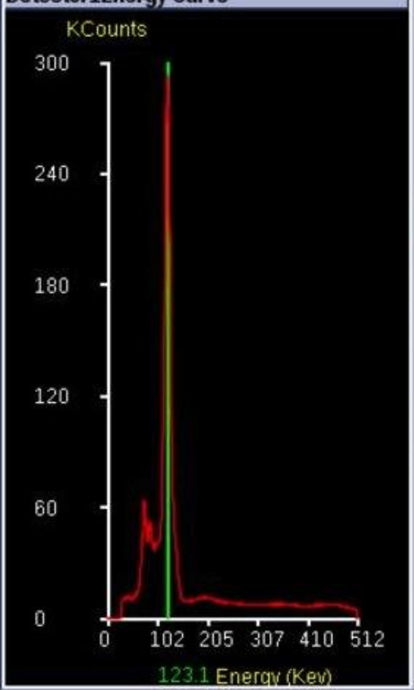
Parameter Name	Value	Acceptance Criteria
Isotope	Co57	
Energy Peak	123.1 kEV	122.0+-3.0
FWHM	10.35 %	<=12.0
Uniformity CFOV	2.005617 %	<=5.0
Uniformity UFOV	2.795772 %	<=5.5
Total Count	4000 Kcts	>=4000.0 and <=400000.0
Count Rate	19.47 Kcts/sec	>=1.0 and <=45.0

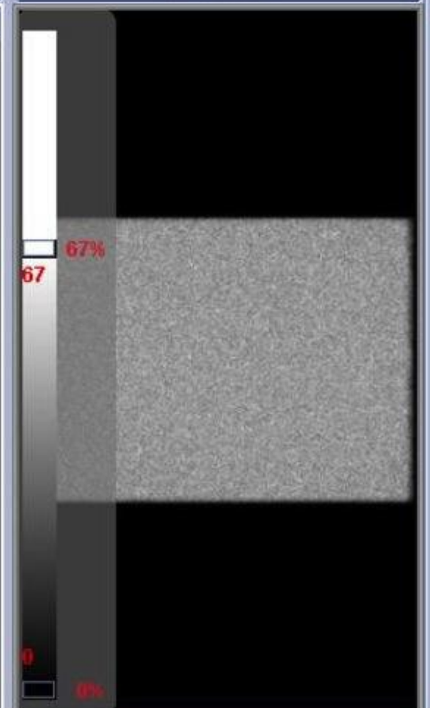
Detector2

Parameter Name	Value	Acceptance Criteria
Isotope	Co57	
Energy Peak	122.95 kEV	122.0+-3.0
FWHM	10.26 %	<=12.0
Uniformity CFOV	2.872601 %	<=5.0
Uniformity UFOV	4.040756 %	<=5.5
Total Count	4212 Kcts	>=4000.0 and <=400000.0
Count Rate	20.51 Kcts/sec	>=1.0 and <=45.0

Detector1PHA | Detector1

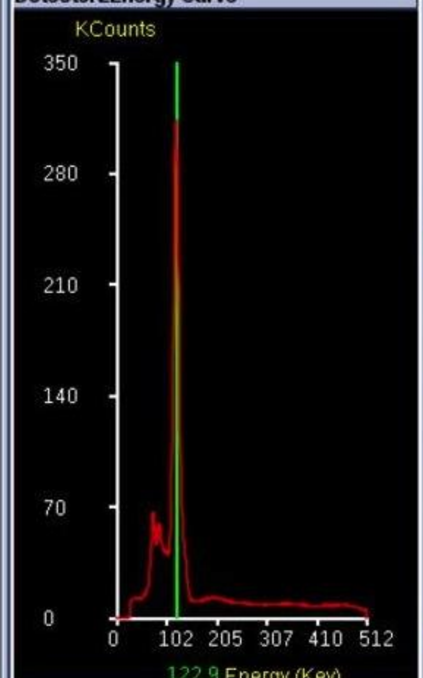
Detector1Energy Curve

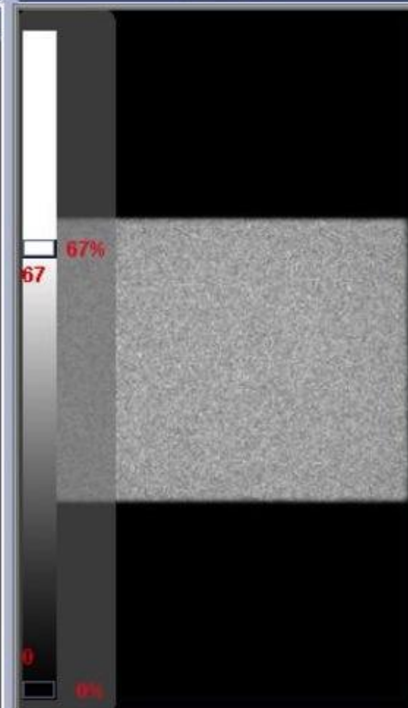




Detector2PHA | Detector2

Detector2Energy Curve



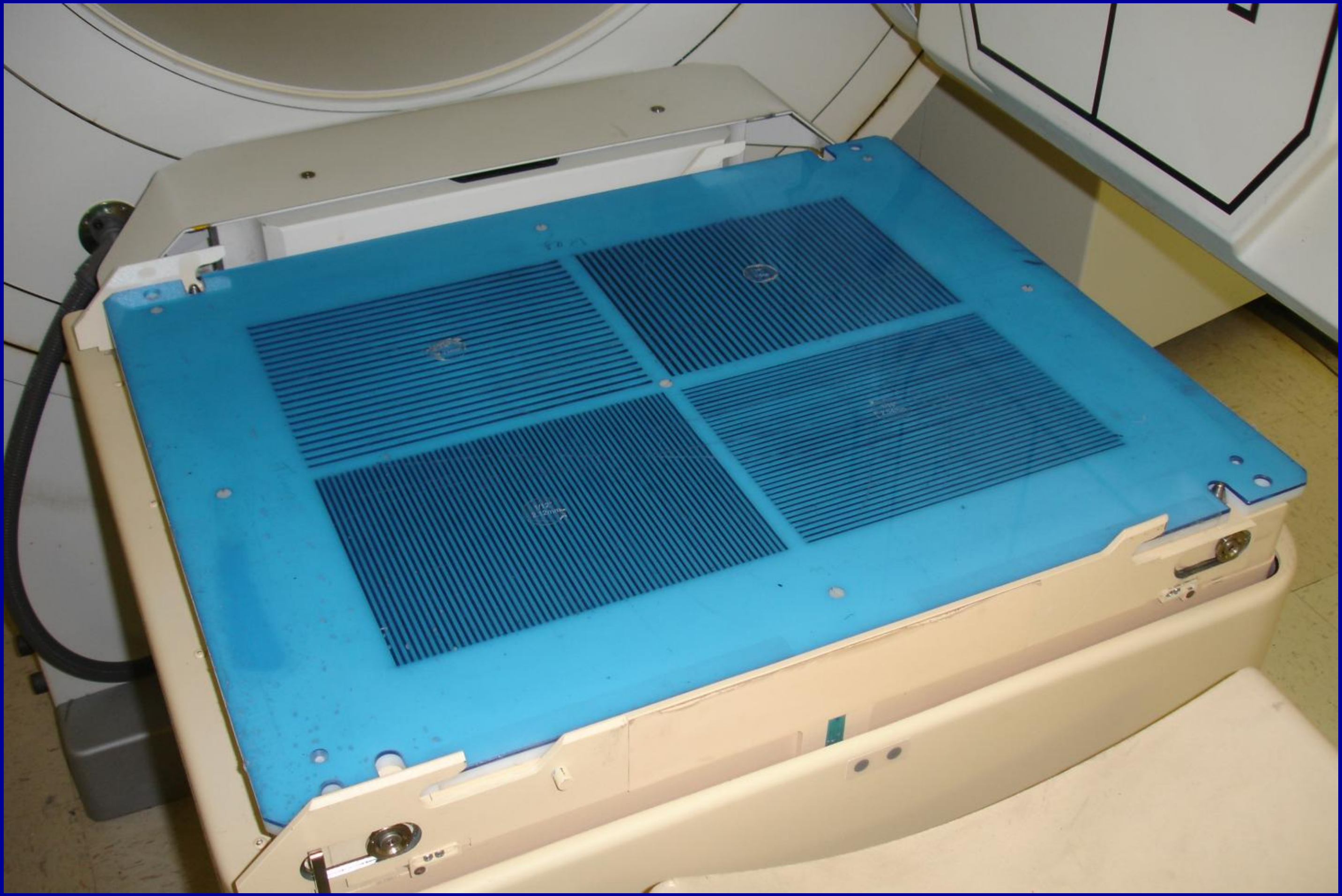


Spatial Resolution and Linearity

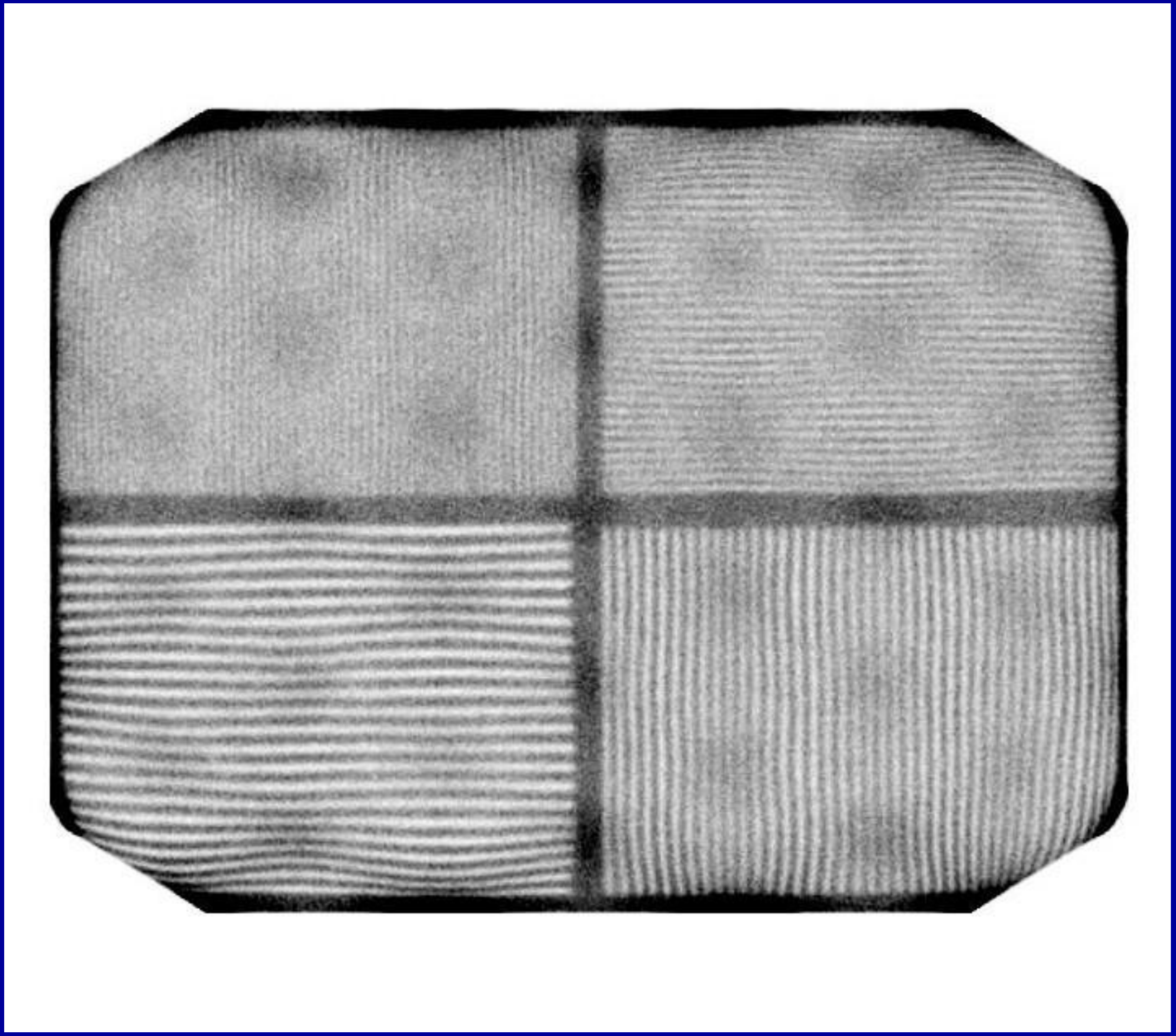
- Routine QC - Image bar pattern at least weekly, extrinsically or intrinsically, to check spatial resolution and linearity
  - Confirm that smallest resolvable bar pattern remains the same with no abrupt changes
  - Ensure that bars do not appear significantly wavy, and no abrupt change in appearance
- 2.5 M counts adequate for weekly QC
- Annual test do intrinsic bars. 5 M counts is required for ACR accreditation submission. Be very careful using bar pattern with collimator off.

UAB MEDICINE
Knowledge that will change your world

Spatial Resolution – Four Quadrant Bar Pattern



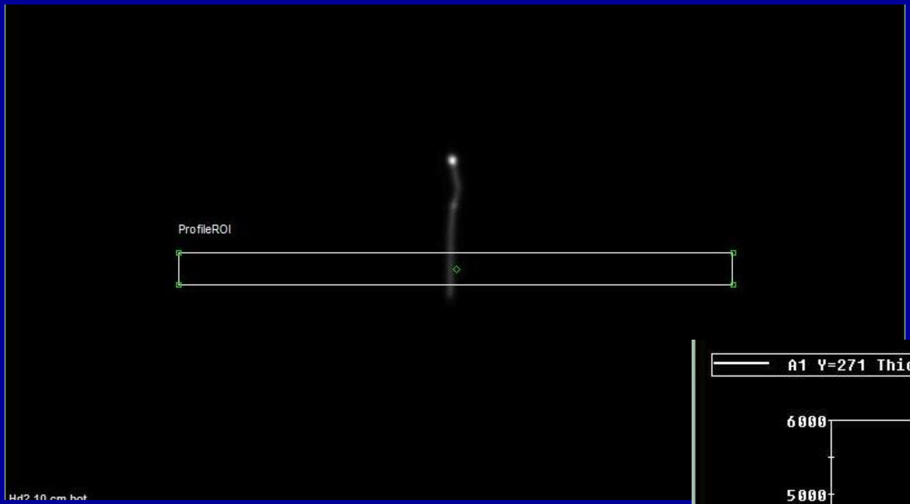
Intrinsic Bars – Linearity Correction Off

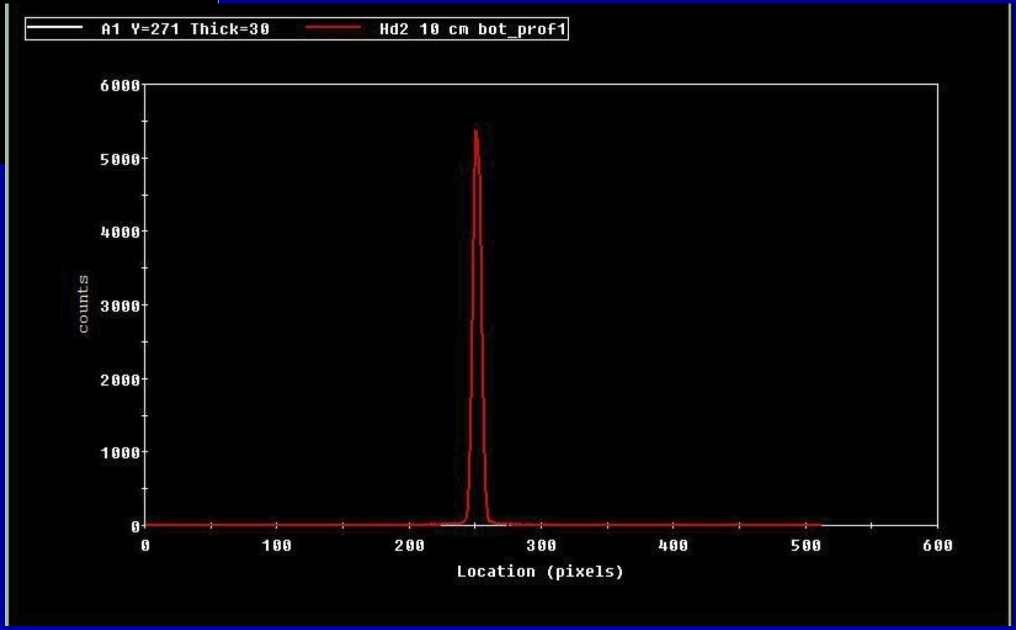


Extrinsic Resolution (FWHM) with Line Source

- Image a thin line source (plastic or glass tube) filled with ^{99m}Tc, (at least ~ 1mCi/ml) 10 cm from collimator
- Use matrix size so that pixel size less than about 1/5 expected FWHM
- Draw profile across image to produce curve of counts vs. pixel
- Determine FWHM with available software, or other means

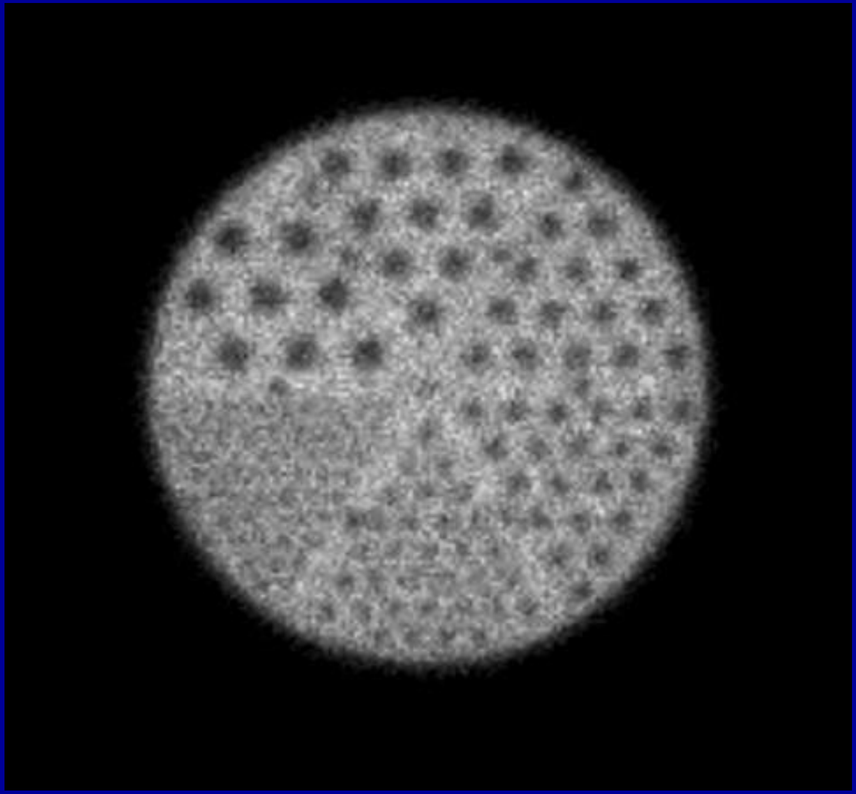
Line source profile and curve



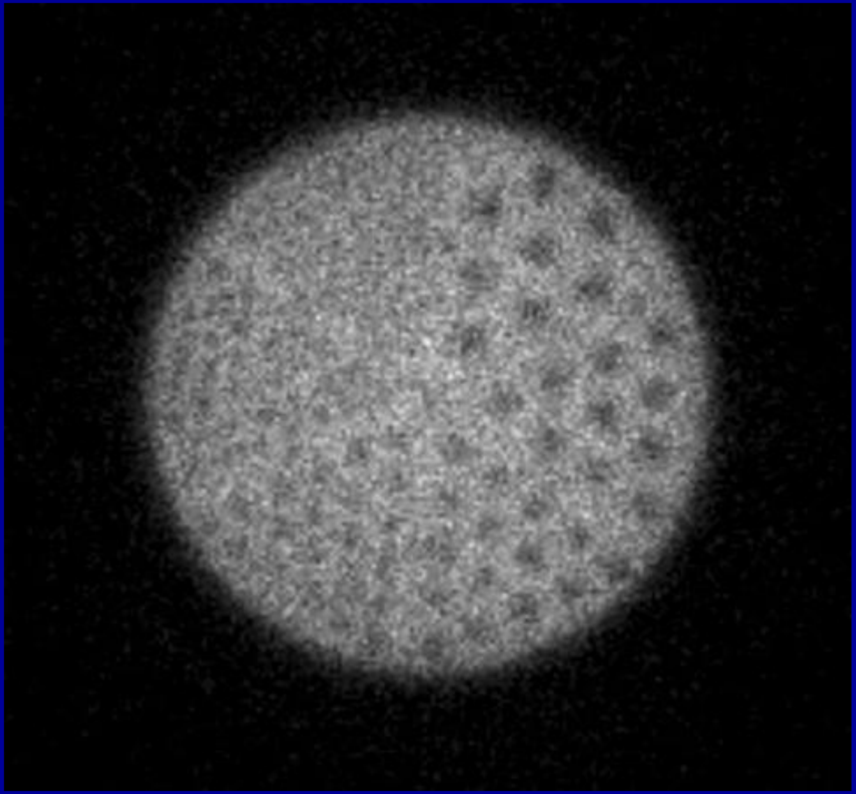


FWHM= 7 pixels = 7.7 mm

System Resolution with Scatter



Tc-99m



Tl-201

Static images of SPECT phantom standing on end on top of collimator. Provides a measure of planar system resolution with scatter.

Measuring Sensitivity

- Place ~1-2 mCi ^{99m}Tc, and small volume of water in plastic flat-bottomed vial on top of Styrofoam cup 10 cm from collimator face.
- Record exact activity and time
- Count for 1 min, also count and subtract background
- Use total counts in image, not an ROI drawn around image

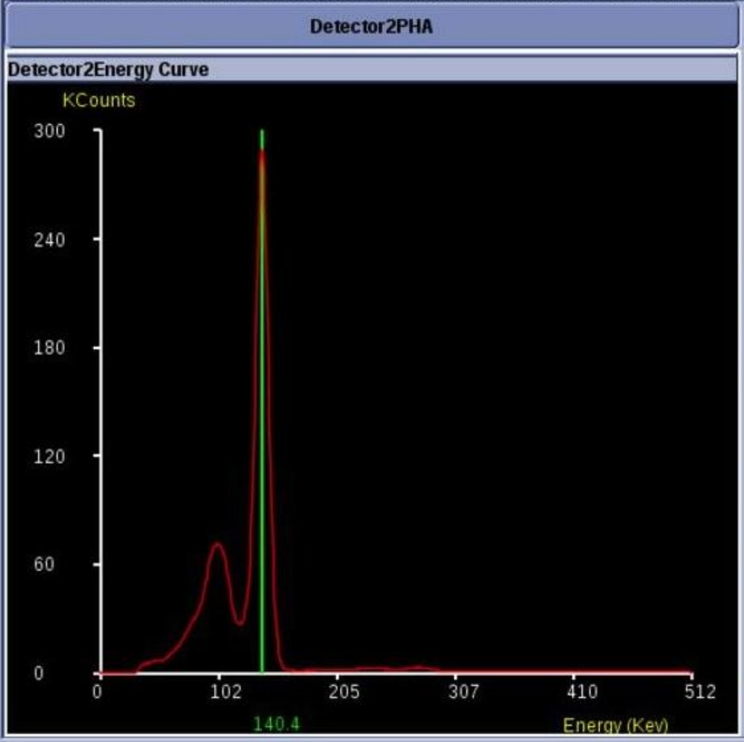
Measuring Sensitivity

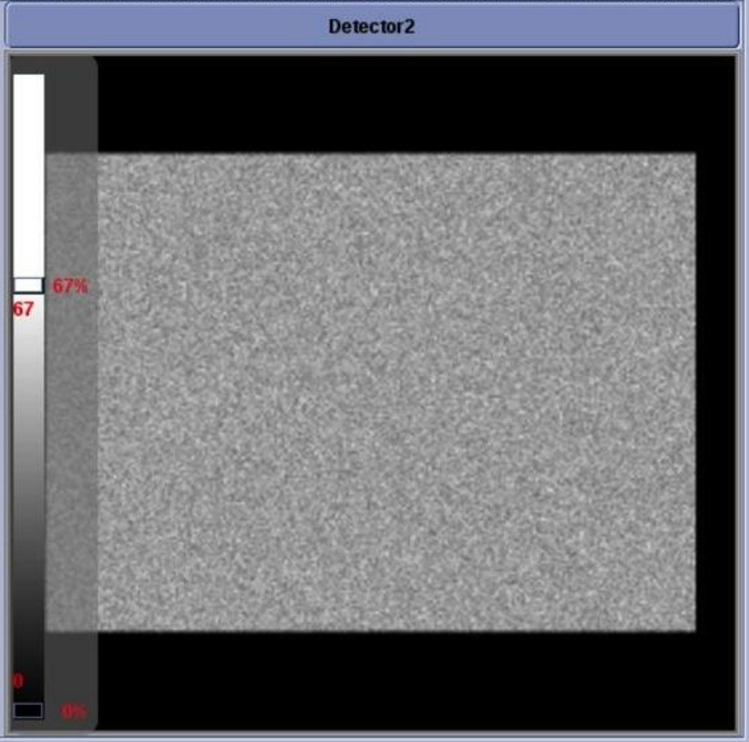
- Compute cpm/μCi and compare with vendor specifications, also check that both heads have comparable sensitivity (within about 5%)
- If camera is off peak it will affect results, also ensure window width is same as manufacturer's specification
- A syringe will give comparable results, use a small volume spread out through syringe rather than a tiny point source

Energy Resolution Measurement

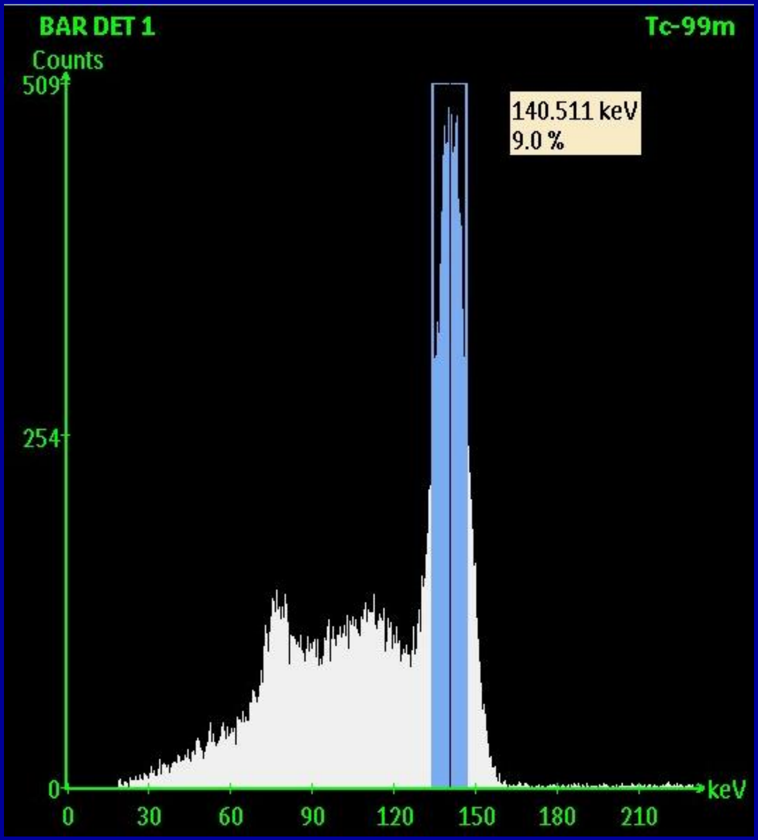
Detector2

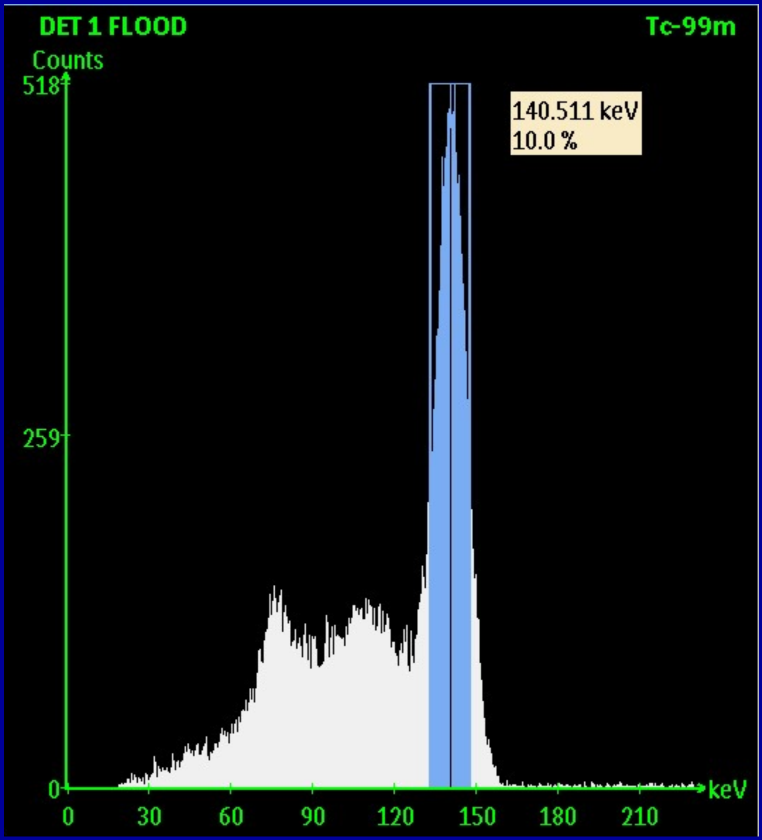
Parameter Name	Value	Acceptance Criteria
Isotope	Tc99m	
Energy Peak	140.39 kEV	140.5+-3.0
FWHM	9.21 %	<=11.0
Uniformity CFOV	1.689503 %	<=5.0
Uniformity UFOV	1.776161 %	<=5.5
Total Count	4000 Kcts	>=4000.0 and <=400000.0
Count Rate	85.04 Kcts/sec	>=1.0 and <=45.0





Estimating Energy Resolution





- Estimate ~ 9% energy resolution – photopeak width is approximate width of 9% window at half the peak height

Count Rate Performance

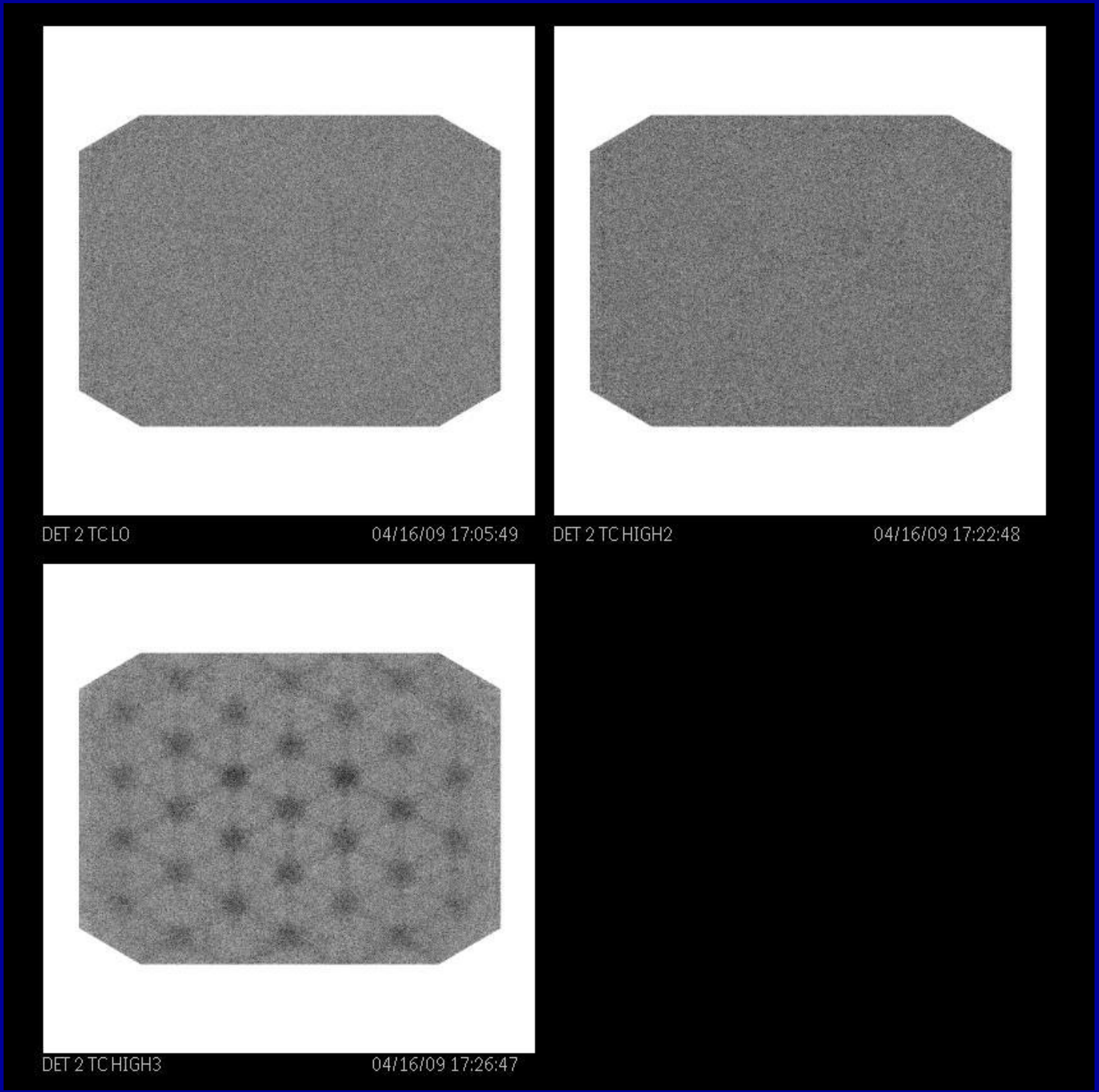
- Measure maximum count rate with point source and collimator off. Approach camera with point source and observe count rate go up, until close enough that it decreases due to dead time. Note maximum count rate (a good estimate). Quickly move source away.
- Acquire uniformity images at high count rate and ensure uniformity is still reasonable (65-80 kcps for most newer cameras, older cameras may have performance degradation at lower count rates)

Low to High Count Rate Intrinsic Floods

19 kcps

79 kcps

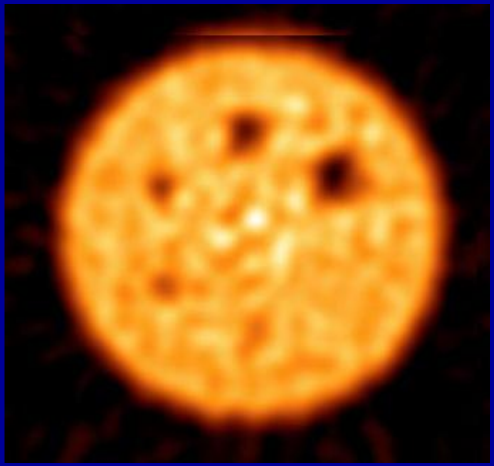
109 kcps (too high without high count rate mode corrections)

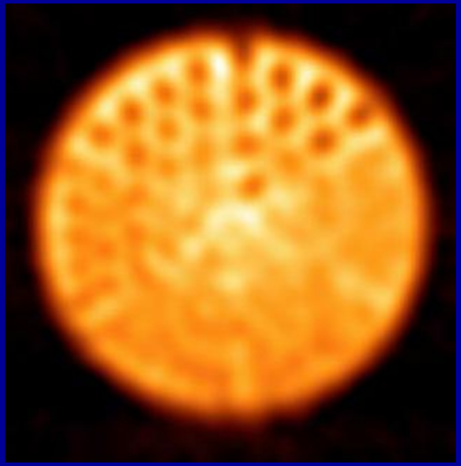


- Acquire images with SPECT phantom to evaluate contrast, resolution and uniformity, including artifact evaluation

SPECT Phantom Imaging

- Deluxe version has spheres of diameters: 31.8, 25.4, 19.1, 15.9, 12.7, 9.5 mm
- Rods of diameters: 12.7, 11.1, 9.5, 7.9, 6.4 and 4.8 mm





SPECT phantom imaging procedure

- Make sure largest sphere lined up with largest rod section (rotate if needed)
- Fill phantom with ~20-25 mCi ^{99m}Tc for high res collimator. Count rate should be < 30kcps
- Use ^{99m}Tc sodium pertechnetate. Some radiopharmaceuticals may stick to the plastic or nylon screws and cause artifacts

SPECT phantom imaging procedure

- Center phantom in field of view
- For cardiac cameras with 180 deg orbit, align largest sphere and rod section with center of leading detector for first frame.
- ACR protocol is for 32 M total counts. Check count rate, adjust time per stop to achieve this.

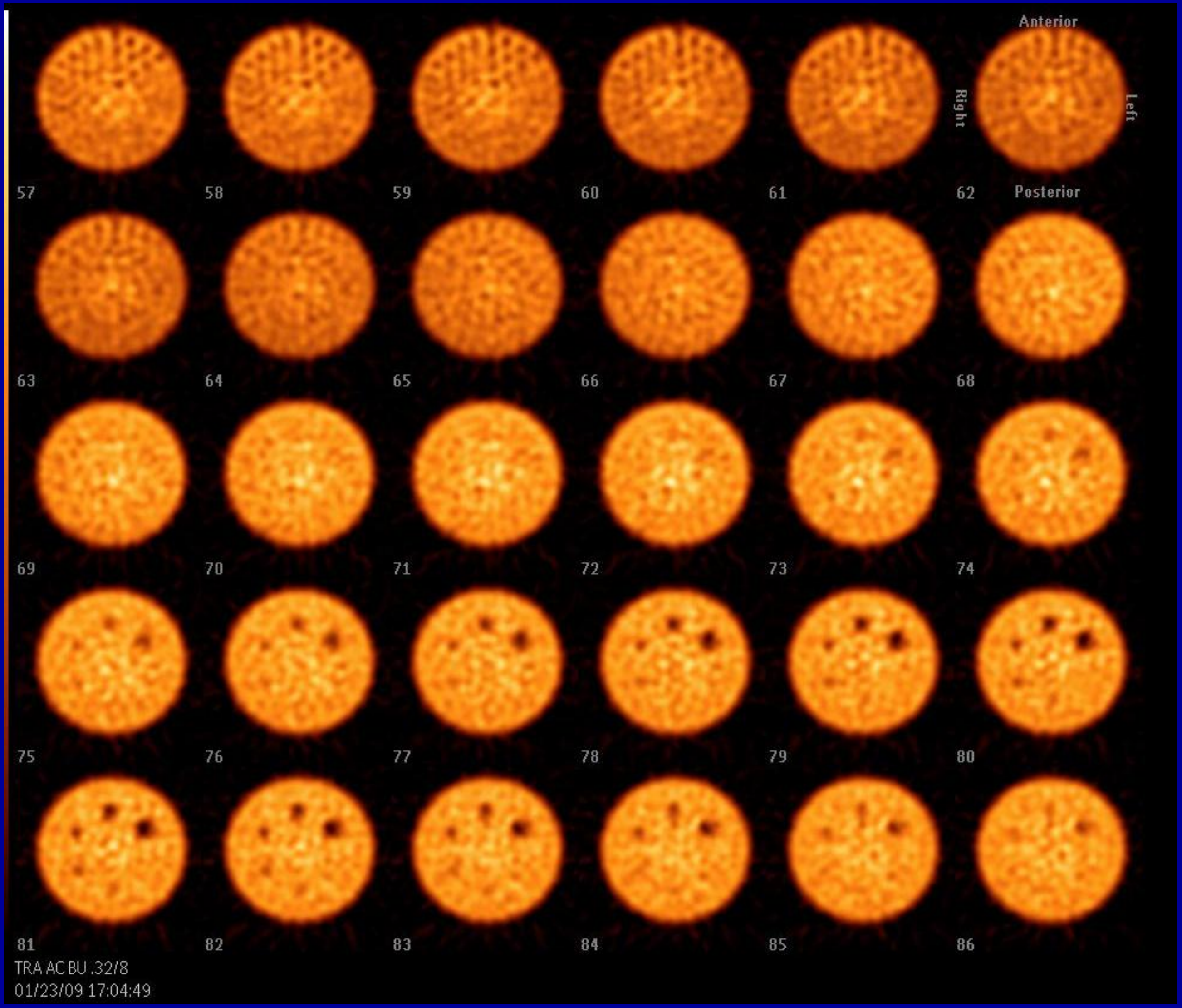
UAB MEDICINE

Knowledge that will change your world

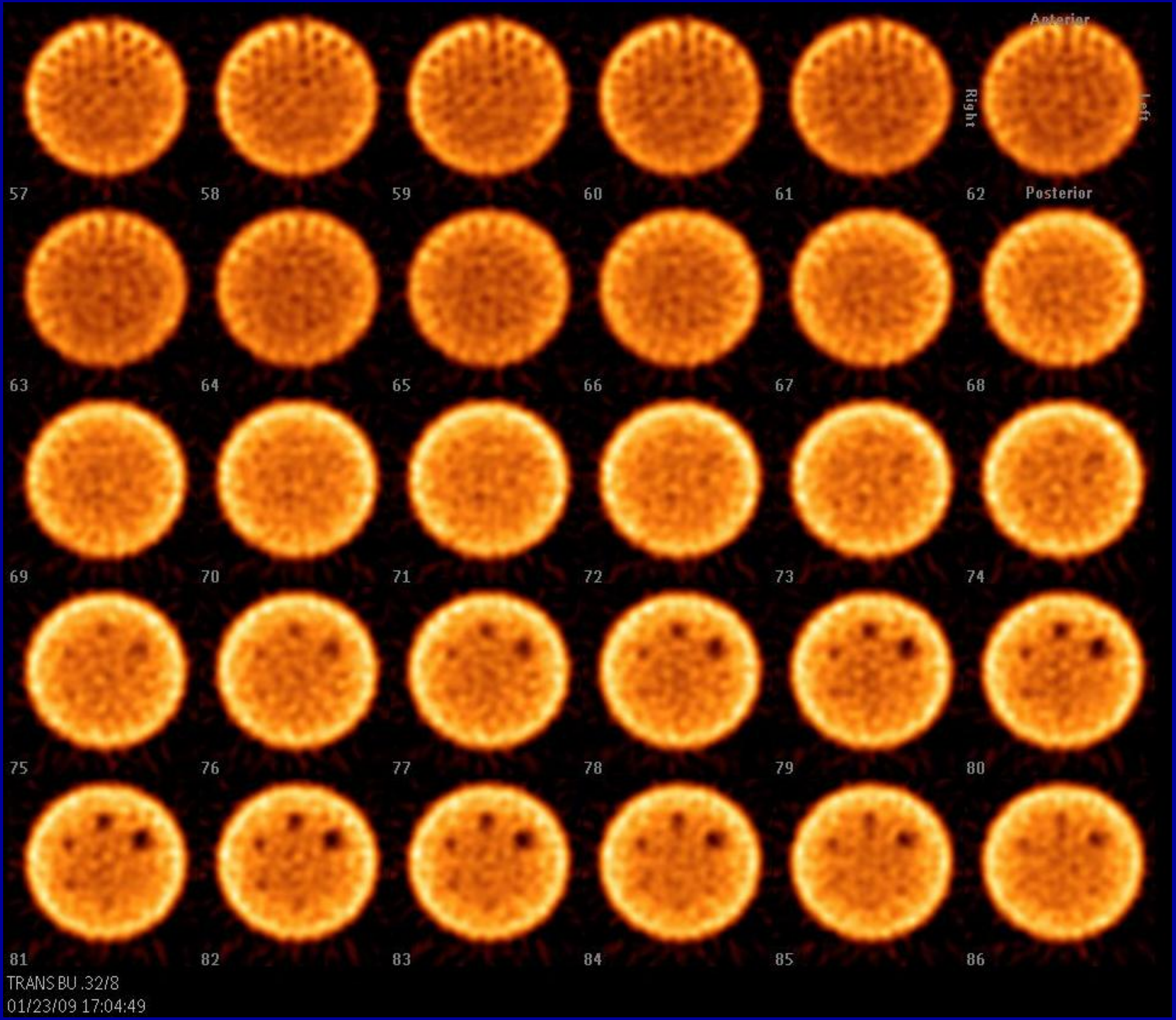
SPECT phantom imaging procedure

- Use 128 X 128 matrix, 120 or 128 views over 360 degrees (180 degrees for a cardiac camera that cannot do 360 degree rotation) Adjust zoom factor as needed to achieve pixel size close to 3 mm. (ACR says 2.7 to 3.3 mm)1.33 to 1.46 are common zoom factors for large FOV camera
- Use a radius of rotation as close to 20 cm as possible (an elliptical orbit is helpful)
- Apply attenuation correction during image reconstruction.

SPECT phantom reconstructed slices



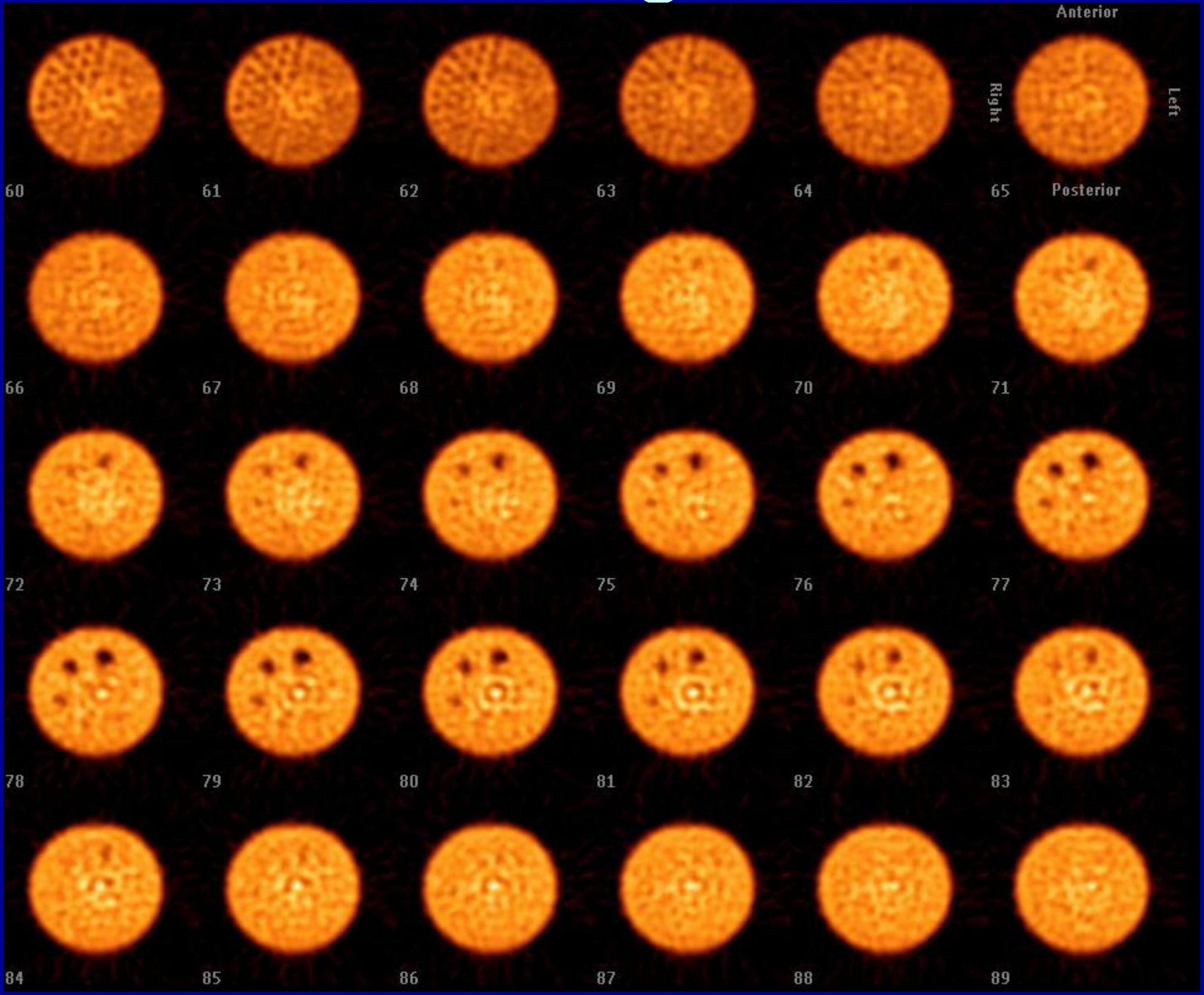
SPECT phantom reconstructed slices – no attenuation correction



SPECT phantom image quality

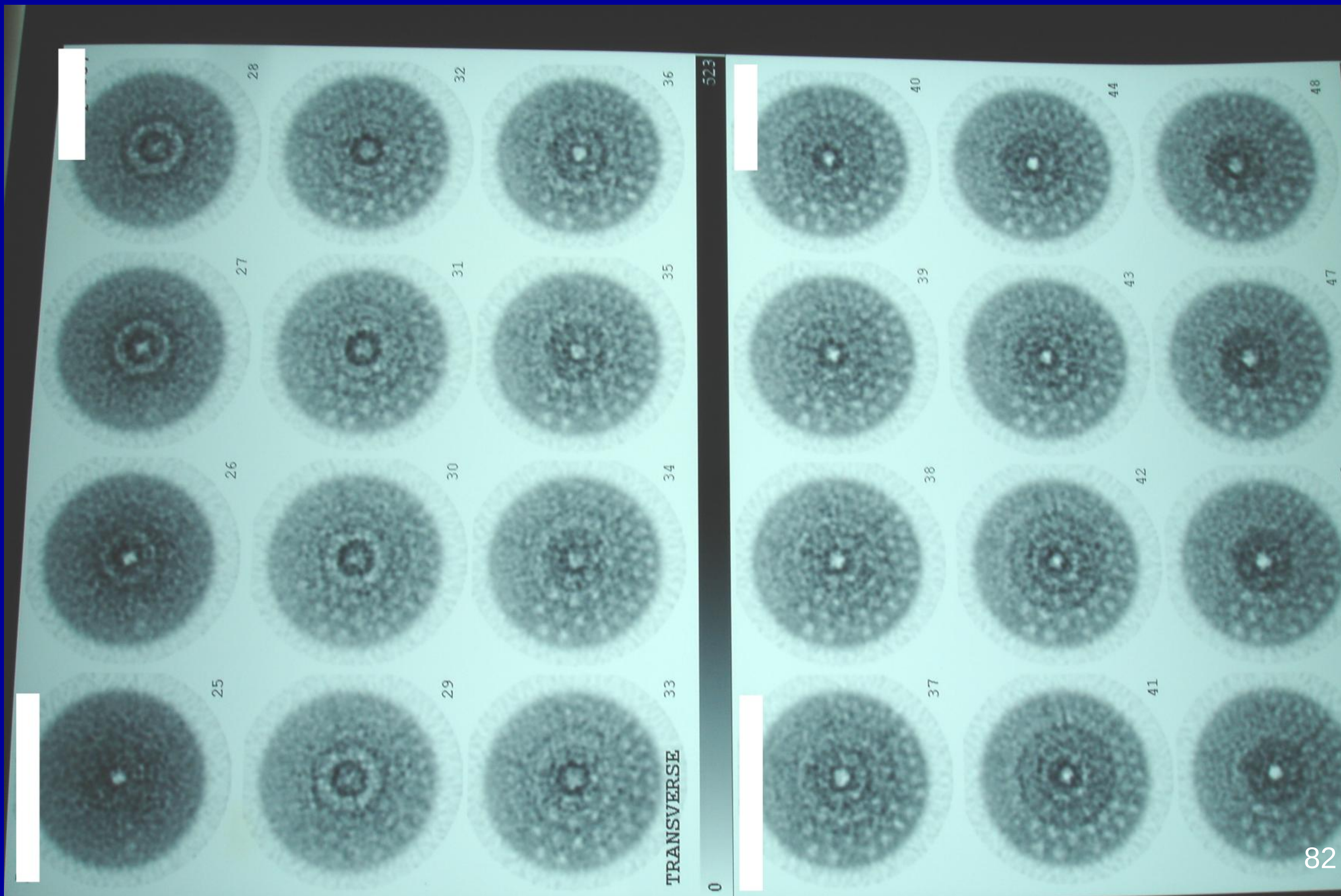
- Phantom images visually inspected for:
  - Resolution – smallest size of rods visible
  - Contrast – number of spheres visible
  - Uniformity – look for ring type artifacts or other artifacts
- For guidelines on acceptable image quality, refer to ACR website for accreditation scoring criteria. Criteria vary according to type of collimator and radionuclide used (although currently it is only required to submit SPECT images for Tc-99m)

Ring Artifacts



Ring artifacts visible

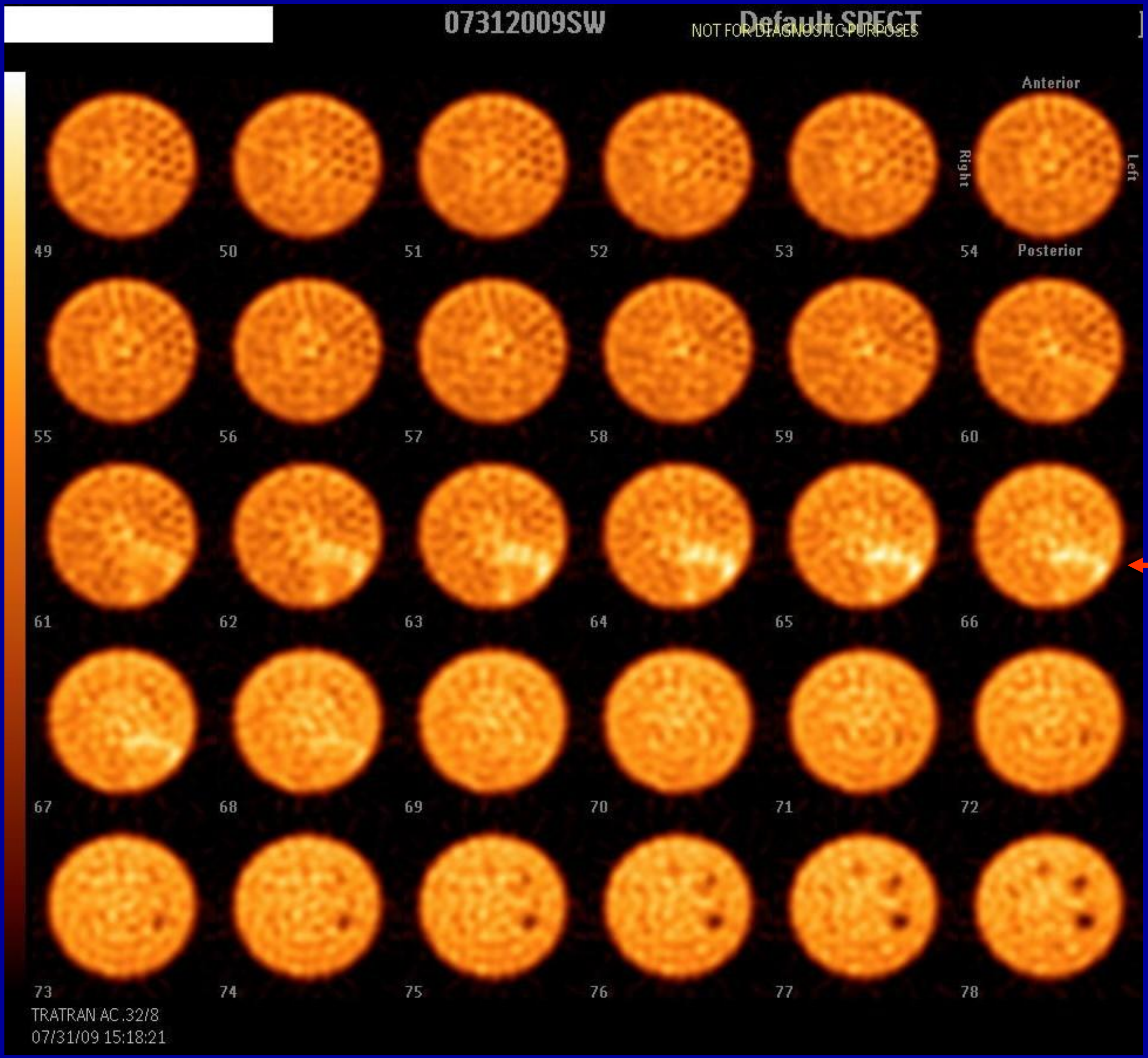
Severe Ring Artifacts



SPECT Ring Artifacts

- Caused by non-uniformities such as:
  - Visible non-uniformities in flood image due to camera being off peak, PMT gain imbalance, or need for new correction tables
  - Shift in photopeak as camera head rotates
  - Collimator defect or damage (not visible in intrinsic flood image)
- Even small non-uniformities can cause ring artifacts

Phantom filled with ^{99m}Tc Sestamibi rather than Sodium Pertechnetate



Artifact

SAMS Question

Which of these is not specifically listed as an annual physics test required by TJC or ACR?

13% A. Sensitivity

74% B. Center of Rotation

0% C. Uniformity

13% D. Energy Resolution

Which of these is <u>not</u> specifically listed as an annual physics test required by TJC or ACR?

A. Sensitivity

B. <u>Center of Rotation</u>

C. Uniformity

D. Energy Resolution

References: The Joint Commission Revised Requirements for Diagnostic Imaging Services, http://www.jointcommission.org/assets/1/6/HAP-CAH_DiagImag_Prepub_July2015release_20150105.pdf

ACR Nuclear Medicine Accreditation Program Requirements, http://www.acr.org/Quality-Safety/Accreditation/Nuclear-Med-PET

SAMS Question

What is the primary cause of ring artifacts in SPECT phantom images?

86%	A. Non-uniformities
14%	B. Center of Rotation error
0%	C. Phantom off center in field of view
0%	D. Using the wrong matrix size

What is the primary cause of ring artifacts in SPECT phantom images?

A. **Non-uniformities**

B. Center of Rotation error

C. Phantom off center in field of view

D. Using the wrong matrix size

Reference: The Essential Physics of Medical Imaging, JT Bushberg, JA Seibert, EM Leidholdt Jr, JM Boone, 3rd edition, 2012, 718-719.

SAMS Question

Imaging and recording counts for a known amount of activity in a small flask for 1 min is a method of measuring ______?

13% A. Uniformity

4% B. Spatial Resolution

79% C. Sensitivity

4% D. Energy Resolution

Imaging and recording counts for a known amount of activity in a small flask for 1 min is a method of measuring ______?

A. Uniformity
B. Spatial Resolution
C. **<u>Sensitivity</u>**
D. Energy Resolution

Reference: AAPM Virtual Library, 2012 Spring Clinical Meeting, talk by James Halama: Nuclear Medicine-Testing of Gamma Camera, SPECT and SPECT/CT Systems in a Clinical Environment, http://www.aapm.org/education/VL/vl.asp?id=125

The End