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Acceptance Testing and Annual Physics Survey Recommendations for Gamma Camera, SPECT, and SPECT/CT Systems

The Report of AAPM Task Group 177

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Contents

1. Introduction

This report makes recommendations for performing acceptance tests and annual physics surveys of gamma camera and SPECT systems. Recommendations are compiled from several documents and publications that define and describe methods for gamma camera testing and from the experience of many medical physicists working in the field of nuclear medicine. Recommendations for SPECT/CT are a new feature of this document. They are of limited scope to address issues of SPECT and CT spatial alignment and tests to assure a certain degree of attenuation correction accuracy and image quality.

For acceptance testing, the focus is on being able to test newly installed systems in a clinic with available phantoms in a day's time that will provide sufficient data to evaluate manufacturer specification and provide clinically relevant results. A subset of results is also to be used as reference data for subsequent annual surveys. An annual physics survey of system performance should become an essential component in any nuclear medicine imaging quality assurance program.

The tests described in this report are categorized into four sections: Physical Inspection, Gamma Camera Planar Tests, SPECT Tests, and SPECT/CT Tests. The tests include recommendations for both acceptance testing and an annual physics survey. Those for acceptance testing are to be performed only once. An acceptance protocol should also include all the tests recommended for an annual survey.

2. Current State of Gamma Camera and SPECT Testing

2.1 Acceptance Testing

Historically, only a minority of gamma camera systems undergo acceptance testing at the time of installation. It is a widely accepted view by experienced medical physicists that the performance tests prescribed in the NEMA and IEC standards are not practical on systems installed in a clinic. In the United States, the reference standard for acceptance testing is NEMA NU 1-2012[1]. Internationally, the reference standards are IEC 60789[2], 61675-2[3], and 61675-3[4]. The NEMA and IEC tests were designed to provide data for comparing system performance between gamma camera models. The specified equipment, test patterns, and software are not readily available, so that arrangements with the camera vendor to provide these tools have become a necessity in order to perform these tests. Acceptance testing is now required by imaging facilities that have been accredited by The Joint Commission (TJC) and the American College of Radiology (ACR) nuclear medicine accreditation program. Therefore, there is a critical need to develop an acceptance testing protocol for medical physicists to use that provides clinically relevant data validating that the gamma camera system is ready to be used for imaging patients and baseline data for subsequent annual surveys.

Many of the performance evaluations listed in this report are derived from the appropriate NEMA standards for gamma camera and SPECT systems. However, the methods that are described in the NEMA documentation are, in some cases, overly conservative and are not always practical to implement for installed systems. As a result, there will be some deviations from the NEMA methods presented in this report. These deviations are not expected to substantially alter the determination of the specified parameters.

2.2 Annual Physics Surveys

The ACR mammography accreditation program introduced the concept of performing an annual physics survey by qualified medical physicists[29] (QMP). This has been carried forward to all of the other accreditation programs that the ACR offers, including the nuclear medicine accreditation program. The set of annual survey tests described in this report are intended to serve as guides for annual physics surveys as required by the ACR[5]. Other guidance documents and technical reports—including

AAPM Task Group TG Report No. 9[6], TG Report No. 22[7], TG Report No. 52[8], and IEC Technical Report IEC/TR 61948-2[9]—are also referenced.

2.3 Expert Survey

Expert medical physicists were surveyed to assist in determining which performance tests are relevant and which should be performed during an acceptance test and follow-up annual physics surveys. Suggestions for additional tests and modifications of standard tests were also solicited. The survey was sent to 343 physicists and scientists listed by the AAPM and the Society of Nuclear Medicine and Molecular Imaging. A large group of physicists was selected to ensure that the largest cross-section of physicists who perform gamma camera testing could be reached. Forty-six responses were received. The respondents' years of experience ranged from 5–26 years with an mean of 22.5 years. The years of experience for those who specifically test gamma cameras ranged from 2–25 years with an mean of 19.1 years. When asked if acceptance tests should be a simplified version of the NEMA tests, 100% of the respondents said yes. Eighty-five percent said that the set of prescribed tests should be completed in a day's time.

The results of the survey are listed in Table 1. The questions on the survey were whether the respondent performs each test described in the documents NEMA NU 1-2007[1] and IEC 60789[2], 61675-2[3], and 61675-3[4]. Not all the respondents answered every survey questions and, therefore, the number of respondents for each test listed varies.

Table 2 lists other tests of interest suggested by the respondents. The measurement of uniformity by using off-peak floods has the greatest interest, looking for crystal hydration. This may be more relevant for annual testing.

3. Preparatory Steps

Prior to acceptance testing or an annual physics survey, several steps should be taken. Arrange for a technologist to assist with drawing up and assaying radionuclides in the hot lab, filling the phantoms, operation of the gamma camera and SPECT systems, and positioning of sources and phantoms for testing.

3.1 Preventive Maintenance and Calibrations

Preventative maintenance should be performed by a service engineer prior to physics testing to ensure that mechanical motions and collimator exchangers are working properly, that the detector photomultiplier tubes (PMTs) are properly tuned, and that energy and linearity corrections are within specifications. All necessary calibrations, including SPECT, should be performed prior to the time of testing by a service engineer or technologist.

3.2 Radionuclides for Testing

Contact the clinic to determine the radionuclides that are used clinically, and determine the amount of each nuclide that will be needed for the appropriate tests. The clinic is responsible for ordering and making these radionuclides available on the day of testing.

The most commonly used radionuclides are ^{99m}Tc, ^{57}Co, ^{201}Tl, ^{123}I, ^{67}Ga, ^{131}I, and ^{111}In. A subset that includes ^{99m}Tc and at least one other radionuclide should be available. Familiarity with the tests described below will help to identify the radionuclides needed. The activities of the sources depend on whether tests are to be performed intrinsically, extrinsically, or for SPECT.

3.3 Test Equipment and Manuals

Contact the clinic regarding the availability of test phantoms and manufacturer operator's manuals for the equipment. The clinic should be able to provide a ^{57}Co sheet source, a quadrant-bar phantom, and a SPECT phantom. The clinic should provide space for test equipment while it decays, should any become contaminated during testing.

Table 1: Expert Survey. Physicists were asked whether they perform the listed performance tests during acceptance testing and during an annual physics survey. Fraction is the fraction of physicists who perform the test.

Test	Acceptance Testing			Annual Survey		
	Number Responding	Number Performing	Fraction	Number Responding	Number Performing	Fraction
Intrinsic Energy Resolution for ^{99m}Tc	45	43	**0.96**	36	34	**0.94**
Intrinsic Spatial Resolution for ^{99m}Tc	44	40	**0.91**	35	21	**0.60**
Intrinsic Spatial Resolution at 75,000 cps	44	16	**0.36**	36	2	**0.06**
Address Pile Up at High Count Rates	44	5	**0.11**	36	3	**0.08**
System Spatial Resolution Without Scatter for ^{99m}Tc	44	34	**0.77**	36	18	**0.50**
System Spatial Resolution With Scatter for ^{99m}Tc	44	16	**0.36**	36	7	**0.19**
Intrinsic Spatial Linearity for ^{99m}Tc	42	36	**0.86**	33	25	**0.76**
Intrinsic Flood Field Uniformity	44	42	**0.95**	35	31	**0.89**
Intrinsic Flood Field Uniformity at 75,000 cps	44	19	**0.43**	35	6	**0.17**
System Flood Field Uniformity	43	35	**0.81**	35	26	**0.74**
Multiple Window Spatial Registration	44	35	**0.80**	36	13	**0.36**
System Planar Sensitivity	45	43	**0.96**	35	28	**0.80**
Collimator Penetration Fraction	44	2	**0.05**	36	1	**0.03**
Intrinsic Count Rate Characteristic	43	28	**0.65**	35	17	**0.49**
System Count Rate Characteristic	44	7	**0.16**	36	4	**0.11**
Detector Shield Leakage Test	43	29	**0.67**	36	2	**0.06**
Tomographic System Alignment–COR	45	43	**0.96**	36	30	**0.83**
Tomographic System Alignment–Head Tilt	43	27	**0.63**	35	17	**0.49**
Collimator Hole Misalignment	44	15	**0.34**	34	1	**0.03**
SPECT Reconstructed Spatial Resolution Without Scatter	44	23	**0.52**	35	8	**0.23**
SPECT Reconstructed Spatial Resolution With Scatter	45	30	**0.67**	36	16	**0.44**
SPECT System Volume Sensitivity	44	12	**0.27**	36	4	**0.11**
Detector–Detector Sensitivity Variation	40	22	**0.55**	32	13	**0.41**
Scatter Fraction	44	3	**0.07**	36	1	**0.03**
Whole-Body System Spatial Resolution Without Scatter	43	25	**0.58**	35	13	**0.37**
Whole-Body Scanning Constancy	44	11	**0.25**	35	3	**0.09**
Intrinsic Flood Field Uniformity Without Uniformity Correction	41	20	**0.49**	35	12	**0.34**
SPECT Image Quality	43	42	**0.98**	36	36	**1.00**
Physical Inspection	42	40	**0.95**	36	34	**0.94**
SPECT/CT Gantry Alignment	40	36	**0.90**	34	29	**0.85**
SPECT/CT–CT Number Linearity	35	30	**0.86**	31	24	**0.77**
SPECT/CT Image Quality, Accuracy of Attenuation, and Scatter Corrections	37	22	**0.59**	32	14	**0.44**

Table 2: Unsolicited tests suggested by survey respondents

Additional Tests	Number of Times Suggested	
	Acceptance Test	Annual Survey
Crystal Hydration	2	1
Energy Linearity	1	1
Intrinsic Off-Peak Flood	3	3
Collimator condition	1	1
Rotational Stability	1	1
SPECT Uniformity	1	1
SPECT/CT Homogeneity & Noise of CT Quality Phantom	2	2
SPECT/CT dose	1	1

3.4 Recommended tests for Gamma Camera and SPECT Systems

The tests described in this report are comprehensive and are intended to provide guidance for assessing the system performance under widely varying conditions. Table 3 provides a summary of the tests that the task group recommends to be performed for routine quality assurance, annual physics surveys, and acceptance testing. Use this table in preparation for appropriate testing. We also refer you to the IAEA Quality Control Atlas for Scintillation Camera Systems[14] which has many examples of the gamma camera tests and results that are being prescribed in this report. The atlas is freely downloadable as a pdf-type file over the Internet.

Table 3: Recommended routine, annual, and acceptance tests on gamma camera and SPECT systems

Type	Test	Frequency
Routine	Extrinsic flood field uniformity	Daily for one set of low energy collimators. All collimators that are used clinically should be tested at least quarterly.
	Intrinsic flood field uniformity	Daily as an alternative to daily extrinsic flood field uniformity.
	Extrinsic spatial resolution	Weekly quadrant bar phantom image with a ^{57}Co sheet source
	Intrinsic spatial resolution	Weekly as an alternative to weekly extrinsic spatial resolution
	SPECT center of rotation/ multiple-head registration	Monthly, or frequency recommended by the manufacturer
	SPECT Phantom	Quarterly with ^{99m}Tc and low-energy collimator
		For Hybrid SPECT/CT quarterly with ^{99m}Tc, low-energy collimator, and with CT attenuation correction, and scatter correction if available.
	Hybrid SPECT/CT spatial registration	Frequency as recommended by the manufacturer
	Hybrid SPECT/CT QA	Ensure that the manufacturer and ACR accreditation guidelines are performed daily, weekly, and monthly.
Annual	Physical inspection	Camera, computer, collimators, and safety locks
	Gamma detector shielding	Qualitative assessment
	Display monitors	System console and monitors used for diagnosis
	Extrinsic flood field uniformity	Test all collimators used clinically.
	Intrinsic flood field uniformity	^{99m}Tc and optionally one other radionuclide used clinically. The other radionuclides tested may be a subset covering the range of gamma energies imaged.
	Intrinsic off-peak uniformity	Test each detector, compare with baseline images
	Intrinsic spatial resolution and linearity	^{99m}Tc imaged with a quadrant bar phantom. Testing other radionuclides used clinically is optional.

Table 3, cont.: Recommended routine, annual, and acceptance tests on gamma camera and SPECT systems.

Type	Test	Frequency
Annual, cont.	Extrinsic spatial resolution	Quadrant bar phantom image with a ^{57}Co sheet source for one low-energy collimator
	Extrinsic planar sensitivity	^{99m}Tc for the commonly used low-energy collimator
	Energy resolution	For ^{99m}Tc
	Intrinsic count rate performance	Measure peak count rate. Optionally measure the dead time with the two-source method.
	Multiple window spatial registration	Optional
	Whole body scanning spatial resolution	Optional
	SPECT spatial resolution	Measured for ^{99m}Tc with a line source
	Evaluation of SPECT center of rotation and gantry tilt	Optional—evaluate with point source or line source projection images
	SPECT phantom	Phantom with ^{99m}Tc and low-energy collimator
		For Hybrid SPECT/CT phantom with ^{99m}Tc, low-energy collimator, and with CT attenuation correction
	Hybrid SPECT/CT spatial registration	Method as recommended by the manufacturer
	Hybrid SPECT/CT dose	Report CTDI dose measurement for commonly used SPECT/CT procedures. May be performed separately by another qualified medical physicist.
	Hybrid SPECT/CT image quality	Report CT image quality measurements with ACR CT Phantom. May be performed separately by another qualified medical physicist.
Acceptance	Physical inspection	Camera, computers, collimator, and safety locks
	Gamma detector shielding	Qualitative assessment
	Display monitors	System console and monitors used for diagnosis
	Extrinsic flood field uniformity	All multi-hole collimators, both parallel and nonparallel
	Intrinsic flood field uniformity	^{99m}Tc and minimally one other radionuclide used clinically
	Intrinsic off-peak uniformity	For each detector to obtain baseline images
	Intrinsic spatial resolution and linearity	^{99m}Tc with slit phantom or quadrant bar phantom. Testing other radionuclides used clinically is optional.
	Extrinsic spatial resolution	^{99m}Tc for all low-energy collimators with a line source, and baseline quadrant bar phantom image with ^{57}Co on one low energy collimator.
	Extrinsic planar sensitivity	^{99m}Tc for one low-energy collimator
	Energy resolution	For ^{99m}Tc
	Intrinsic count rate performance	Measure peak count rate. Optionally measure the full count rate characteristics for ^{99m}Tc, or the dead time with the two-source method.
	Multiple window spatial registration	Optional
	Whole body scanning spatial resolution	Optional–System spatial resolution perpendicular and parallel to detector motion
	SPECT spatial resolution	Measured with a line source
	SPECT center of rotation and gantry tilt	Optional—evaluate with point source or line source projection images.
	SPECT Phantom	Phantom with ^{99m}Tc and low-energy collimator
		For Hybrid SPECT/CT phantom with ^{99m}Tc, low-energy collimator, and with CT attenuation correction.
	Hybrid SPECT/CT spatial registration	Method recommended by the manufacturer
	Hybrid SPECT/CT Dose	Report CTDI dose measurement for commonly used SPECT/CT procedures. May be performed separately by another qualified medical physicist.
	Hybrid SPECT/CT Image quality	Report CT image quality measurements with ACR CT Phantom. May be performed separately by another qualified medical physicist.

4. Physical Inspection and Computer Monitor Inspection

4.1 Physical Inspection

Any acceptance testing or annual survey should include an inspection of the physical condition of the gamma camera system, the integrity of its shielding, safety and interlocks, and the basic functioning of its computers and monitors. The results of the inspection should be reported.

4.1.1 Physical Condition

Examine the camera system for the following:

- Dents, scratches, loose covers, paint wear, and other mechanical defects
- Condition of the air filters
- Smooth detector and table motions without noise or erratic motion
- Identify and note condition of all collimators. Verify that the collimators mount and unmount smoothly.
- Examine room conditions. During acceptance testing, inquire about shielding and make recommendations in the report if necessary. While radiation protection of surrounding areas is almost certainly driven by the requirements of the CT component of a SPECT/CT system, it is recommended that the physicist evaluate the clinic for the potential of hot patients to interfere with gamma camera patient acquisitions. The workload of the CT component may be very different than that of a diagnostic CT unit.
- Examine the condition of all computers and displays connected to the camera system. Note the software version and note any operational problems.

4.1.2 Safety Interlocks

Evaluate the working condition of safety devices and interlocks at acceptance testing and all subsequent annual physics surveys:

- Locate and test the emergency stop switches.
- Locate and test collision detection devices for touch sensitivity. The collision detection devices are compression sensitive sheet panels that may be located on the collimator face and the gantry yoke to detect contact with another object or patient when the gantry or detectors move.

4.1.3 Camera Detector Shielding

The adequacy of detector shielding must be established by the manufacturer. The procedure described in NU 1-2012 provides for a quantitative assessment and publication of the design specifications. This assessment may be repeated at acceptance testing. We recommend that at a minimum the physicist perform a survey using a radionuclide looking for radiation leaks on the top and sides of the detector. Use a 40 MBq (~1 mCi) ^{99m}Tc source placed into a cylindrical lead shield with the top cover removed. Initiate a static acquisition and enable the persistence scope display prior to the start of the survey. Move the source pointed toward the detector sides and top slowly while observing the count rate and persistence scope image. Carefully examine the interface in the shielding between the detector and collimator. Report any breaches in the shielding, including images showing background artifacts that may result. Determine whether the radiation leak is the result of a design flaw of the system or from damage.

For annual physics surveys, visually examine the detector shielding for possible shielding damage. A leakage survey should be performed if damage is suspected.

4.2 Computers Monitors Used for Image Processing and Interpretation

4.2.1 Monitors Used for Image Processing

We recommend that the performance of monitors on computer workstations that are directly associated with the gamma camera system and used by technologists for image processing be evaluated regularly. This should be done by the physicist during acceptance and annual testing. These evaluations should include:

- Examine the monitors for cleanliness, dead pixels, and other artifacts.
- Assess the ambient lighting conditions.
- Measure the monitor maximum luminance (white) and the minimum luminance (black) in the presence of ambient light in units of cd/m^2.
- Measure the luminance uniformity of the monitor near the four corners and compare those measurements to that in the center.
- Display the TG18QC or SMPTE test pattern. Verify that the 5% and 95% patches are visible in the 0% and 100% luminance squares. For spatial resolution, identify the smallest bar size observed in each of the four corners of the test pattern. For geometric linearity, identify any distortion of displayed objects across the entire test pattern.
- Other test tools and procedures identified in Reference 11 may also be used.

Report the following:

- Identify the monitors and workstations and their location.
- For each monitor, report the maximum and minimum luminance and luminance uniformity.
- Report the test pattern used, the visibility of 5% and 95% test patches, the spatial resolution, and geometric linearity.

4.2.2 Monitors Used for Image Interpretation

We recommend that the performance of monitors used by physicians for interpretation of nuclear medicine images be evaluated regularly.

The evaluation may be done by the physicist during acceptance and annual testing, or it may be done by informatics or other qualified physicist or service. These evaluations should include:

- Examine the monitors for cleanliness, dead pixels, and other artifacts.
- Assess the ambient lighting conditions.
- Measure the monitor maximum luminance (white), and the minimum luminance (black) in the presence of ambient light in units of cd/m^2.
- Measure the luminance uniformity of the monitor near the four corners and compare those measurements to that in the center.
- Display the TG18QC or SMPTE test pattern. Verify that the 5% and 95% patches are visible in the 0% and 100% luminance squares. For spatial resolution, identify the smallest bar size observed in each of the four corners of the test pattern. For geometric linearity, identify any distortion of displayed objects across the entire test pattern. If the TG18QC test pattern is used, identify how many letters of “Quality Control” are visible.

Report the following:

- Identity and location of workstations and monitors that are used for nuclear medicine image interpretation.
- Assessment of room lighting conditions, including room illuminance. Report any observed specular reflections from the monitor.
- The type of workstation (nuclear medicine specific or PACS), display monitor type, and monitor gray scale calibration (DICOM GSDF).
- For each monitor, report the maximum and minimum luminance, and the luminance uniformity.
- Report the test pattern used, the visibility of 5% and 95% test patches, the spatial resolution, and geometric linearity. Report on how many letters of "Quality Control" are visible in TG18QC test pattern if used.

The ACR Technical Standard[12] specifies that the maximum luminance of diagnostic monitors used for image interpretation should be at least 350 cd/m^2, have a minimum luminance of 1.0 cd/m^2, and that the DICOM GSDF should be used. However, nuclear medicine is unique in that its spatial resolution, signal-to-noise ratio, and contrast-to-noise ratio are all significantly lower than is encountered in other modalities. It is reasonable to argue that in the condition of increased noise inherent in nuclear medicine images, there is no need to display subtle changes in intensity that are important in other modalities. Furthermore, much of the diagnostic information in nuclear medicine is transformed from grayscale intensity into ranges of color before it is displayed, often with a relatively small number of displayed colors.

In the absence of any definitive study to determine the display characteristics needed for nuclear medicine monitors used for image interpretation, the task group recommends that nuclear medicine monitors should have a display white (maximum luminance) greater than 120 cd/m^2, minimum luminance for black <2 cd/m^2, and luminance nonuniformity of less than 20%. The ambient lighting conditions in rooms with softcopy monitors may have a brighter room illumination of 20–40 lux as compared to radiology reading rooms when view boxes were used.[12,13]

5. Gamma Camera Planar Tests

Planar tests measure the performance of the gamma camera detectors and collimators that comprise the system. Depending on the clinical applications designated for a given camera system, some of the tests described in the NEMA document have been designated as optional. They may become useful, however, when troubleshooting performance failures. We refer you to the IAEA Quality Control Atlas for Scintillation Camera Systems[14] which has many examples of the gamma camera tests that are being prescribed in this report. The atlas is freely downloadable as a pdf-type file over the Internet.

Some of the tests described in the NU 1-2012 document are not recommended for use in the clinic. These include tests to measure:

- Intrinsic spatial resolution at 75,000 counts per second
- Intrinsic flood field uniformity at 75,000 counts per second
- Extrinsic spatial resolution with scatter
- Extrinsic count rate performance with scatter
- Collimator septal penetration

The majority of the physicists polled in the national survey do not perform these additional tests. The task group believes that the added information does not justify the added time needed to complete these tests.

Evaluating the performance of the gamma camera is not complete without including tests that are performed on a routine basis. These are described where appropriate. Any or all of the planar tests may be used during acceptance testing, annual physics surveys, and routine quality control. The appropriate use and frequency of the tests are provided for guidance.

The planar tests must be performed for each detector and collimator combination in a multiple-detector system. The tests are categorized as being intrinsic or extrinsic. Intrinsic tests are performed without an installed collimator and are designed to measure the performance of the imaging detector only. Extrinsic tests include the collimator and detector combined.

Many of the performance measurements are made in reference to the gamma field-of-view size. The NU 1-2012 convention for defining the field size is used, namely:

- UFOV (Useful Field of View): the total area useful for gamma imaging whose dimension is defined by the manufacturer.
- CFOV (Central Field of View): the imaging area defined by scaling the linear dimension of the UFOV by 0.75.

Multi-Crystal Detector Arrays—The performance measurements described in this section have been developed and optimized for single-crystal Anger detectors. The discrete sampling imposed by a rectangular array of crystals in multi-crystal detectors invalidates some measurements or requires modification in others. These are:

- *Flood-Field Uniformity*—For clinical imaging, the only useful flood-field uniformity calibration may be an extrinsic calibration using a sheet source. Therefore, only routine extrinsic flood images should be evaluated. The alignment of the collimator holes over the rectangular crystal array is likely to introduce aliasing artifacts that are removed by an extrinsic calibration. An intrinsic uniformity measurement is more likely performed by a service engineer to evaluate individual crystal energy response and sensitivity, identify dead crystals, and evaluate crystals and photodiodes for possible replacement. An additional test of intrinsic flood-field uniformity obtained without applying a uniformity correction may be considered in order to observe the location and number of dead crystals.
- *Spatial Resolution*—In essence, the intrinsic spatial resolution is fixed and defined by the dimensions of an individual crystal[15]. The extrinsic resolution continues to be defined by the collimator characteristics and source distance. Measurement of spatial resolution with a quadrant bar phantom or line source is extremely difficult because of possible under-sampling that occurs by the size of the discrete crystals. As a rule of thumb, the crystal size must be less than 1/3 the expected spatial resolution measured as a FWHM. For extrinsic spatial resolution, even imaging the quadrant bar phantom set at a 45-degree angle may be inadequate. An extrinsic spatial resolution measurement of a line source placed at a distance 10 cm may also be used.
- *Spatial Linearity*—The location of an event is identified by determining which crystal is activated rather than a calculation of an event position by centroid calculation. Therefore, measurement of spatial linearity is not necessary.
- *Multiple-Window Spatial Registration*—Since the location of an event is identified by determining which crystal is activated and is independent of gamma energy, measurement of multiple-window registration is not recommended.

- *Count Rate Characteristic*—The multi-crystal detectors employ many more data channels for counting individual events. The paralyzable model used for testing the dead time of Anger detector may not necessarily apply. The count rate capabilities of these detectors far exceed that encountered clinically, with near zero count losses from dead time.

5.1 Radionuclide Test Sources

The activity, configuration, and placement of the selected radionuclide sources depend on whether tests are performed intrinsically or extrinsically.

5.1.1 Point Source

Intrinsic measurements are performed with a point source that consists of a single near-spherical volume of 0.3 ml or less. Any source of ^{99m}Tc, ^{201}Tl, ^{67}Ga, and ^{111}In may easily be prepared in this way. When placed at a sufficient distance, the point source uniformly illuminates the detector UFOV. The source placed at the bottom of a v-shaped vial is ideal, but it also may be placed at the bottom of a small syringe. The syringe's needle should be removed and its fill port (tip) capped. Exercise great care when handling the sources so as not to fractionate the point source when assaying it in a dose calibrator or when placing it in front of the detector.

The activity that is used depends on the type of measurement and the source distance. The detector count rate should be between 20,000 and 40,000 counts/second (cps). Although NU 1-2012 specifies that the count rate not exceed 20,000 cps, the task group believes that modern systems are able to handle count rates up to 40,000 cps without performance issues. Always refer to the gamma camera user's manual for manufacturer's recommendations for acceptable activities and count rates.

5.1.2 Line Source

The line source is used for measuring spatial resolution and spatial linearity. Any source of ^{99m}Tc, ^{57}Co, ^{201}Tl, ^{67}Ga, and ^{111}In may be measured in this way.

For intrinsic measurements, the line source is fashioned with the use of a slit phantom defined by NU 1-2012 that consists of a 3 mm lead sheet into which equally spaced 1 mm slits separated by 30 cm that span the detector UFOV that have been milled into it.

For extrinsic measurements, the line source consists of a thin-walled plastic or glass tube into which a test radionuclide is placed. The radioactive concentration of the test radionuclide should be at least 40 MBq/ml (~1 mCi/ml). The inside diameter should be less than 1/4 times the expected spatial resolution. A line source with a minimum length of 100 mm is recommended.

Capillary tubes of length of 100 mm or longer can be filled by capillary action.

5.1.3 Sheet Flood Source

For extrinsic performance measurements on a gamma camera with a collimator, a sheet source is necessary to uniformly illuminate the detector UFOV. In theory the sheet source would be a water-filled tank into which a test radionuclide is mixed. We recommend, however for practical reasons, that a sealed sheet source containing ^{57}Co be used. The optimal activity of the radionuclide depends on the radionuclide and collimator used, and may range from 80–600 MBq (~2–15 mCi) in order to produce a detector count rate between 10,000 and 40,000 cps.

The radioactivity of a ^{57}Co sheet source at the time of purchase may have from 400–800 MBq (~10–20 mCi). The calibration date of the source should be identified in order to calculate the current activity contained in the source. New sources may contain a significant amount of ^{56}Co ($T_{1/2}$ 78.8 days) and ^{58}Co ($T_{1/2}$ 70.8 days) activity with gamma energies exceeding 511 keV. These high-energy photons may cause excessively high count rates, particularly for high-activity sources above 600 MBq from septal penetration of the collimator and cause nonuniformity artifacts to occur in the flood images. The septal penetration may be decreased by placing the sheet source away from the collimator

at a distance of 10 cm or greater. It is advised to allow a new source to decay for a period of time (one month or longer) until count rates have decreased and no perceptible nonuniformities are observed[16].

If it is necessary to test extrinsic performance for sources other than ^{57}Co, a water-filled sheet source is required. Some camera systems use a water-filled sheet flood source of a selected radionuclide for their uniformity calibration. If a water-filled sheet source is used, ensure that the test radionuclide is well mixed, is properly filled (avoiding under- or over-filling), is without air bubbles, and is significantly rigid so it does not bow within the detector UFOV.

5.1.4 Collimator Sensitivity Source

A distributed source of area smaller than the detector UFOV is used for measuring extrinsic sensitivity. The radionuclide shall be ^{99m}Tc. Other radionuclides used clinically may be also be measured.

NU 1-2012 specifies that the test source be diluted into a layer of water of 2–3 mm depth in a 150 mm diameter flat plastic disk (e.g., a Petri dish). Alternatively, a culture flask of similar dimensions may be used. However, any distributed source of uniform thickness with negligible self-attenuation will be adequate for this test. A 5-ml syringe with the plunger fully extracted to 5 ml and filled with an activity volume of 3 ml will also produce a water depth of 2–3 mm.

The activity used for the test radionuclide should range from 20–80 MBq (~0.5–2.0 mCi). It is critical that the exact activity in the test source be known. Residual activity in a source syringe or vessel used for transferring the source into a culture flask or other dish must be subtracted. If a 5-ml syringe is to be imaged, the needle on the syringe should be replaced with an uncontaminated needle before the final activity assay is made.

5.2 Gamma Camera Detector Setup and Source Placement

5.2.1 Energy Window Width and Peak

Refer to Table 4 for recommended energy windows and levels to be used for radionuclides encountered in nuclear medicine. The energy level is centered within the energy window. Visually verify that the energy peak coincides with the center of the corresponding window. If not, the energy level should be adjusted so that it is properly centered. For most cameras, this is an automated procedure. Record the energy levels and windows actually used.

Table 4: Energy and energy windows for commonly used radionuclides

Radionuclide	Gamma Energy #1		Gamma Energy #2		Gamma Energy #3	
	Level (keV)	Window (%)	Level (keV)	Window (%)	Level (keV)	Window (%)
^{201}Tl	70	20	167	20		
^{133}Xe	81	20				
^{57}Co	122	20				
^{99m}Tc	140	15/20*				
^{123}I	159	20				
^{67}Ga	94	20	184	20	296	20
^{111}In	171	20	247	20		
^{131}I	364	20				

*Note some manufacturers recommend slightly different windows and peaks.

5.2.2 Intrinsic Measurements

For intrinsic measurements, the collimator is removed and the detector is oriented toward the test point source of prescribed radionuclide, activity, and distance. Although NU 1-2012 specifies that a UFOV mask be installed, the uniformity measurement may be performed in the absence of the mask, so long as the performance criteria can be met.

Exercise care when working around the camera detector with a collimator removed. Although there is a thin protective covering over the crystal, impact of an object (lead shielding, test phantoms, rulers, pens, screwdrivers, etc.) could irreparably damage or crack the crystal. Be careful to not contaminate the crystal area with radioactivity. For added protection, a thin layer of corrugated cardboard or absorbent paper pad, plastic, or Saran Wrap may be used.

Prior to positioning the test source, measure the room background count rate. If the background count rate exceeds 2% of the expected test source count rate, or an image pattern is visible on the camera's persistence scope, then it is necessary to locate and remove contaminating sources from the area.

5.3 Flood-Field Uniformity

The purpose of this test is to measure the sensitivity variation over the gamma camera UFOV by uniformly flooding the detector crystal with gamma radiation.

The flood images are assessed both visually and quantitatively. Acquiring a sufficient count density is necessary for proper assessment. The NU 1-2012 standard flood image has approximately 30 million counts within the camera UFOV. For routine quality control, flood images of 10 and 5 million counts are ordinarily specified for intrinsic and extrinsic flood images, respectively. For visual assessment, matrix dimensions of at least 256×256 should be used. Refer to the manufacturer procedure manual for recommendations.

For quantitative analysis, NU 1-2012 defines two measures of nonuniformity, integral uniformity (IU), and differential uniformity (DU). The analysis is performed on a 64×64 flood image matrix after a low-pass 9-point smoothing filter has been applied. Routine flood images of a larger matrix dimension should be compressed to the 64×64 (pixel size of 6.4 mm ±30%) matrix so long as the total counts are preserved. The manufacturers are expected to provide the NEMA analysis software to calculate IU and DU.

IU is the more useful measurement, expressing the range of pixel values in the processed flood image as a percentage of the nonuniformity observed over the camera UFOV or CFOV. In order to compare IU values between intrinsic and extrinsic flood measurements, cameras, and camera models it is best to standardize on the pixel count density rather than total counts, as shown in Table 5.

Table 5: Total count requirements based on flood image type. The baseline IU is the minimum expected IU on detectors that have zero nonuniformity and is based on the stochastic noise level in these images[17,18].

Flood Image Type	Total Counts (Millions)	Counts/Pixel (compressed 64x64 matrix)	Baseline IU (%)
NU 1-2012 Standard for acceptance testing and for annual surveys	30	10,000	1.6
Routine intrinsic flood images	10	3,333	2.7
Routine extrinsic flood images with collimator	5	1,667	3.9

These are standard acquisitions on large UFOV cameras that would yield the specified counts/pixel in a 64×64 image matrix. To obtain the specified count density and total flood counts for a particular camera model, one must determine the number of pixels in the camera UFOV and multiply by the specified pixel count density. For example, a particular rectangular SPECT system performs IU analysis over a 52×38 pixel area, or 1976 pixels. Thus, the NU 1-2012 standard flood requires at least 20 million counts in this case.

Lastly, regarding flood field uniformity, the task group has included a test to examine off-peak flood images acquired with two energy windows—one just above and one below the photopeak—such that the two energy windows are abutting each other at the photopeak energy for ^{99m}Tc. The purpose of this test is to evaluate the gamma camera detector at acceptance and for annual surveys for photomultiplier tube imbalance or decoupling, and crystal-related problems such as hydration.

5.3.1 Intrinsic Flood Field Uniformity

This test measures the count density variation over the gamma camera UFOV without the influence of a collimator. This is the preferred and most practical means for measuring the uniformity with point sources of any of the radionuclides listed in Table 4. Ordinarily, the radionuclides tested are limited to radionuclides that are used in the clinic (e.g., ^{201}Tl, ^{99m}Tc, ^{111}In, ^{123}I, ^{131}I, and ^{67}Ga).

Frequency

- Acceptance testing—test ^{99m}Tc and at least one of the other radionuclides listed above that would be used clinically.
- Annual physics survey—test ^{99m}Tc and optionally test one of the other radionuclides listed above that are used clinically.
- Routine quality assurance—Daily as an alternative to daily extrinsic flood field uniformity.

Testing Procedure

1. Detector Arrangement and Point Source Placement

   With the collimator removed, rotate the detector toward the point source. The source can be placed on gypsum wallboard or on the floor as long as specifications can be met. Make adjustments so that the point source is centered over the detector UFOV.

   To minimize backscatter, the source may be placed into a lead shield with copper attenuating plates as described by NU 1-2012, suspended in air, or affixed to a backing material of a combination of lead, copper, and aluminum.

   NU 1-2012 specifies that the point source be centrally located over the detector UFOV at a distance of at least five times the larger detector UFOV dimension. However, a distance of four times the UFOV is sufficient. At this shorter distance, the count rate at the edge of the detector as compared to the center is lower, less than 2% lower, and is adequate for obtaining acceptable results. If the point source must be placed closer than four times the larger UFOV dimension, computer software should be used to correct the flood images for the nonuniform illumination by the source.

2. Image Acquisition

   Acquire flood images with an image matrix size of at least 256×256, or larger (e.g., 512×512). The total counts acquired depend on whether the image is used for acceptance testing, annual survey, or for routine quality control. Refer to the manufacturer's recommendations or to Table 5. It may be necessary to acquire a test flood image to ensure that the specified count density is achieved.

During acceptance testing, it is useful for future comparison to also acquire lower-count density flood images for comparison with routine testing.

3. Image Analysis

   Visually inspect the flood images for nonuniformities. No patterns, such as the PMT array, should be visible. Report areas of nonuniformity.

   Quantitative analysis of the flood images to obtain the IU and DU in the UFOV and CFOV should be performed. The acquired flood images should be compressed to a 64×64 matrix prior to analysis. Most manufacturer uniformity analysis software performs this task automatically.

4. Report

   Report visually identifiable nonuniformities for ^{99m}Tc and for all other radionuclides tested.

   Report the IU and DU in UFOV and CFOV results for ^{99m}Tc and for all other radionuclides tested.

5. Performance Specifications

   For acceptance testing, refer to the manufacturer's NU 1-2012 specifications.

   Acceptable performance depends on how the gamma camera is used clinically. The IU for 5 million count floods over the UFOV should be less than 5%.

   A new flood calibration may be necessary to correct the nonuniformities. Refer any uncorrectable nonuniformity defects for service and repair.

5.3.2 Extrinsic Flood Field Uniformity

This test checks the overall system uniformity, which includes checking for collimator defects. All parallel-hole collimators in use in the clinic shall be tested with a planar sheet source separately. Other multi-hole collimators may also be tested.

It should be noted that extrinsic floods with ^{57}Co are routinely used to assess the uniformity on a daily basis of both the collimator and detector. This is an efficient method for routine daily testing, but it cannot substitute for annual physics surveys or acceptance testing.

Frequency

- Acceptance testing—test all multi-hole collimators, both parallel and nonparallel.
- Annual physics survey—test all collimators that are used clinically.
- Routine quality assurance—test all collimators that are used clinically at least quarterly.

Testing Procedure

1. Image Acquisition

   Place the sheet source directly on the collimator. For parallel-hole collimators an air-gap of up to 15 cm is permissible and is preferable for dual-detector gamma camera systems so that flood images for both detectors may be acquired simultaneously. The observed count rate from parallel-hole collimators is independent of source distance. Be aware of possible contaminants in new ^{57}Co sources.

   It is advisable to acquire the flood image in a 256×256 image matrix or larger.

   Acquire a minimum of 10 million counts for acceptance and annual surveys to assess collimator defects, and 5 million counts for routine testing. The total counts for a detector with a small UFOV may be less so long as the count density is consistent with Table 5.

2. Image Analysis

   Visually inspect the flood images for nonuniformities. Identify singular areas of nonuniformity attributed to a collimator defect. No structured pattern (e.g., PMT array) should be visible. One may see a structured pattern on an HE collimator due to the ability of the detector to resolve the thick septa in areas between the PMTs. This should not be mistaken for a PMT pattern.

   Quantitative analysis of the flood images to obtain the IU over the UFOV should be performed. The acquired flood images should be compressed to a 64×64 matrix prior to analysis. Most manufacturers' uniformity analysis software performs this task automatically.

3. Report

   Report results for each collimator and note any unusual nonuniformity, such as a collimator defect or a visible PMT pattern.

   Report the IU of the UFOV.

4. Performance Specifications

   Acceptable performance depends on how the gamma camera is used clinically. The IU over the UFOV should be less than 5% for 5 million count floods.

   If unusual nonuniformity is visible, identify the location of the defect on the collimator. Depending on the severity of the damage, it may be necessary to remove the collimator from use and replace it with an acceptable collimator.

5.3.3 Intrinsic Off-Peak Flood Field Uniformity

This test evaluates the gamma camera detector for PMT imbalance or decoupling, and for crystal-related problems such as hydration. Intrinsic flood images of a ^{99m}Tc point are acquired with a photopeak energy of 126 (–10% energy level shift) and 154 (+10% energy level shift) keV, respectively, and with a 20% energy window (15% if used clinically). These off-peak flood images are visually inspected for unusual pattern of nonuniformities. A mild PMT pattern is typical and is not a cause for concern.

Frequency

- Acceptance testing—perform test for each detector to obtain baseline images.
- Annual physics survey—test each detector and compare with baseline images.
- Routine quality assurance—none.

Testing Procedure

1. Image Acquisition

   Place the detector orientation and the point source as described for testing intrinsic uniformity. For each detector, acquire at least 5 million count flood images in a 256×256 matrix or larger with photopeaks set to 126 and 154 keV, respectively, and with the clinical energy window. If the camera system allows, set to acquire both images simultaneously using a dual-isotope window acquisition. On camera systems on which it is difficult to specifically set acquisition energies to 124 and 154 keV, choose ^{57}Co and ^{123}I radioisotope energy windows instead.

2. Image Analysis

   Visually inspect the off-peak flood images for nonuniformities. All PMTs may be identifiable, which is expected. If a single or several PMT are visibly different than the others, then tube

imbalance or decoupling may exist. If multiple hot spots or a "measles-appearing" pattern exists, then crystal hydration may be present.

3. Report

   Report any crystal hydration defects or an atypical PMT pattern. Compare patterns to prior images, if available, to assess for change in pattern.

4. Performance Specifications

   If an unusual PMT pattern is identified, the gamma camera detector should be scheduled for evaluation and repair by a service engineer.

   For any hydration defects, the camera detector should be scheduled for service evaluation and possible crystal replacement.

5.4 Spatial Resolution and Spatial Linearity

The spatial resolution is obtained by measuring the width of a line-spread-function (LSF) obtained by plotting a count density profile drawn orthogonally across a line source image. The spatial resolution is specified as the width of the LSF at half-height, better referred to as the full-width-at-half-maximum (FWHM). A second measurement taken at the full-width-at-tenth-maximum (FWTM) may also be specified. The results are expressed in mm. The FWTM provides a measure of image contrast losses that may occur from collimator septal penetration and scatter.

Another and routine method for measuring spatial resolution is by imaging bar phantoms. The most common bar phantom is a quadrant bar phantom consisting of four different panels of parallel bars of decreasing size and spacing that covers the detector UFOV. The bar phantom should have a bar width in the smallest quadrant that is approximately half of the expected intrinsic spatial resolution (the smallest commercially available bars are 2 mm). It is recommended that the bar phantom be purchased from the manufacturer that designed the gamma camera system. It is important, however, that the bar phantom meet the testing requirements in this report. The objective for the bar phantom test is to identify the smallest quadrant of bars visible in the image. The FWHM of LSF is approximately 1.6 times the smallest visible bar size. A method described by Hander[19,20] to calculate the FWHM from the bar pattern image, applicable to intrinsic measurements, is also described in this report.

Spatial linearity refers to the ability of a gamma camera to locate acquired events accurately, and it is measured by imaging line sources over the detector UFOV. For testing, a nonlinearity is measured and is expressed as a deviation in mm between the true and imaged line source locations. The most common cause of nonlinearity is associated with PMT calibrations. The nonlinearity may be observed in line or bar pattern images, in which the bars appear to bend around the PMTs.

Both spatial resolution and linearity measurements involve imaging a line source and, therefore, may be obtained from the same image.

5.4.1 Intrinsic Tests of Spatial Resolution and Spatial Linearity

These tests measure the spatial resolution and spatial linearity of the gamma camera detector without the influence of a collimator.

For acceptance testing, either the slit phantom as specified by NU 1-2012 or a quadrant bar phantom from which the spatial resolution is calculated as described by Hander[19,20] may be used. Ordinarily, two patterns (horizontal and vertical) are used to separately measure spatial resolution in X and Y. It may be necessary to arrange for the gamma camera manufacturer to provide these phantoms. They will be of the proper size to match the detector UFOV. Software for analysis may also be provided.

For routine testing and annual surveys, the quadrant bar phantom is recommended. In the absence of a slit phantom, the quadrant bar phantom that has the appropriate minimum bar size may be used for acceptance testing.

Frequency

- Acceptance testing—The spatial resolution and spatial linearity of ^{99m}Tc shall be tested. Either a slit phantom or a quadrant bar phantom may be used. The quadrant bar phantom images are also used for future reference. If available, the manufacturer's NEMA software may be used for analysis. Testing other radionuclides used clinically on this system is optional.
- Annual physics survey—Acquire and analyze images of the quadrant bar phantom with ^{99m}Tc. Testing other radionuclides used clinically on this system is optional.
- Routine quality assurance—One may acquire an intrinsic quadrant bar phantom weekly instead of an extrinsic bar phantom. Only a visual inspection of the image is performed.

Testing Procedure

1. Slit Phantom Measurement

   For measurement, remove the collimator and install the slit phantom. The slit phantom should be in contact with the detector crystal. Care must be taken so as to not damage the crystal. The manufacturer-designed phantom should have means to fasten the slit phantom to the detector. It is permissible to place a 2–3 mm layer of cardboard or acrylic between the slit phantom and the detector crystal.

   If a slit phantom from a source other than the manufacturer is used, the slit width and lead sheet thickness should match those specified by NU 1-2012. Additional lead sheeting must be installed to cover areas of the detector that are not covered by the slit phantom.

   A point source is positioned at least 4 UFOV from and centered over the detector. For this measurement, the activity of the point source should be between 200–400 MBq (5–10 mCi).

   a. Image Acquisition

   The camera zoom factor and computer image matrix should be chosen so that the pixel size perpendicular to the slit is less than 0.2 FWHM. If the digital resolution is greater than 0.2 FWHM, then curve fitting will be required to identify the peak of the line-spread function.

   Acquire a minimum of 250 counts per pixel at the peak locations of the slits in the image.

   b. Analysis for Spatial Resolution

   On a computer workstation, obtain LSFs by placing a wide profile (30 mm or as wide as the workstation software provides) orthogonally across each of the slit images. At least 1500 counts in the peak location of the LSF profile should be obtained. A longer acquisition time may be necessary to achieve this.

   If the pixel size is greater than 0.2 FWHM, the peak of the LSF may be determined by applying a parabolic fit of the three largest count values of the LSF peak. Use linear interpolation to identify the half-maximum locations on either side of the LSF peak.

   The 30 mm separation between slits may be used to check the system pixel calibration. Note that the spatial resolution is not constant over the field of view.

   c. Analysis for Spatial Linearity

   Visually inspect the slit images for nonlinearity. The slit should be straight lines in the images. Failure of the linearity correction software most often leads to a nonlinearity. Bending of the

line image around a PMT may indicate a loss of tube balance. The results may be reported as follows:

- no observable nonlinearity,
- just noticeable and may be less than 1 mm, or
- significant and may be greater than 1 mm.

Refer to the pixel size to determine the extent of displacements.

NU 1-2012 specifies that differential and absolute linearity be calculated. This requires that a line of best fit be drawn through the peaks of the count density for the slits in the image. The differential linearity is the standard deviation in mm of the difference of actual peak locations from a line of best fit. The absolute linearity is the maximum displacement in mm of any peak from the line of best fit. If analysis software is not available, report any visible nonlinearity.

2. Quadrant Bar Phantom Measurement and Analysis for FWHM by Hander Method

For measurement, remove the collimator and install the quadrant bar phantom. Care must be taken so as to not damage the crystal. A manufacturer-designed phantom should have a means to fasten the pattern to the detector. It is permissible to place a 2–3 mm layer of cardboard or acrylic between the bar phantom and the detector crystal.

If the quadrant bar phantom cannot be set directly on the detector crystal, a gap of up to 2.5 cm can be used without compensation for bar pattern magnification. The magnification factor for a point source at 2 meters with bar pattern placed with a 2 cm gap is 1.013.

A point source is positioned at least 4 UFOV from and centered over the detector. Note that for this measurement, the activity of the point source should be between 40–200 MBq (1–5 mCi).

a. Image Acquisition

Choose the largest computer image matrix available. The pixel size should be less than one-half of the width of the smallest bars. Some image magnification may be necessary to achieve this.

A point source is positioned as described above. The total counts acquired should be at least 5 million counts.

b. Spatial Resolution Based on Inspection

Visually identify the smallest perceptible bar size. It is necessary that at least one-half of the length of the bars be observed in a portion of one quadrant for that quadrant to be considered visible.

c. Spatial Resolution Based on the Hander Method

Hander[19,20] describes a method to calculate the FWHM from quadrant bar phantom images by comparing the average and standard deviation of counts in a region drawn in an image quadrant. Draw a circular region of interest (ROI) over a visible quadrant with a bar size that best matches the expected FWHM. Center the ROI in the quadrant, making it as large as possible

without including the edges. The ROI analysis tool must report the average and standard deviation of the pixel values in the ROI. The FWHM is calculated as follows[19,20]:

$$\mathrm{MTF} = \left[2(\sigma_{\mathrm{ROI}}{}^2 - \mu_{\mathrm{ROI}})\right]^{1/2} / \mu_{\mathrm{ROI}}$$

$$\mathrm{FWHM} = 1.058\ w_{\mathrm{ROI}} \left[\ln(1/\mathrm{MTF})\right]^{1/2}$$

where $\sigma_{\mathrm{ROI}}{}^2$ and μ_{ROI} are the variance and average in the ROI and w_{ROI} is the bar size width in mm in the ROI. μ_{ROI} in the numerator is an estimate for the Poisson noise variance in the ROI.

d. Analysis for Spatial Linearity

The bar pattern images should be straight with no patterned distortions. Bending of the bars around a PMT may indicate a loss of tube balance. The results may be reported as follows: no observable nonlinearity, just noticeable and may be less than 1 mm, or significant and may be greater than 1 mm. Refer to the pixel size to determine the extent of displacements.

3. Report

   Report the FWHM for ^{99m}Tc and for the other radionuclides that were tested. Report the method of measurement.

   Report the smallest observed bar size observed for ^{99m}Tc and for other radionuclides tested if the quadrant bar phantom was imaged.

   Report the absolute and differential linearity, if they were calculated. Report the observed linearity from the visual inspection of the quadrant bar phantom.

4. Performance Specifications

   For acceptance testing, refer to the manufacturer's NU 1-2012 specifications. The typical intrinsic spatial resolution of contemporary systems is 3–4 mm FWHM with ^{99m}Tc. These systems should be able to resolve 2.5 mm bars.

   Any nonlinearity should be less than 1 mm.

5.4.2 Extrinsic Spatial Resolution

This test measures the overall spatial resolution of the gamma camera with an installed collimator. The measurement is made with a line source in air at a distance of 10 cm from the face of the collimator. Other source-to-collimator distances may be considered. Each detector in a multi-detector gamma camera system should be tested.

An additional measurement may be made with a quadrant bar phantom and a ^{57}Co sheet source for low-energy collimators. For medium- and high-energy collimators, the collimator hole size may approach the width of the bars, resulting in Moiré patterns that render the results meaningless.

Frequency

- Acceptance testing—The extrinsic spatial resolution using ^{99m}Tc for all low-energy collimators with a line source should be measured. The measurement of extrinsic spatial resolution with other collimators and appropriate radionuclides may be considered optional. It is recommended that the quadrant bar phantom be imaged with a ^{57}Co sheet source and one of the low-energy collimators. The resulting image should be used as a baseline measurement for future reference.
- Annual physics survey—Acquire a quadrant bar phantom image with a ^{57}Co sheet source in situations where an intrinsic bar phantom cannot be imaged.

- Routine quality assurance—Acquire a quadrant bar phantom image with a ^{57}Co sheet source once per week.

Testing Procedure

1. Image Acquisition

   Install the appropriate collimator for the radionuclide that is to be imaged. Line sources are positioned parallel to and at a distance of 10 cm from the face of the collimator and perpendicular to the axis of measurement. Separate images should be acquired along the X and Y axis. The computer image matrix and camera zoom factor should be chosen so that the digital resolution perpendicular to the capillary tubes is less than 1/5 of the expected FWHM. Acquisition continues until the peak count in the line image exceeds 500 counts.

   For imaging bar phantoms, use only a low-energy collimator. Place the bar phantom directly on the collimator face and then the ^{57}Co sheet source over it. Choose the finest, highest-resolution image matrix available. The pixel width should be less than ~~the~~ one half of the width of the smallest bars. Acquire at least two images per detector by rotating the phantom either 90 or 180 degrees between imaging. The total counts acquired should be at least 5 million counts for each image.

2. Analysis for Spatial Resolution

   On a computer workstation, obtain LSFs by placing a wide profile (30 mm or as wide as the workstation software provides) orthogonally across each of the slit images. Draw profiles at several locations spanning the detector UFOV. The peak of the LSF may be determined by applying a parabolic fit of the three largest count values of the LSF peak. Use linear interpolation to identify the half-maximum locations on either side of the LSF peak.

   For bar phantom images, visually identify the smallest perceptible bar size. It is necessary that at least one half of the length of the bars be observed in a portion of one quadrant for that quadrant to be considered visible.

3. Analysis for Spatial Linearity

   The line source or bar pattern images should be straight with no patterned distortions. Bending of the bars around a PMT may indicate a loss of tube balance. The results may be reported as follows:

   - no observable nonlinearity,
   - just noticeable and may be less than 1 mm, or
   - significant and may be greater than 1 mm

   Refer to the pixel size to determine the extent of displacements.

4. Report

   Report the FWHM for ^{99m}Tc and for the other radionuclides and collimator combinations tested.

   Report the smallest observed bar size for ^{57}Co.

   Report the observed linearity from visual inspection of the line sources and bar phantom.

5. Performance Specifications

   For acceptance testing, refer to the manufacturers' NU 1-2012 specifications.

Typically, the system spatial resolution for ^{99m}Tc with a high-resolution, low-energy, parallel-hole collimator at 10 cm is 8 mm FWHM.

5.5 Extrinsic Planar Sensitivity

The planar sensitivity of a gamma camera system is measured in units of counts per minute per unit activity, CPM/kBq (CPM/μCi), for radioactive sources placed within the detector's UFOV. The sensitivity is obtained by measuring the count rate from the radionuclide in a disk source of known activity under low attenuation and scatter conditions. In a multi-detector gamma camera system, the sensitivity of each detector for a selected collimator should be measured separately and compared.

The measurement shall be made for ^{99m}Tc with the low-energy, parallel-hole collimator that is routinely used in the clinic. Other combinations of radionuclides and collimators that are used in the clinic may be measured. Measurements should be made with radionuclides for which each collimator is designed.

Frequency

- Acceptance testing—Measure the sensitivity of ^{99m}Tc for at least one low-energy collimator. Additional combinations of radionuclides and collimators may be tested.
- Annual physics survey—Measure the sensitivity of ^{99m}Tc with at least one low-energy collimator.
- Routine quality assurance—none.

Testing Procedure

1. Image Acquisition

   Position the sensitivity source centered over the gamma camera detector UFOV. The exact distance is not crucial, but it should be consistent for each measurement. A very low-attenuating source holder, such as a thin cardboard box, may be used to stand the source container off at the measurement distance from the collimator.

   The acquisition computer matrix size is not critical. The acquisition time should be for at least 1 minute. Repeat the acquisition for all detector, radionuclide, and collimator combinations selected to be measured. Record the time of the assay and the time of imaging.

   Acquire a background image for 1 minute after removing the sensitivity source.

2. Image analysis

   Obtain the total counts in both the source and background images for each detector, radionuclide, and collimator combination. Use the entire image matrix rather than a smaller ROI to obtain the total counts. The total counts vary with the size of the ROI due to counts being recorded from septal penetration at some distance from the source.

   Calculate the system sensitivity for each detector, collimator, and radionuclide combination. Apply the appropriate background and decay corrections. For multiple-detector systems, calculate the ratio of the sensitivity of one detector to that of the other.

3. Report

   Report the system sensitivity for all detector, radionuclide, and collimator combinations measured. For multiple-detector systems, report the percentage difference of each pair of detectors.

4. Performance Specifications

   For acceptance testing, refer to the manufacturers' NU 1-2012 specifications for the radionuclide and collimators that were measured.

   For camera systems with multiple detectors, a pair of detectors should not differ in their system sensitivities by more than 5% for each detector per radionuclide and collimator combination.

5.6 Energy Resolution

This test measures the energy resolution of the gamma camera detector by measuring the FWHM of an energy peak expressed as a percentage of the energy peak.

The measurement of the 140 keV gamma energy of ^{99m}Tc is required. The energy resolution of other radionuclides may be measured.

For acceptance testing, the keV/channel shall also be measured. Therefore, the energy spectra for two radionuclides must be acquired, namely ^{99m}Tc and ^{57}Co. This procedure ensures that the proper energy scaling per channel is determined. For subsequent measurements it is sufficient to measure the energy resolution using one radionuclide, namely ^{99m}Tc.

Frequency

- Acceptance testing—Measure the energy resolution for ^{99m}Tc, applying a quantitative method. The energy resolution for other radionuclides used in the clinic may be measured.
- Annual physics survey—Measure the energy resolution for ^{99m}Tc and compare to previous results. An increase in the energy peak FWHM (i.e., a loss of energy resolution) may lead to an increase in the scatter contribution and, hence, a loss of image contrast, a loss of spatial resolution, and diminished system sensitivity. Energy resolution losses may be the consequence of an aging crystal or an improperly tuned detector.
- Routine Testing—none.

Testing Procedure

1. Energy Spectrum Acquisition

   The energy spectrum is measured intrinsically using a point source such as the one prepared for uniformity imaging. Each detector is measured separately. An intrinsic acquisition ensures that all PMTs are illuminated uniformly. Only an energy spectrum display is used. Images are not acquired. Three methods can be used for measurement. The non-stored spectrum may only be used for follow-up testing.

   a. Stored Spectrum *(the preferred method used for acceptance testing)*

   Refer to the manufacturer's manual for instructions on how to acquire and store an energy spectrum. Perform the acquisition with the smallest keV/channel available. The peak channel should have a minimum of 10,000 counts. The manufacturer may have special software to perform this acquisition and to determine the FWHM of the spectral peak. Use of this software is highly recommended.

   For acceptance testing, two stored spectra will be acquired, one for ^{99m}Tc and one for ^{57}Co. For annual physics surveys, only a ^{99m}Tc spectrum is required.

   b. Manual Spectrum Acquisition *(may be used for acceptance testing)*

   Make a series of measurements of the counts in a narrow 2% energy window. Shift the center of this energy window across the range of energies that span the photopeak of the radionu-

clide, and record the counts for a fixed time that is sufficient to accumulate at least 10,000 counts at the peak of the spectrum.

In the case for acceptance testing, two stored spectra will be acquired, one for ^{99m}Tc and one for ^{57}Co. For annual physics surveys, only ^{99m}Tc spectrum is required.

c. Non-stored Spectrum (may be used for annual testing only)

On some gamma camera systems, the energy spectrum cannot be stored. The energy resolution may be estimated by analyzing a display of the acquired energy spectrum that simultaneously shows an overlay of a set energy window. Change the energy window width until the intersection of the energy window corresponds to the half-maximum count level on each side of the energy peak. This energy window width then approximates the FWHM that would be measured from a stored energy spectrum.

2. Analysis

From stored energy spectra or from a manual spectrum acquisition, locate the energy on either side of the photopeak that has a count level of one half of the counts at the spectral peak. It may be necessary to interpolate between energy points on the spectral curve to identify the peak location, the peak counts, and the half-maximum count values. Whenever the energy spectrum of a second radionuclide is acquired, use peak channel locations to calculate the keV/channel. Compute the FWHM as a percentage of the energy peak for ^{99m}Tc.

If the non-stored spectrum method is used, record the energy window width corresponding to the FWHM of the energy peak.

3. Report

Report the energy resolution as the percentage of the energy peak for ^{99m}Tc and for any other radionuclides that were tested.

4. Performance Specifications

Refer to the manufacturer's specifications.

In general, the FWHM of a NaI(Tl)-crystal Anger camera for ^{99m}Tc is 9–10%. If greater than 11%, refer to service for evaluation and repair.

5.7 Intrinsic Count Rate Performance

This test measures the count loss due to dead time at high count rates. The count rate is plotted as a function of the source activity. Record the maximum observed count rate and the count rate at which 20% count losses are identified. For multiple-detector systems, the count rate characteristic must be measured for each detector.

There are multiple methods for measuring count loss and dead time. NU 1-2012 specifies that the count loss be measured using the decay method, in which the count rate of a ^{99m}Tc source is measured at several time points while the source decays. The starting activity of ^{99m}Tc is such that the observed count rate falls in the fold-over region past the maximum achievable gamma camera count rate. Measurements are repeated until the observed count rate falls below a specified value, at which the count losses are deemed to be insignificant. For ^{99m}Tc with a 6-hour half-life, this requires an overnight acquisition. NU 1-2012 also suggests that multiple attenuating layers of 1-mm thick Cu sheets can be used to decrease the count rate to the gamma camera[21]. For acceptance testing, this is the recommended approach, and the test can be completed within a few minutes. The reader is also referred to a recent article on the count rate performance characteristics of modern gamma cameras[22]. A two-source method may also be used to measure system dead time, assuming the camera system behaves

as a paralyzable system. Additionally, a measurement of the maximum peak count rate is recommended.

Ideally, the count rate performance would be measured under clinical conditions with a collimator installed on the detector and with a scatter spectrum similar to that from a patient. These conditions are difficult to create for testing purposes. Fortunately, the count rate capability of the gamma camera system far exceeds the count rates that are routinely encountered clinically and, thus, an assessment of the clinical count rate performance is not critical. However, in clinical dynamic imaging situations for which dead time count loss corrections would be applied, a measurement with scatter would be required. We refer the reader to the IEC 60789 Standard[2] for gamma testing describing a procedure for measuring an extrinsic detector count rate performance.

Frequency

- Acceptance testing—Measure the maximum peak count rate. Optionally measure the full count rate characteristics for ^{99m}Tc using either the attenuating method with Cu plates or the decay method. Or use the two-source method to measure the paralyzable dead time value.
- Annual physics survey—Measure the maximum peak count rate. Optionally, using the two-source method measure the paralyzable dead time value.
- Routine quality control—none.

Testing Procedure

1. Image Acquisition

   Prior to the start of acquisition, remove the collimator and measure the background count rate with the energy window for testing, which should be less than 500 cps. A minimum of background scatter is required and, thus, the point source should be shielded. The point source may be placed into a lead cylinder with a Cu filter top as described by NU 1-2012 or in a similar type of container. The point source should have high enough activity to produce a count rate that is in the fold-over region of the count rate-activity curve as described above. Note for each measurement whether the detector is in normal or high count rate mode. Depending on the source distance, the activity required may exceed 160 MBq (~4 mCi).

   a. Decay Method

   Place the point source within its container at a fixed distance (~5 times the larger dimension of the UFOV). Depending on the source distance, the activity required for this measurement may exceed 160 MBq (~4 mCi) in order to achieve a count rate in the fold-over region. Acquire images at multiple time points until the last time point has a count rate that drops below 10,000 cps. Acquire each image for 10 seconds. At the end of the acquisition, acquire one background image for two minutes with the point source removed from the vicinity of the camera.

   b. Attenuating Cu-Plate Method

   Place the point source within its container at a fixed distance (~5 times the larger dimension of the UFOV). Depending on the source distance, the activity required for this measurement may exceed 160 MBq (~4 mCi) in order to achieve a count rate in the fold-over region. Acquire separate images with increasing thicknesses of Cu sheets until the count rate falls below 10,000 cps. The measurement order of Cu-plate thicknesses may be reversed. Acquire each image for a minimum of 100,000 counts or 10 seconds, whichever is shorter. At the end of the acquisition, acquire one background image for two minutes with the point source removed from the vicinity of the camera.

c. Two-Source Method

The two-source method determines the gamma camera system dead time. It can be done either intrinsically or extrinsically, although much larger source activity is required for the extrinsic measurement. Two approximately equal sources of ^{99m}Tc (A & B) should be made where each source results in approximately 10% count rate loss. Typically, that loss level occurs with an observed count rate of 80,000–100,000 cps.

We recommend performing the intrinsic measurement. The activity of each source for an intrinsic measurement depends on the size of the detectors and the source distance, which may be as close as 30 cm for this test. For a LFOV camera (~2000 cm^2 area), a 1.3 MBq (35 uCi) source will yield a count rate of about 75,000 cps at 30 cm distance. That activity would have to be altered by 2000/(Area of detector) for a different-sized detector. The sensitivity of a LEHR collimator is about 75 cps/MBq (165 cpm/uCi). To achieve 75,000 cps you would need about a 740 MBq (20 mCi) source.

The gamma camera should be set up to acquire 3 static images for 10 seconds each. Position source A and acquire the first 10-second image. Without moving source A, place source B next to it and acquire the second 10-second image of both sources. Remove source A for the third 10-second image of source B.

Dead time (τ) is determined by using the paralyzable formula for the two-source method:

$$\tau = 2 \times C_{AB} / (C_A + C_B)^2 \times \ln\left[(C_A + C_B) / C_{AB}\right]$$

where C_A is the count rate (cps) of source A, C_B is the count rate (cps) of source B, and C_{AB} is the count rate (cps) of sources A and B measured together. The dead time should be reported in microseconds.

d. Maximum Peak Count Rate Measurement *(may be used for subsequent measurements)*

The activity of the point source in air for this measurement should be 40 MBq (~1 mCi). Images are not needed; only the maximum observed count rate is recorded. Begin by measuring the count rate of the point source in air at a large distance. Then measure the count rate as the source is slowly moved closer and closer to the detector until the count rate reaches the fold-over region where rates decrease. This measurement should be made quickly so as to not oversaturate the detector for a long time.

2. Image Analysis

This analysis is required only for the Cu-plate and the decay methods. For each image, extract the total counts in the entire image without the use of an ROI, background correct, decay correct to a common time point, and calculate the count rate in counts per second. If the Cu sheets are used, record the total Cu sheet thickness at each acquisition.

Plot the observed count rate versus source activity for the decay method, or Cu sheet thickness in mm for the attenuation method. Identify the maximum count rate and the count rate at which there is a 20% count loss.

3. Report

Report the maximum count rate and, if measured, the count rate at 20% count loss, and the dead time, if measured. Indicate whether the maximum count rate was achieved in normal or high-count-rate mode.

4. Performance Specifications

   For acceptance testing, refer to the manufacturer's specifications.

   The expected intrinsic maximum count rate should typically exceed 150,000 cps for an Anger camera.

5.8 Multiple-Energy Window Spatial Registration *(Optional)*

This test determines the accuracy with which the gamma camera positions events as a function of energy. The multiple-energy window registration is measured by imaging point sources of a multiple-energy radionuclide such as ^{67}Ga. Each photopeak is imaged in a separate energy window. The pixel coordinates of the centroid of the point images are calculated, and their positions are compared for each photon energy.

In current systems with digital signal processing, this test is considered optional. Older systems in use that do not have digital processing should be tested annually.

Frequency

- Acceptance testing—optional.
- Annual physics survey—optional. The test may be used when a multiple-energy registration problem is suspected, such as in cases where images of ^{201}Tl, ^{67}Ga, or ^{111}In that combine multiple-energy windows, exhibit a halo effect at the edges of objects with decreased spatial resolution.
- Routine quality assurance—none

Testing Procedure

1. Test Source

   NU 1-2012 specifies that point sources of ^{67}Ga with photon energies of 93, 184, and 300 keV be used. Alternative radionuclides, such as ^{111}In or ^{201}Tl, may be used.

   NU 1-2012 specifies that the point source be placed in a lead-lined cylinder with a 5-mm diameter hole at its bottom. The source is placed directly on the detector crystal or may be placed on an installed low-energy, parallel-hole collimator. Alternatively, five "point" sources of radionuclide in unshielded plastic vials—one placed in the center of the FOV and four near the corners of the camera field-of-view on a parallel-hole collimator—could be used.

2. Image Acquisition

   The test source is imaged at nine positions: at the central point and at four points on the X-axis and four points on the Y-axis. The off-central points shall be located 0.4 times and 0.8 times the distance from the central point to the edge of the UFOV along the respective axes.

   Acquire an image for every energy window of 20%. Acquire point source images until the peak pixel count is at least 1,000 counts.

3. Image Analysis

   Draw line profiles in both the X- and Y- directions of 5–10 pixels wide over each of the point sources on each of the acquired images. The line profile should be centered on the point source and of short length, and it should have of an odd number of pixels that includes the half-maximum of the peak counts on each side of the peak. Calculate the centroid of counts in mm for each point source using the line profiles drawn in the X- and Y-directions.

   Calculate and compare the displacement in mm for each energy window combination.

4. Report

   Report the radionuclide used and the maximum displacement.

5. Performance Specifications

   For acceptance testing, refer to the manufacturer's specifications.

5.9 Whole-Body Scanning Systems *(Optional)*

Many gamma camera systems are designed to perform whole-body scanning. It is essential that the camera maintain its spatial resolution and sensitivity as the camera system moves over the patient. Only ^{99m}Tc is required for these measurements.

5.9.1 System Spatial Resolution

The system spatial resolution is measured by scanning twice over two line sources whose long axes are placed parallel and perpendicular to the system motion.

Frequency

- Acceptance testing—measure the system spatial resolution perpendicular and parallel to detector motion.
- Annual physics survey—optional
- Routine quality assurance—none

Testing Procedure

1. Spatial Resolution Perpendicular to Motion

   To measure the spatial resolution perpendicular to the system motion, position the two line sources parallel to one another, 10 cm apart, and arranged with their long axes perpendicular to the direction of motion, at the mid-point of the scan motion. The imaging distance of the line sources to each detector should be 10 cm. The pixel size should be close to 0.2 times the expected FWHM. Adjust the scan speed to obtain 1,000 counts in the peak channels.

2. Spatial Resolution Parallel to Motion

   The same procedure is used as described for the perpendicular measurement, except that the two lines sources are arranged so that their long axes are parallel to the direction of motion.

3. Image Analysis

   On a computer workstation, obtain LSFs by placing a 30-mm-wide profile orthogonally across each of the line source images. Use linear interpolation to identify the half-maximum locations on either side of the LSF peak and calculate the FWHM in mm.

4. Report

   Report the average of the spatial resolution from the two line sources both perpendicular to and parallel to the direction of motion.

5. Performance Specifications

   The measured spatial resolution should be equal to within $\pm$10% the spatial resolution measured in Section D.2.

5.9.2 Whole-Body Scanning Uniformity

It is expected that the sensitivity to a source is constant and independent of scan position. Because of the accuracy and stability of current systems, this test is considered optional.

Frequency

- Acceptance testing—optional
- Annual physics survey—optional
- Routine quality assurance—none

Testing Procedure

1. Image Acquisition

   To test the sensitivity stability, scan a ^{57}Co sheet source three times at three source locations over the length of the scan table. Set the imaging distance for each detector to 10 cm, adjust the scan length to be twice the length of the sheet source, and adjust the scan speed to obtain approximately 50,000 counts over the entire sheet source.

2. Image Analysis

   For each detector, determine the total counts acquired for each scan. Calculate the average, the standard deviation of counts, and the coefficient of variation as a percentage of the average counts.

3. Report

   Report the standard deviation and coefficient of variation.

4. Performance Specification

   The coefficient of variation should be less than 2%.

   For camera systems with multiple detectors, the system sensitivity of each detector per radionuclide and collimator combination should not differ by more than 5%.

5.10 Testing of Nonparallel-Hole Collimators *(Optional)*

Collimators other than the parallel-hole type may also be used on a gamma camera. Testing of these types of collimators is considered optional for acceptance and annual testing. The descriptions below are intended to be used as a guideline for measurements of spatial resolution and sensitivity.

Among the more common collimator variants are converging and diverging hole collimators, converging hole for nuclear cardiology imaging, and pinhole designs (thyroid and nuclear cardiology).

A pinhole system may include more than one opening so as to increase the device's inherently low sensitivity. An additional possible variable is the physical size of the aperture(s). This last parameter may be adjustable downward using an insert that is clipped into the intrinsic opening so as to improve spatial resolution—but at the price of lowered sensitivity.

5.10.1 Spatial Resolution

Both spatial resolution and the magnification factor may be measured with a pair of capillary tubes containing ^{99m}Tc using a 10 cm stand-off, or other appropriate clinical distance. If the two capillary tubes are positioned in parallel 5 cm apart, their apparent separation at the camera crystal gives a direct measure of the magnification factor. The change in magnification with distance should also be measured.

5.10.2 Sensitivity

An extended planar ^{99m}Tc source that is at least 5 cm in diameter may be used to test sensitivity for nonparallel collimators. If the camera-collimator system is intended for a specific application, such as cardiology or thyroid imaging, an appropriately sized planar source should be used instead of the standard 5-cm size. Stand-off distance may be set at 10 cm, or at another clinically relevant distance. Geo-

metric factors reduce the count rate at the edges of the camera crystal. Thus, as noted above for resolution, the sensitivity would be a function of the distance from the collimator face. This variation should be evaluated initially upon acceptance testing.

6. Gamma Camera SPECT

The single photon emission computed tomography (SPECT) tests evaluate the performance of the gamma camera when used to acquire and reconstruct SPECT images. The NEMA Standards Publication NU 1-2012 is the principle reference. AAPM TG Report 52[8] is also used as a reference. Table 1 in the introduction lists the tests and the fractions of survey respondents who felt the test should be done at acceptance testing and for an annual survey. The tests described below are a subset of the NU 1-2012 tests determined to be the most important by the task group, while taking into consideration the response from the expert survey. It is assumed that all of the calibration procedures described by the manufacturer for SPECT cameras have been completed prior to the performance of these tests. This would include, at a minimum, calibration of the uniformity correction and the center of rotation. It would also include head alignment for SPECT cameras with more than one detector. See Appendix A for methods to test center of rotation and head alignment. There may be other calibrations that are necessary for a particular camera. The following tests evaluate the performance of the system and the effectiveness of these calibrations.

There are two methods for testing tomographic spatial resolution. The preferred method in this report uses a line source and is described below. A second method is described in Appendix B for those who would prefer to use a test that is equivalent to that described in NU 1-2012 which uses three point sources. Although the second method is more time consuming, both in source preparation and data analysis, more quantitative results are obtained.

6.1 Test Sources and Phantoms

Principally, all radionuclides that are used for SPECT imaging should be considered when testing SPECT performance. In common practice, the performance for ^{99m}Tc is measured.

6.1.1 Point Sources

Point sources are not used in the methods described in this section. The method described by NEMA is in Appendix B, along with the description of how to prepare the point sources.

6.1.2 Line Source

The line source as prepared for measuring extrinsic planar resolution may be used to measure SPECT tomographic spatial resolution. However, the rigidity of the line source must be such that it can be extended and suspended in air over the end of the imaging pallet and remain straight. Commercial line source fixtures are available. The triple line insert phantom specified by NU 1-2012 may also be used. The procedure described below uses the protocol described in TG Report 52, which specifies that a single line source be measured. Since the recommended measurement is to be performed in air, the triple line insert would be imaged while suspended in air and not placed inside a SPECT phantom.

6.1.3 Image Quality SPECT Phantom

The image quality SPECT phantom is a water-filled 20.4-cm diameter cylinder into which a test radionuclide is mixed. The phantom contains solid objects that displace the water in order to assess spatial resolution (rods) and contrast resolution of cold objects (spheres or cylinders) in a hot (radioactive) background. The phantom scan results are also very sensitive for identifying artifacts that may appear in the hot background as the result of improper gamma camera calibrations.

The suggested phantom is the ACR Accreditation SPECT phantom. The phantom is a 20.4-cm diameter cylinder and with a height of 18.6 cm. The rod insert diameters are 4.8, 6.4, 7.9, 9.5, 11.1,

and 12.7 mm in diameter, and the sphere diameters are 9.5, 12.7, 15.9, 19.1, 25.4, and 31.8 mm. However, any phantom that meets the ACR criteria would be acceptable. The phantom is commercially available from Data Spectrum Corporation[23]. The phantom may require assembly prior to use. Ensure that the largest rods are aligned with the largest sphere. Fill the phantom with water (tap water is acceptable) leaving a 30–40 ml air bubble, which will be used for mixing, and secure the top faceplate fill port caps. Dry the outside of the phantom and tip it on its side to verify that there is no water leakage.

Through the fill port, add 400–1000 MBq (~10–27 mCi) ^{99m}Tc, recap, and mix thoroughly. Multiple inversions of the phantom are necessary to completely mix the radionuclide. After mixing, add additional water to reduce the size of the air bubble to less than 5 ml. The activity added to the phantom should be such that the detector count rate does not exceed 30,000 cps. On occasion, SPECT imaging using ^{201}Tl, ^{111}In, or ^{67}Ga may be desired. A lower activity of 200–400 MBq (~5–10 mCi) may be used for these radionuclides.

6.2 Gamma Camera Detector Setup

6.2.1 Energy Window and Level

Refer to energy levels and windows identified in Table 4. For ^{99m}Tc, the energy window parameters that are used clinically should be selected.

6.2.2 Collimator Selection

Install the appropriate collimator for each radionuclide. For ^{99m}Tc, use the low-energy high-resolution collimator, or equivalent. For other radionuclides, use the collimators that are routinely used clinically for those radionuclides.

6.3 Tomographic Spatial Resolution

The reconstructed tomographic spatial resolution depends on the:

- System spatial resolution for planar imaging with a specified collimator
- Detector orientation and radius of rotation (ROR).
- Electronic center of rotation (COR), axial head tilt, and multiple-head registration (MHR) in the case of multiple detectors
- Reconstruction algorithm—Standard filtered backprojection (FBP) with a ramp filter should be used

The tomographic spatial resolution is measured by imaging a line source in air at a fixed ROR with the collimator used most frequently in the clinic for ^{99m}Tc, typically a low-energy, high-resolution, parallel-hole collimator. The recommended method follows the protocol described in TG Report 52.

For a properly calibrated SPECT system, the reconstructed tomographic spatial resolution should closely match the planar spatial resolution for sources imaged at the same distance from the collimator as the ROR. A procedure to test this is described below. The tomographic spatial resolution may be degraded by inaccuracy in the gamma camera detector calibration for COR, MHR, and axial head tilt. Procedures to evaluate these characteristics are described in Appendix A. The inaccuracies can be identified by carefully examining the locations of the SPECT line or point sources in the projection images obtained during the SPECT acquisition of the line source. In a multiple-detector SPECT system, it is possible that a loss of tomographic spatial resolution is associated with only one of the detectors. Additional SPECT acquisitions may be necessary, such that a full 360-degree acquisition rotation is obtained independently for each detector.

Frequency

- Acceptance testing—The tomographic spatial resolution should be measured using a line source. If possible, for a multiple-detector system, separate 360-degree acquisitions for each detector should be obtained. Optionally, the SPECT point source method described in Appendix B may be used.
- Annual physics survey—The tomographic spatial resolution should be measured using a line source. If SPECT point sources were imaged during acceptance testing, then this method may be used to maintain consistency in the measurements (see Appendix B). Separate 360-degree acquisitions for each detector in a multiple-detector system may not be necessary unless there is a suspicion that a problem exists with only one of the detectors.
- Routine quality assurance—none

Testing Procedure

1. Line Source Placement
   - The line source should be extended past the end of the imaging pallet and over the gamma camera detectors.
   - Position the source so that it is parallel to and centered as close as possible to the axis of rotation (AOR).
   - Set the detectors to a ROR of 20 cm. If that is not possible, set the ROR to the smallest possible radius and record this value. It is important to use the same ROR for all acquisitions.
2. SPECT Acquisition
   - Acquire projection images using a circular orbit in the step-and-shoot mode.
   - Acquire a minimum of 60 images over a 360-degree arc. In multiple-detector systems, the gantry rotation angle will be 360/n degrees, where n is the number of detectors. The number of stops is also decreased by a factor of n. For some cardiac imaging systems, it may only be possible to acquire projection images over a 180-degree arc.
   - Set the acquisition matrix and acquisition zoom to provide a pixel width that is at least 5 pixels spanning the expected FWHM. On many cameras this is achieved by selecting a 128×128 acquisition matrix with a magnification (zoom factor) of 2. Set the acquisition time per stop to obtain at least 2,000–3,000 counts in the first image.

   Additional 360-Degree SPECT Acquisitions for each Detector *(Optional):* Depending on the SPECT system, this acquisition may not be possible. In the step-and-shoot acquisition mode, acquire a complete set of projection images over a 360-degree arc for each detector. For example, for a dual-detector SPECT camera, there should be two data sets, one for each detector. The acquisition time, matrix, and zoom should be chosen as above. This option is useful for isolating a problem to a single detector and may be helpful in evaluating head misregistration problems.
3. SPECT Image Reconstruction

   For all data sets, including additional acquisitions for 360-degree SPECT for each detector, reconstruct the SPECT data over the entire volume occupied by the line source. Reconstruct the images with FBP and ramp filter. An iterative reconstruction algorithm may be used if FBP is unavailable. Any resolution-enhancement options for iterative reconstruction must be disabled.

4. Planar Image Acquisition

   Without moving the line source, acquire a planar image with the detector set to a distance equal to the ROR that was used during the SPECT acquisition. Return the detectors and gantry to the starting angle of the previous SPECT acquisition.

   Use the same acquisition matrix and magnification factor as for the SPECT acquisition and acquire at least 100,000 counts per image.

5. Image Processing and Analysis for Spatial Resolution

   The axially reconstructed images of the line source appear as point source distributions. Image processing involves measuring the FWHM of corresponding point-spread functions (PSF) obtained from count density profiles drawn across the point source distributions. The processing is the same for all SPECT data sets, including the data sets from a full 360-degree acquisition arc for each detector.

   For reconstructed transaxial images:

   - Analyze the point source images in three transaxial slices, one at the line source center, and the other two approximately 1 cm from each end of the line source. Draw count density profiles centered over the point images in the X direction of 3–5 pixels thick to obtain the PSFs. Both the X and Y directions are not needed when the line source is at the AOR.
   - Measure and record the FWHM in mm for all PSFs obtained in the axial slices. It may be necessary to interpolate between data points in the PSF in order to identify the maximum and half-maximum positions.

   For the planar line source image of each detector:

   - Measure and record the FWHM in mm of the LSF obtained at the corresponding three slice locations of the lines source in the planar image using the method as described for measuring planar spatial resolution in Section 5.4.2.
   - Calculate and record the average FWHM.

   Then calculate the average FWHM over all of the detectors.

   For each reconstructed data set, compare the spatial resolution measurements:

   - Compare the average of the tomographic spatial resolution to the average planar spatial resolution from all detectors.
   - Identify the cases for which the SPECT-reconstructed spatial resolution exceeds the planar resolution by 10%.

6. Analysis for MHR, COR, and Head-Tilt Errors

   Review the sinogram and a linogram (or cyclogram) of the line source projection images for all of the SPECT data sets.

   The sinogram displays the path of the line source projected onto the camera detector as it rotates. It should be seen as a sinusoidal curve. If the line source is placed at the AOR, it should be seen as a straight line. Take note of a distorted curve or any gaps, breaks, or discontinuities of the sinogram image. A distorted curve may result from a detector's sagging during rotation. In multi-detector systems, a gap or discontinuity may be observed in transitioning from one detector to the next in the sinogram. Determine the magnitude of such a break or discontinuity to a distance of one half pixel.

The linogram (or cyclogram) displays the projected line source position axially (in the Y-direction) as the camera rotates. Any displacement should be less than the manufacturer's specification. If there is detector head tilt (i.e., the detector is not parallel to the AOR), the displacement displays as a sinusoidal curve in the linogram. In multi-detector systems, a gap or discontinuity may be observed in transitioning from one detector to the next in the linogram. Determine the magnitude of the break or discontinuity to within a distance of one half pixel.

7. Report

   Report the method that was used for measuring the tomographic spatial resolution and whether or not data sets were also collected for a full 360-degree rotation of each detector. If image reconstruction was other than FBP, report the method of image reconstruction that was used.

   Report the average FWHM values for the planar and reconstructed SPECT data.

   Report any significant findings regarding error in COR, MHR, or detector head-tilt.

8. Performance Specifications

   The reconstructed FWHM of the tomographic images should not exceed the planar resolution by more than 10%.

   Any shifts that may be observed in the sinogram and linogram should be within manufacturer's specifications.

6.4 Image Quality Phantom

SPECT image quality is tested by evaluating phantom images for spatial resolution, contrast, and uniformity. The radionuclide shall be ^{99m}Tc. Other radionuclides may also be evaluated.

Frequency

- Acceptance testing—The SPECT phantom image quality study is to be used for baseline comparison of overall SPECT performance of subsequent annual and routine quality assurance testing.
- Annual physics survey—performed by a physicist or by a technologist under the supervision of a physicist.
- Routine quality assurance—performed quarterly by a technologist.

Testing Procedure

1. Phantom Positioning

   For imaging, install the highest-resolution collimator available that is appropriate for the energy of the radionuclide to be evaluated.

   Place the phantom loaded with activity lengthwise on the imaging table in the head-foot direction and center it in the axial field of view so the center of the phantom is aligned with the axis of rotation. Rotate the phantom so that the largest spheres and rods are on the top, away from the table pallet. This rotation is critical for cardiac SPECT systems that acquire images only through a 180-degree arc.

   A circular or noncircular orbit may be used for acquisition. Set the radius of rotation as close to 20 cm as possible. On some cameras the table limits the closest radius to about 25 cm for a circular orbit. In the latter case, noncircular orbits are recommended.

2. Image Acquisition

   Use a 128×128 matrix, with a zoom factor chosen to produce a pixel size of 2.5 to 3.5 mm. Acquire 120 or 128 views over 360 degrees. For a dual-headed camera, two views are acquired at the same time, so, for example, 64 stops (or angles) will give the 128 views.

   The total counts for the acquisition should be 32 million. The time per view is calculated by dividing 32 million by the product of the number of views (120 or 128) and the count rate. If the count rate is not displayed by the camera, a convenient method to measure the count rate is to perform a short static acquisition for 60 seconds with the phantom in position for the SPECT acquisition.

   If there are concerns regarding SPECT performance and artifacts, additional 360-degree SPECT acquisitions for each detector may be performed.

3. Image Reconstruction

   Reconstruct the slices by FBP and with a Butterworth low-pass frequency filter using an order and cutoff frequency that would be used for clinical studies. Adjustment of the cutoff frequency may be done to achieve the desired result of images having the highest resolution and contrast with a mid-range of noise level. Do not over-smooth the images.

   Perform attenuation correction using Chang's Method on the reconstructed transaxial slices using the software provided by the vendor. The attenuation is calculated by defining the phantom boundaries in the image slices and assigning a linear attenuation coefficient. For ^{99m}Tc, the coefficient is 0.11 to 0.12/cm. This value may be adjusted so that the count density at the center of the corrected slices is the same as that at the periphery.

   Save only transaxial slices.

4. Image Analysis

   The reconstructed phantom slices are visually inspected for spatial resolution, contrast, and uniformity. The physicist may optionally wish to reformat or otherwise adjust the slice thickness to approximately 1-cm-thick slices before analyzing the reconstructed slices. If so, the reconstructed slice thickness should be clearly indicated in the report.

   a. Spatial Resolution

   Identify the smallest rod sector that can be visualized in the image slices and record the corresponding diameter of the rods. A sector is considered to be visualized when more than half of the rods in that sector can be identified. Note whether the smallest rods are clearly visualized or visualized with low contrast. Summing of 10–12 slices may be useful.

   b. Contrast Detectability

   Identify the smallest sphere that can be visualized in the image slices and record the corresponding sphere diameter. Note whether the smallest visualized sphere has contrast that is greater or less than that of the noise. Additionally, calculate the contrast for each sphere identified in the reconstructed image as follows:

   Sphere contrast = (mean pixel count from uniform section –
   minimum sphere pixel count) / mean pixel count from uniform section

   c. Uniformity

   A uniformity index is not calculated for SPECT. Rather, the image slices are inspected for specific artifacts:

- Attenuation— attenuation artifacts are either not present, under-corrected, or over-corrected.
- Ring—Concentric rings of alternating high- and low-count density surrounding the center of reconstruction. In some cases, only a center ring (solid or doughnut) at axis-of-rotation can be identified. Compare the magnitude of the rings with that of the noise. Ring artifacts whose magnitudes are less than of the noise may be considered clinically insignificant. Record the numbers of slices in which the magnitude of the ring artifacts exceeds the noise.
- Focal—high or low count density focal areas that could be miss-interpreted as a rod or sphere.

5. Report

   Report all findings identified in the image analysis section.

6. Performance Specifications

   For ^{99m}Tc, the criteria that would be considered satisfactory are:

   - Spatial Resolution: 11.1 mm rods fully resolved.
   - Contrast: The 15.9 mm sphere is visualized.
   - Uniformity: No ring artifacts with magnitude greater than the magnitude of the noise, or if ring artifacts are visible in a few slices, they should not be considered likely to be clinically significant.

7. Hybrid SPECT/CT Systems

Similar to the evolution of PET/CT systems, CT scanners have been added to SPECT systems for the added value of image co-registration of the SPECT and CT images. The CT images are also used to provide attenuation correction of the SPECT. These hybrid systems have separate SPECT and CT acquisition hardware. As such, performance measurements of both modalities are specified and performed separately. We will describe tests that address the combination of the two.

There is a wide range in CT capabilities and design, whether it is diagnostic, conventional multi-slice CT, flat panel, or otherwise. It is necessary to identify the type of CT system that has been incorporated into the hybrid SPECT/CT system, and to understand its performance capability and its intended use in the clinic. We will refer the reader to previous publications and guidelines for performance testing and quality assurance of conventional multi-slice CT systems. This report will provide guidance for testing of nonconventional CT systems.

In addition to the tests outlined in the Planar and SPECT sections, three additional tests have been identified that are specific to performance of hybrid SPECT/CT systems:

A. SPECT/CT image quality

B. SPECT/CT spatial co-registration

C. CT dose and image quality assessment

In addition to performance evaluation, an assessment of the radiation dose from the CT is necessary and should be reported.

7.1 Test Sources and Phantoms

In principle, all radionuclides used for SPECT/CT imaging could be considered. The performance for ^{99m}Tc is required.

7.1.1 Image Quality SPECT Phantom

Prepare the Image Quality SPECT Phantom as described in Section VI.A.3 of this report.

7.1.2 Point Sources for Co-Registration Measurements

One of two types of point sources may be used.

1. ^{99m}Tc Point Sources with CT Contrast in Capillary Tubes

   Combine ^{99m}Tc pertechnetate of high concentration (e.g., 400 MBq/ml) and iodinated CT contrast agent (e.g., Optiray 320) in a 2:1 ratio and mix thoroughly to make a volume of 1–2 ml solution. Though the glass capillary tubes can be visualized in CT images, the addition of iodinated CT contrast medium to the ^{99m}Tc solution greatly enhances the visualization of the point sources in CT images. Make three point sources using three capillary tubes of internal diameter less than 1 mm (Figure 1). To fill, dispense multiple small drops (<1 mm^3) of mixture on a clean surface, such as waxed paper. Load the end of each tube using capillary action with approximately 1 mm^3 of volume. Seal the capillary tubes on both ends with an appropriate clay sealer. The end into which the liquid was introduced should be sealed first to avoid having the liquid forced out of the tube as the clay is introduced into the other end, which compresses the air between the liquid and the clay.

2. ^{57}Co Button Sources

   Obtain three ^{57}Co button sources, each with an activity of approximately 2 MBq (50 uCi).

7.2 Gamma Camera Detector Setup

7.2.1 Energy Window and Level

Refer to the energy levels and windows identified in Table 4. For ^{99m}Tc the energy window parameters that are used clinically should be selected.

7.2.2 Collimator Selection

Install the appropriate energy-rated collimator for each radionuclide. For ^{99m}Tc, use the low-energy, high-resolution collimator, or equivalent. For other radionuclides, use the collimator that is routinely used clinically.

7.3 SPECT/CT Image Quality

This tests the overall SPECT/CT image quality using CT-based attenuation correction and all other processing and reconstruction parameters that are recommended by the manufacturer for routine use

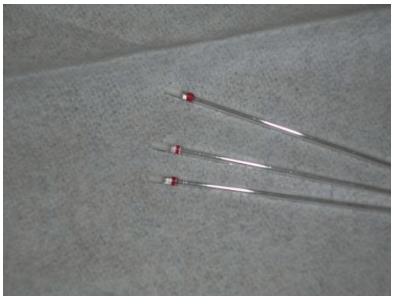

Figure 1. Capillary tubes used to make point sources of size approximately 1 mm^3 solution containing ^{99m}Tc. Iodinated CT contrast medium may be added to the ^{99m}Tc solution in order to more clearly identify the source location on the CT images.

in clinical SPECT/CT imaging (e.g., scatter corrections, iterative reconstruction parameters, resolution recovery, etc.). The test uses the same SPECT phantom as described above for SPECT-only systems except that CT attenuation correction and scatter correction is applied. In this case, only one phantom acquisition is necessary to satisfy testing requirements.

Frequency

- Acceptance—use results as the baseline for comparison to future measurements.
- Annual—compare with the baseline image quality measurements.
- Routine quality assurance—perform quarterly by a technologist.

Testing Procedure

The testing procedure is the same as that described in this report in Section 6.4, except that the additional CT scan is used for attenuation correction. The CT may be acquired prior to, or following the SPECT acquisition.

1. Image Quality SPECT Phantom Positioning

   Position the Image Quality SPECT Phantom as described in Section 6.4 #1 of this report.

2. Acquire the SPECT Emission Data

   Acquire SPECT emission data in accordance with the commonly used protocol for whole body imaging making sure that 32 million total counts are acquired.

3. Acquire the CT Transmission Data

   Acquire the CT scan of the phantom with scan parameters that are commonly used for whole-body SPECT/CT procedures.

   The CT transmission scan may be performed prior or following the acquisition of the SPECT emission data.

4. Reconstruct the SPECT Images with CT Attenuation Correction

   Reconstruct the SPECT images using the iterative algorithm used clinically with CT-based attenuation correction, and with scatter correction and resolution recovery when available. The number of iterations chosen and any additional smoothing filter may be adjusted in order to compare reconstructed results of the SPECT/CT system with a SPECT phantom using the Chang's attenuation correction method described in Section 6.4 #3 above.

5. Image Analysis

   a. Uniformity

   Inspect images of the uniform section for specific artifacts as described in Section 6.4 #4c.

   b. Noise Analysis

   Draw a large ROI (>100 cm^2) in a SPECT slice within the central portion of the uniform section and measure the mean pixel count and standard deviation. Calculate the root-mean-squared (RMS) noise (TG Report 52) as shown below:

   RMS noise (%) = 100 x standard deviation / mean pixel count

c. Spatial Resolution

Inspect the images of the rods sections of spatial resolution as described in Section 6.4

d. Contrast Detectability

Inspect the images of the cold-sphere sections as described in Section 6.4 #4.

6. Report

   Report the uniformity, RMS noise, spatial resolution, and contrast detectability.

7. Performance Specifications

   Determine the baseline values as part of Acceptance Testing. For ^{99m}Tc SPECT/CT the minimum image quality criteria that are considered satisfactory are:

   - Spatial Resolution: 11.1 mm rods fully resolved.
   - Contrast: The 15.9 mm sphere is visualized.
   - Uniformity: No ring artifacts with magnitude greater than the magnitude of the noise, or if ring artifacts are visible in a few slices, they should not be considered likely to be clinically significant.

7.4 SPECT/CT Spatial Registration

Spatial registration tests measure the accuracy of the spatial registration (or alignment) of the field-of-view between the reconstructed SPECT and CT images. The motivation for SPECT/CT image registration is that spatial registration is critical for accurate SPECT image reconstruction using CT-based attenuation correction and the display of fused images for clinical interpretation.

Frequency

- Acceptance—Compare with the manufacturer's registration specifications. Use the results from acceptance testing as the baseline for future measurements.
- Annual—Compare with the manufacturer's registration specifications or with baseline spatial co-registration measurements.
- Routine Quality Assurance—Perform as recommended by the manufacturer or anytime that the mechanical alignment of the SPECT and CT components has been adjusted (e.g., when the SPECT and CT gantries have been physically separated as part of service).

Testing Procedure

- We recommend using the manufacturer's registration test phantom procedure and analysis tools to evaluate the spatial registration of SPECT and CT images.
- The reconstructed SPECT and CT images obtained in Section 7.3 may be inspected for spatial registration. To test for table deflections, we recommend that additional weight of approximately 70 Kg (weight of an average patient) be added to the table along with the SPECT phantom during SPECT/CT acquisition.
- Appendix C describes a procedure in which both the image quality SPECT phantom and the registration images of the ^{57}Co point sources are acquired simultaneously.

1. Evaluate Spatial Registration

   To evaluate the spatial registration, display both SPECT and CT images series from either the manufacturer's test procedure or the SPECT phantom acquisition using available clinical SPECT and CT fusion software. The location of objects in the test phantoms should be clearly

observed within the CT images and should spatially align with the same objects (hot or cold) in the SPECT phantom images. Hot spots of point sources within the manufacturer's test phantom should be centered within the corresponding CT objects. Cold spheres within the SPECT phantom should align with the corresponding spheres seen in the CT images.

If there is mismatch in the locations of each source between the CT and SPECT images, use the fusion software to move (translate) the CT images to align them with the SPECT images. Record the absolute value of the offset in each direction in units of pixel shifts or mm for all sources evaluated ($\Delta x1$, $\Delta y1$, $\Delta z1$). Calculate the mean deviation between the SPECT and CT images along each direction (x, y, or z):

2. Report

   Report the voxel dimensions and the mean shifts along the three axes to co-register the images.

3. Performance Criteria

   The mean deviation along any axis should be $\leq$ 5 mm, or that specified by the manufacturer.

7.5 CT Dose and Image Quality Assessment

The description of a complete evaluation of the CT component of the system is beyond the scope of this report. AAPM TG Report 96[24] and ACR guidelines CT Quality Control Manual[25], Phantom Testing Instructions[26], and CTAP Phantom Data/Dose Forms[27] are useful references for this purpose.

It is prudent, however, that the physicist who is responsible for monitoring SPECT performance ensures that certain features of the CT system are evaluated at acceptance testing, annual surveys, and for routine quality control. If the CT component is to be used for diagnostic CT scans, then a complete evaluation of the CT scanner should be performed by a qualified medical physicist. Results reported by the QMP who performed a recent CT-specific survey of the SPECT/CT unit may be referenced in the SPECT/CT evaluation.

7.5.1 CT Dose Assessment

The CT dose index ($CTDI_{vol}$) for the routinely used CT protocols imaging should be reported.

There are various models of CT that have been incorporated into SPECT/CT systems. The CT dose should be measured as per published guidelines[24,25,26,27]. For SPECT/CT systems that have non-conventional CT detector configurations, such as is the case for flat-panel CT detectors, it may be necessary to make CT dose measurements based on measurements using a small thimble chamber, such as a Farmer chamber (see AAPM TG Report 111[28]), or by following the manufacturer's recommendations.

Frequency

- Acceptance—Compare the $CTDI_{vol}$ measurements with the manufacturer's dose reports. Use the results from acceptance testing as the baseline for future measurements.
- Annual—Compare the $CTDI_{vol}$ measurements with the manufacturer's dose reports and those made at acceptance testing.
- Routine Quality Assurance—none.

7.5.2 Image Quality Assessment

Assessment of the image quality, paying particular attention to CT image artifacts, should be performed routinely. The quality assurance procedures recommended by the manufacturer should be followed. The ACR guideline *CT Quality Control Manual* is a useful reference, especially if the CT

scanner is also used for diagnostic imaging. The main aspects of CT image quality that need to be evaluated are:

- Laser accuracy and table indexing accuracy
- CT image quality indices (image homogeneity, CT number accuracy, CT resolution, and noise). The ACR accreditation CT Phantom[27] may be used. For low-dose protocols, the acceptance criteria established by the ACR Accreditation program may not be attainable.
- Evaluation of CT artifacts. CT artifacts may be propagated into the SPECT images by SPECT reconstruction using the CT for attenuation correction.

Frequency

- Acceptance—Measure or report a qualified medical physicist's measurement of the initial image quality indices obtained during the acceptance testing. These will be used as a baseline for future measurements.
- Annual—Measure or report a qualified medical physicist's measurement of the image quality indices.
- Routine Quality Assurance—Ensure that the manufacturer and ACR accreditation guidelines are performed daily, weekly, and monthly.

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Appendix A

Center-of-Rotation, Multiple-Head Registration, and Head Tilt

The tomographic spatial resolution may be degraded by inaccuracy of the gamma camera detector center-of-rotation (COR) calibration, multiple-head registration (MHR), or axial head tilt. A procedure to evaluate and calibrate in the alignment of the COR and MHR is incorporated into all SPECT systems. This procedure is performed by technologists as a routine quality control procedure either monthly or per manufacturer specification. This procedure may also be performed by the qualified medical physicist to evaluate for proper calibration during an annual survey or for trouble shooting at any other time.

The COR calibration procedure aligns the projection of the SPECT system axis of rotation (AOR) with the center pixel column in the acquired projection image matrices. The MHR is a calibration to ensure that each detector head in a multiple-detector SPECT system samples the same volume. It is necessary, however, that the detector heads always be parallel to the AOR.

Calibration of both COR and MHR is ordinarily combined into one measurement. The method of measurement is provided in the manufacturer's procedure manual and must be followed. On some SPECT systems, separate measurements are required for both the 180- and 90-degree detector configurations. The 90-degree configuration is typically used only for cardiac SPECT imaging.

To perform the measurement, point sources are placed on the imaging table or into a specially designed fixture. The SPECT acquisition of the point sources is a full 360-degree rotation of each detector head. The projected location of each point source in the sinogram of the camera images is identified by the calibration software and tracked as a function of detector angle. No tomographic reconstruction is performed. The COR and MHR are calculated from the projected source positions.

Axial head tilt cannot be observed in the sinogram. It may be observed in a cine display of the SPECT projection images. Any sinusoidal oscillation in the axial (vertical) direction indicates the presence of head tilt. There is no calibration procedure for axial head tilt. Its correction requires mechanical adjustment by a service engineer.

Point Source Preparation

One or more point sources are used for testing the center of rotation (COR) and multiple-head registration (MHR) calibrations. A source placed at the bottom of a v-shaped vial is ideal, but it also may be placed at the bottom of a syringe. The syringe needle should be removed and the tip capped. Exercise great care when handling the sources so as not to fractionate the point source when assaying it in a dose calibrator or when placing it in front of the detector. The activity of each source depends on the manufacturer's specifications and may range from 20–60 MBq (~0.5–1.5 mCi). When preparing multiple sources, ensure that the activities of all sources are within ±10% of each other.

Always refer to the gamma camera user's manual for recommendations for the number of point sources to prepare and the recommended activity level. Failures in testing and calibration may result if the manufacturer's instructions are not followed.

Testing Procedure

1. Point Source Placement

   - Place the point sources on the imaging table set at an offset distance from the axis of rotation (AOR) or measurement accessory phantom as described by the manufacturer.
   - Set the detector radius of rotation (ROR) to the recommended distance.

2. SPECT Acquisition
   - Acquire projection images as prescribed by the manufacturer's protocol. Note that a full 360-degree rotation for each detector head is ordinarily obtained.
   - The acquisition time per stop may be adjusted longer in the case that insufficient activity is used in the point sources.
3. Projection Image Processing and Analysis

   The manufacturer's software is programmed to acquire the data and report deviations of the position of the point sources from the AOR. Refer to the manufacturer's manual for specifications of the maximum allowable deviation. Current analysis programs issue a failure message if the results exceed the manufacturer's tolerance for these measurements.

Appendix B

Point Source Method for Measuring SPECT-Reconstructed Spatial Resolution

The point source method described here is equivalent to that in NU 1-2012, which uses three SPECT point sources. Although the method is more time consuming, both in source preparation and data analysis, more quantitative results are obtained.

Point Source Preparation

In principle, all radionuclides that are used for SPECT imaging could be considered when testing SPECT performance. In common practice the performance is measured only with ^{99m}Tc.

Prepare three point sources as described previously in 7.1.2, except without the iodinated CT contrast agent. The point source activity within the tubes should be 8–20 MBq (~200–500 μCi) each, and each be within ±10% of the others. Alternatively, three ^{57}Co button sources of 8–20 MBq (~200–500 μCi) could be used.

Testing Procedure

1. Gamma Camera Detector Setup

   The energy level, window, and the installed collimator should be the same as described in Section 5.2.

2. Point Source Positioning

   - Position the three SPECT point sources in the same horizontal plane as described in NU 1-2012, and extending past the end of the imaging pallet as shown in the Figure B.1. These sources may be attached to a block mounted on top of the imaging pallet. The center source should be placed along the detector's axis of rotation (AOR) and centered within the detector's UFOV. Extend the sources beyond the end of the imaging pallet as shown. If shorter, 75-mm capillary tubes are used, then the source extension axially should be 30 mm instead of 40 mm.
   - Set the detector ROR as close to 20 cm as possible. Record this value. It is important to use the same radius-of-rotation (ROR) in subsequent evaluations.

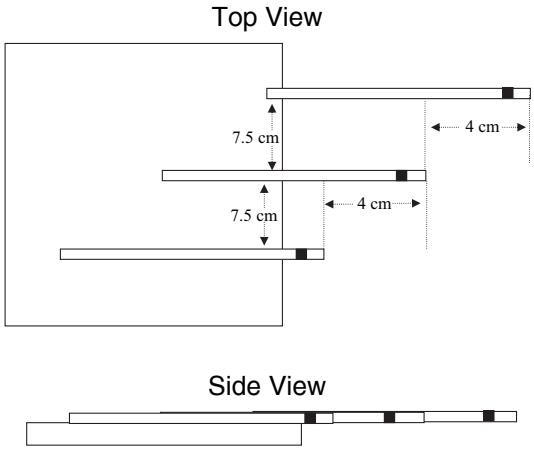

Figure B.1 Point source configuration and location for SPECT spatial resolution and multiple-detector alignment using three SPECT point sources.

3. SPECT Acquisition

   - Acquire projection images using a circular rotation in the step-and-shoot mode.
   - Acquire 120 or 128 images over a 360-degree arc. In multiple-detector systems, the gantry rotation will be 360/n, where n is the number of detectors. The number of stops is also decreased by a factor of n. For some cardiac imaging systems it may be possible to acquire projection images only over a 180-degree arc.
   - Set the acquisition matrix and acquisition zoom to provide a 1.5 mm pixel width so that there should be at least 5 pixels spanning the expected FWHM. On many cameras, this is achieved by selecting a128×128 image matrix with a magnification (zoom factor) of 2.
   - Set the acquisition time per stop to obtain at least 6,000 counts in the first image.

   Additional 360-Degree SPECT Acquisitions for each Detector *(Optional):* Depending on the SPECT system, this acquisition may not be possible. In the step-and-shoot acquisition mode, acquire a complete set of projection images over a 360-degree arc for each detector. For example, for a dual-detector SPECT camera there should be two data sets, one for each detector. The acquisition time, image matrix, and zoom should be chosen as above.

4. Planar Image Acquisition

   Following SPECT acquisition and without moving the sources, acquire a planar image with each detector set to a distance equal to the ROR that was used during the SPECT acquisition. Return the detectors and gantry to the starting angle of the previous SPECT acquisition.

   Use the same acquisition matrix and magnification factor as for the SPECT acquisition, and acquire at least 20,000 counts in each image.

5. SPECT Image Reconstruction

   For all data sets, including any additional acquisitions for 360-degree SPECT for each detector, reconstruct the SPECT images using FBP with a ramp filter over the entire volume occupied by the point sources. If only iterative reconstruction is available, use the number of iterations and subsets that are used for clinical whole-body protocols. This choice may not lead to full convergence and, hence, the FWHM might be larger than that which could be obtained by using FBP.

   Save also the sagittal and coronal cross-sectional images.

6. Image Processing and Analysis

   The axially reconstructed images show as point source distributions. Measure the FWHM of the corresponding PSF obtained from count density profiles drawn across the point source distributions. The processing is the same for all SPECT data sets, including data sets from all the 360-degree acquisition arcs for each detector.

   For each reconstructed data set:

   - Analyze the tomographic slices in the transaxial, sagittal, and coronal images, if available, that correspond to the center of the point sources located in the tomographic volume. Draw count density profiles of 3–5 pixels thick across the center of the point source images to obtain PSFs in two directions as follows:
     - Transaxial: X (radial) and Y (tangential)
     - Coronal: X (tangential) and Y (axial)

  - Sagittal: X (radial) and Y (axial)
  - Measure and record the FWHM in mm for all PSFs (see Table B.1). It may be necessary to interpolate between the data points in the profile in order to identify the maximum and half-maximum positions (see Table B.1). If the distance measurement tool reports distances as pixels, then use the known distance between two line sources to determine the pixel size.
- For each of the point sources, calculate the average tangential, radial, and axial FWHM. There should be two measurements along each direction.

For the planar image of each detector:

- Draw a count density profile of 3–5 pixels thick to obtain the PSF across the center of each of the point images in the X and Y directions.
- Measure and record the FWHM in mm for all PSFs (see Table B.1). It may be necessary to interpolate between the data points in the profile in order to identify the maximum and half-maximum positions. If the distance measurement tool reports distances as pixels, then use the known distance between two line sources to determine the pixel size.
- For each source location, calculate the average FWHM of the X and Y directions. Calculate the average FWHM of all three sources.

Then, calculate the average FWHM of all detectors.

For each reconstructed data set, compare the spatial resolution measurements:

- For each source location, compare the tangential, radial, and axial spatial resolution for each detector, if measured, and the combined detector data. The tangential and radial FWHM should be nearly equal for the center source. There can be as much as a 2 mm increase in tangential FWHM for the peripheral point sources. The axial FWHM should be nearly the same for all point sources.
- For the central point source nearest to the AOR, compare the average FWHM to the average of the planar spatial resolution of all detectors.
- Identify the cases for which any difference exceeds $\pm$0.5 times the pixel size (~0.75 mm). The positive loss in reconstructed tomographic spatial resolution could be caused by problems with multiple-detector registration, COR calibration of an individual detector, or head tilt.

Table B.1: Table of the measurements to assess SPECT-reconstructed spatial resolution using three point sources

	Point Source Position	Det. 1 (Opt)	Det. 2 (Opt)	Det. 1 & 2
Planar Resolution FWHM (mm)	Left			
	Center			
	Right			
	Average			

	Point Source Position	Tangential		Radial		Axial	
		Transaxial-Y	Coronal-X	Transaxial-X	Sagittal-X	Coronal-Y	Sagittal-Y
Det.1 (Opt.) Tomographic Resolution FWHM (mm)	Left						
	Center						
	Right						
	Average						
	Point Source Position	**Tangential**		**Radial**		**Axial**	
		Transaxial-Y	**Coronal-X**	**Transaxial-X**	**Sagittal-X**	**Coronal-Y**	**Sagittal-Y**
Det.2 (Opt.) Tomographic Resolution FWHM (mm)	Left						
	Center						
	Right						
	Average						
	Point Source Position	**Tangential**		**Radial**		**Axial**	
		Transaxial-Y	**Coronal-X**	**Transaxial-X**	**Sagittal-X**	**Coronal-Y**	**Sagittal-Y**
Det.1 & 2 Tomographic Resolution FWHM (mm)	Left						
	Center						
	Right						
	Average						

Appendix C

Data Acquisition for Combined Evaluation of Both SPECT/CT Spatial Co-Registration and SPECT/CT Image Quality

Two separate SPECT/CT scans can certainly be performed for evaluation of image quality and spatial co-registration of the SPECT/CT system. However, it is possible to combine both tests into a single data acquisition and separately process the data as per the needs of the two different tests. It will be necessary to attach the point sources for the co-registration test to a cylinder of the same diameter (a Styrofoam cylinder is recommended) as the Image Quality SPECT phantom.

It is possible to image ^{57}Co simultaneously with ^{99m}Tc. ^{57}Co has a 136 keV gamma emission besides the more common 122 keV emission. About 20% of 122 keV and all of the 136 keV gamma emissions will be accepted using a conventional ^{99m}Tc photopeak window. Therefore, ^{57}Co button sources will appear with reasonable sensitivity in the ^{99m}Tc image (Figure C.1).

Phantom Preparation and Placement

Attach the three point sources to a cylinder of diameter 20–25 cm and a length of 10 cm or more (a Styrofoam cylinder or another cylinder such as a nonradioactive SPECT phantom can be used). Point sources of either ^{99m}Tc or ^{57}Co may be used. The axial length of the foam block should be small enough such that all three point sources can be visualized in a single SPECT bed position. Attach two point sources on the cylindrical at the 12'o clock and 3 o'clock positions on the cylindrical surface and the third at the iso-center on one end of the cylinder (Figure C.2). Attached the cylinder to one end of the SPECT phantom. Fill the SPECT phantom and add activity as described in Section 6.1.3. Center the phantom on the imaging pallet. To test for table deflection when transporting the patient pallet between the CT and SPECT scanners, add approximately 70 kg (170 lbs) of weight to the table prior to scanning.

Image Acquisition and Reconstruction

Smaller than routine clinically used voxel sizes are recommended for registration testing over the entire SPECT and registration phantoms. SPECT images should be acquired using a relatively larger matrix size or a zoom acquisition to acquire projection images that have 2.0–2.5 mm pixels or smaller. SPECT reconstruction using smaller voxel sizes with FBP reconstruction are recommended for evaluation of the SPECT/CT spatial registration test over registration point sources. For assessment of

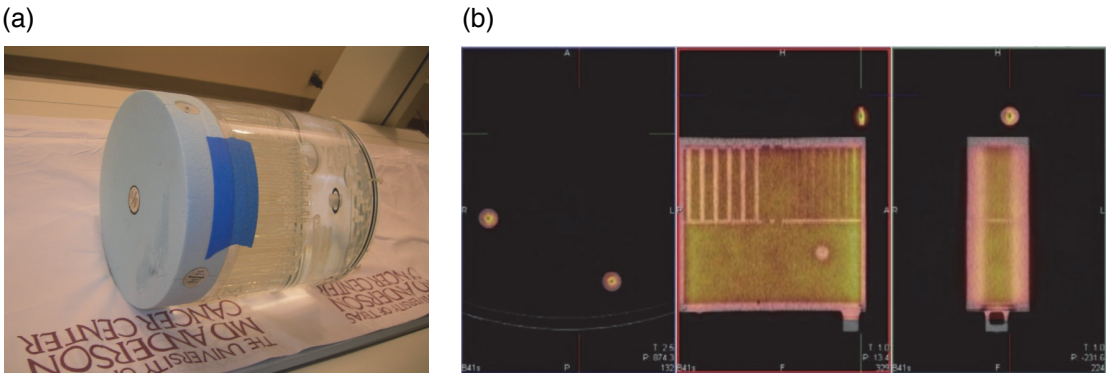

Figure C.1 (a) The button sources attached to the end of the SPECT phantom. (b) Transverse, coronal, and off-center sagittal reconstructed images of the ^{57}Co button sources and the ^{99m}Tc-filled SPECT phantom acquired in the ^{99m}Tc photopeak window.

Figure C.2 ^{57}Co button sources attached to a cylindrical foam block.

SPECT image quality, SPECT projection images can be re-binned to larger pixels (around 5 mm) that better reflect clinical SPECT voxel sizes. As described in Section 7.3 #3, SPECT images for image quality should be reconstructed using the processing and reconstruction parameters that are routinely used in clinical SPECT/CT images (e.g., iterative reconstruction, scatter corrections, resolution recovery, number of iterations and subsets, post-reconstruction smoothing filter, etc.

Likewise, the CT images should be acquired with 1–2 mm slices as specified by the co-registration testing procedure. With multi-detector CT, however, it is straightforward to acquire data in thin channels and reconstruct them to image thicknesses necessary for attenuation correction of the data to be used for image quality assessment.

1. CT Acquisition
   - Acquire using tube potentials of 100 or 120 kVp, a tube current of 150–250 mAs, an axial or helical scan with a pitch of less than 1, and the thinnest detector rows available.
   - Reconstruct to slices with a thickness of 1 mm with a high cut-off frequency filter (e.g., bone or head). Adjust the reconstruction diameter as necessary to achieve cubic voxels.
2. SPECT Acquisition
   - Use a relatively fine matrix size (e.g., 256×256) or a zoom acquisition to acquire projection images that have 2.0–2.5 mm pixels or smaller.
   - Acquire a minimum of 128 views over 360 degrees for approximately 15 sec per view with either a circular or a noncircular gantry rotation.
   - Reconstruct SPECT images using FBP with a ramp filter and no attenuation correction. An iterative reconstruction algorithm may be used if FBP is unavailable.

Image Analysis

If possible, resample and save the resampled SPECT images that match the reconstructed CT voxel size. Resampling of the SPECT data can usually be performed using the manufacturer's workstation software.

Display the SPECT and CT images in the same reference frame using SPECT and CT fusion software. For the ^{57}Co button sources, a small pocket filled with epoxy that seals the ^{57}Co within the acrylic button source corresponds to location of the ^{57}Co radioactivity in the CT image and should be

spatially registered with the hot spot of in the SPECT image. If using the ^{99m}Tc point sources, the location of the iodinated CT contrast within the capillary tube in the CT image will be spatially registered with the hot spot of the ^{99m}Tc point source in the SPECT image. The hot spot should also be located within the high-density ring of the glass capillary tube walls.

If there are mismatches in the locations of each source between the CT and SPECT images, use the fusion software to move (translate) the CT images to align them with the SPECT images. Record the absolute value of the offset in each direction in units of pixel shifts or mm for all three point sources: (Δx1, Δy1, Δz1), (Δx2, Δy2, Δz2), and (Δx3, Δy3, Δz3). Calculate the mean deviation between the SPECT and CT images along each direction (x, y, or z):

$$\text{Mean deviation along x-axis} = (\Delta x1 + \Delta x2 + \Delta x3)/3$$

$$\text{Mean deviation along y-axis} = (\Delta y1 + \Delta y2 + \Delta y3)/3$$

$$\text{Mean deviation along z-axis} = (\Delta z1 + \Delta z2 + \Delta z3)/3$$

Alternatively, calculate the centroid of each point source in both the CT and SPECT images and calculate the pixel shift values (Δx, Δy, Δz) required for each point source.