Gamma Camera Overview

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General

1. Introduction

Most gamma cameras can be used in three essentially different modes: for planar images, for tomography (SPECT) and for whole-body scanning. Equipment must comply with the (electrical) requirements as described in IEC-601. These recommendations address the specific requirements for the testing of nuclear medicine equipment, based on planar checks for all detectors present, supplemented by specific tests for SPECT and whole-body scanning if the camera is used for this purpose.

2. Selection of tests and frequency

The tests and frequencies are selected using the principles described in the general introduction under Equipment, and subsequently reviewed by experienced users with the help of the IAEA Quality Control Atlas for Scintillation Camera Systems. Performing a test from these recommendations is useful if clinical thresholds for action and/or specifications for the camera are available. If both are missing, there is generally no point in carrying out the test unless changes in the results are meaningful and can be compared to a baseline. When purchasing a new camera, agreements should be made about how to deal with missing specifications. Occasionally, it is important that the user is aware of the test results and any limitations that these may entail with regards to clinical use. In such cases, it still makes sense to carry out a test even if no specifications are available.
The tests are primarily based on the NEMA protocols. Table 1, gives an overview of the NEMA tests. Table 2 is a summary of how the NEMA tests are reflected in these Recommendations. These recommendations are also substantiated by tests not included in the NEMA tests, for example the testing of the background radiation.
The three key elements for checking the gamma camera are: uniformity, sensitivity and COR (Centre of Rotation). These elements should be checked frequently. The specific frequency is dependent on the circumstances (e.g. half the frequency if no discrepancy has been found on four occasions, see the General Recommendations on Equipment Checks, Section 3: Frequency). The remaining tests need only be conducted following (re) acceptance (installation, relocation or very extensive repairs or modifications), after major maintenance (or major repairs) or if there are problems.
If radionuclides other than ^{99m}Tc are used (such as ^{67}Ga, ^{111}In, ^{123}I and ^{201}Tl) certain tests must be repeated using these radionuclides. In addition, collimators other than the LE collimator will also need to be tested. If the gamma camera has several detectors or several different configurations (detectors both under 180 and under 90 degrees) tests will need to be performed for each detector and/or each configuration separately.
In some cases (e.g. pixel size, COR) systems are poorly protected against "accidental" changes to the settings. This can be a reason for performing very frequent checks (possibly even a check during clinical recordings where the settings are important).

These recommendations focus on standard clinical use. If the gamma camera is used for unusual applications, it may be necessary to carry out additional tests. One example is the quantitative applications for the benefit of therapy. If, in this regard, whole-body or SPECT images are required, then it will be necessary to use an adaptive checking scheme to check the sensitivity when making these images.

3. Measuring conditions

An excessively high count rate can have a detrimental effect on detector performance. Tests should be carried out with a count rate under 20 kcps unless the manufacturer advises otherwise. With most tests, an indication is given of the source intensity required. The user must take care not to exceed the maximum count rate.

If the gamma camera is to be used with high count rates, some tests described here (such as uniformity, spatial resolution) can be repeated at, e.g. 75 kcps.

For full NEMA tests: whenever a collimator is not used the edge of the crystal should be covered with a lead ring mask of at least 3 mm in thickness, the visual field (inner diameter) of which corresponds to the field of view of the collimators (UFOV). However, testing without a lead ring yields very useful results whilst being faster, simpler and often with less risk of damage to the crystal. If there are deviations, the test must be repeated with the lead ring, if necessary with assistance from the manufacturer.

When open radioactive sources (line source, point source, spray, bottle, etc.) are used directly on the detector, it is advisable to cover the detector with a plastic foil to prevent any radioactive contamination.

In carrying out these tests without a collimator, all unnecessary radioactive sources, including patients, must be removed from neighbouring areas, since thin walls often provide insufficient shielding.

Tests should always be carried out under exactly the same conditions, thus with the detector in the same position and with the same orientation.

Historically, a 20% window was used as standard, however nowadays a 15% window is often the norm. NEMA NU 1-2001 specifies a 15% energy window everywhere for ^{99m}Tc and ^{57}Co (except for the COR check with ^{57}Co, where 20% is still used). The manufacturer's instructions must be followed for other radionuclides. Clinically however, a 20% window may be desirable, e.g. when a relatively weak ^{57}Co marker source is used in ^{99m}Tc studies. Thus, it can be useful to repeat specific tests with an energy window of 20%.

If the manufacturer specifies measurement conditions which deviate from the NEMA conditions or the conditions recommended here, then the manufacturer's directions must be followed if the purpose is to check the specifications. In order to perform a uniformity test or to check clinical reference values, the measuring conditions recommended here are to be used.

4. Equipment required, including phantoms and sources

Phantoms and radioactive sources are needed for quality control of the gamma camera. Phantoms are not standardised, that is to say, there are many different phantoms in circulation. These may need to be filled with activity (line phantom, Jaszczak) or irradiated with a planar source (lead bar phantom, slit phantom etc.). For most tests, the phantoms, or the sources, must be large enough to allow the entire field of view to be tested at once.

A flood source of ^{57}Co is preferable as a planar source as its photo energy is

approximately equal to that of ^{99m}Tc and the source is available at all times. The source must have a sufficiently homogeneous activity distribution i.e. the standard deviation of the activity per cm^2 must be less than 1%. Contamination with ^{56}Co, ^{58}Co and ^{60}Co may produce high background activity, especially with a new source; due to septal penetration of high energy photons. These contaminants, expressed as the fraction of radioactivity, should not exceed 0,1%. The high-energy photons of ^{57}Co also contribute to this high background activity (in the order of 0,1%). If there is excessively high contamination or if problems with high-energy photons are suspected, the source can be placed at a greater distance (0,5 m) from the collimator.
The use of fillable planar sources is discouraged. Especially with the simple fillable sources, problems may be expected with bulging if the walls are too thin, poor mixing (including the radionuclide bond sticking to the source wall), and air bubbles. Thus the use of fillable planar sources is time consuming. Also, they result in a relatively high radiation exposure and the results obtained are unreliable. Systems that include a pump and thick walls are more reliable but expensive and not very easy to use.
To fully implement the recommendations detailed below, the following phantoms, tools and sources are required:

- clinical radionuclide point sources, typically about 10 MBq.
- flood source ^{57}Co, ca 150-400 MBq. Too weak a source leads to impractically long recording times, and too strong a source results in unnecessary radiation exposure.
- at least three point sources of ^{57}Co of at least 1 MBq. If more sources and several strengths are available, fewer recordings need to be made for each test.
- glass(beaker), linearity
- line phantom (inner diameter 1 mm) (commercially available, but can also be made by stretching connecting tube)
- source holder for COR (this is often supplied with the camera)
- spirit level, stopwatch, ruler, tape measure
- fixed distance source holder
- Jaszczak phantom with line source insert
- optional: bulbs and fillable bulb inserts for the Jaszczak phantom
- optional: lead bar or BRH (Bureau of Radiological Health) phantom with flood source ^{57}Co

5. Planar tests

When checking the gamma camera, one can distinguish two fields of vision: the Useful Field of View (UFOV) corresponding to most of the visual field of the collimator and the Central Field of View (CFOV) corresponding to the central part of the UFOV. This distinction is made because some parameters, such as uniformity and linearity, may display larger and unavoidable deviations in the periphery than would be acceptable for the central area. These peripheral deviations are acceptable because the central part of the field of view is the most critical part (especially with SPECT, where indeed the whole strip along the central axis is important in relation to the emergence of interfering ring artifacts).
The UFOV is determined as follows: mount the collimator; place a planar source on the collimator; collect enough counts (see 'Uniformity' protocol); calculate the average number of counts per pixel in the middle of the field of view; determine the isocount contour at 50% of

this mean. According to NEMA, the UFOV is then defined as equal to the area having linear dimensions (radius or, as the case may be, length and width) that are equal to 95% of the 50% isocount area. In practice, the UFOV is usually specified by the manufacturer.
The CFOV is the area with linear dimensions of 75% of the UFOV.
Some tests are performed both with and without a collimator. When testing without a collimator, only the detector - that is the crystal, the PMT's and all electronic circuits - are tested. These are the intrinsic values of the test parameters. When testing with the collimator mounted, the entire system is tested as it is used in practice: the extrinsic test parameters.

6. SPECT checks

SPECT images are a series of images taken from different directions around a patient and reconstructed into a 3D dataset. Making images in this way places extra demands on the mechanical properties of the camera and the collimators. In addition, the reconstruction algorithm and correction algorithms determine the outcome. Thus the software is also tested.
The results of a SPECT study are largely determined by the properties of the collimator. Therefore system tests are required for every collimator which is used for SPECT. In general, collimators with the best planar spatial resolution deliver optimal SPECT result, even if this is at the expense of sensitivity.
After start-up or immediately prior to a SPECT acquisition, some gamma cameras run automatic system calibrations. If these system parameters have an effect on or are needed in the reconstruction process, then one must process the studies immediately after the acquisition.
To the extent applicable, tests must be performed by the acquisition method used clinically (dual-head acquisition 2x90°, 2x180° or 2x360°, triple-head acquisition 3x120° or 3x360°).

7. Total body/ whole body checks

The gamma camera has a limited field of view. Nowadays it is often a rectangular field of view of about 40 by 55 cm. To be able to record the distribution of activity in an entire patient in a single image, the detector can be moved in one or more tracks along the patient's axis. During this movement, an electronic picture is built up. Older cameras may have a narrower field of view requiring image construction from multiple tracks.
Most often a parallel collimator which allows for constant spatial resolution and sensitivity for the entire scan area is used. However, there are also gamma cameras with a collimator divergent perpendicular to the direction of movement. This enlarges the field of view so a single track is usually sufficient to depict the entire width of the patient. Spatial resolution and sensitivity in a divergent collimator depend on the position within the field of view. Assessment of such images requires the necessary caution and a quality protocol adapted to the specific camera.
The mechanical load of the system can affect the parameters to be measured. In particular, one must be mindful of the load of a moving table. Also, depending on the mechanical construction, the height of the detector can have an effect.
In dual-head cameras, the tests described here, must be performed for both detectors.
With regards to the use of whole body scanning, no specific tests are included in the international protocols. However, the IAEA tests for rectilinear scanners can serve as examples for testing the motion of the whole body table.
In the following sections, the tests are described for each parameter separately. In practice,

however, it is possible to determine a number of parameters in one single measurement. Where this is applicable, a reference to the other tests will be made.

8. Archiving and log book

An archive of test results and log books specifying problems, faults and maintenance are essential. These can be kept either on paper or in electronic form (with sufficient backups).

9. Miscellaneous

These recommendations describe the specific demands made on nuclear medicine equipment.

Apart from these, a number of other issues must be addressed.

a. Safety

- Mechanical safety (such as the presence and operation of collision detection)
- Electrical safety.

b. Interfering influences

from the environment, such as susceptibility to electromagnetic fields (especially if there is an MRI scanner in the vicinity) and interference by the presence of radioactive materials (especially of 511 keV, including the presence of patients).

c. The presentation of the images on screen or on film/paper

How the images are presented is important to the overall quality of the system. Several of the tests described below implicitly verify that the recorded images are correctly displayed (such as pixel size). One must be aware that images on the monitor do not display the actual pixel value, but use interpolation which causes the result to appear better than it actually is. Also, software tools might be "shifted" relative to the image. Furthermore, the quality of the monitor must of course be adequate to assess the images. There are no hard and fast general criteria for this. Such criteria would not be particularly meaningful because the capabilities of the software (level, window, gamma adjustment) help determine what requirements should be set for the monitor. Please also look at the viewing conditions (e.g. sunlight).

d. Software functioning

For equipment provided with a CE or FDA mark of approval, it may be assumed that the software is error-free. However, the user must remain alert to minor software errors. In addition, a gamma camera uses algorithms that are not always perfect. This is especially noticeable in quantitative measurements, and it can cause the results of different types of cameras to vary. It may be necessary to check the quantification after software upgrades have been installed. Verification of software is otherwise beyond the scope of these recommendations (see, for example, Busemann-Sokole 1990).

e. Power cuts

Processing computers should be protected with an uninterruptable power supply to prevent data loss. Unexpected power failure can lead to dysfunction. After an unexpected power failure, a short uniformity recording should be done with a flood source to verify that all photomultiplier tubes are still working. This must be done before patients are injected with radiopharmaceuticals or before long investigations are started. If there is insufficient time for such an acquisition, then we recommend doing a short recording with a (^{57}Co) source to verify that the camera is actually recording again.

f. New developments

- Quality control of SPECT-CT equipment does not essentially differ from the standard SPECT equipment. However, the geometric conformity of SPECT and CT parts must be checked, as described in chapter SPECT/CT.
- For discrete pixel cameras it is advisable to include, in the maintenance contract terms, details about the number of dead pixels that are allowed before the detector must be replaced.
- Certain tests are not applicable to the newly designed cameras e.g. SPECT cameras with fixed pinholes do not require ROI checks. However, sensitive tests like homogeneity and spatial resolution remain relevant. Because there are still very few cameras on the market with these new designs, our current advice is to follow the maintenance tests suggested by the manufacturer. More information on this topic can be found in: Cardiac Dedicated Ultrafast SPECT Cameras: New Designs and Clinical Implications: Ernest V. Garcia.

10. Key words and abbreviations

CFOV	=	central field of view
cps	=	counts per second
cts	=	counts
FWHM	=	Full Width at Half Maximum
FWTM	=	Full Width at Tenth Maximum
HE	=	High Energy
IAEA	=	International Atomic Energy Agency
IEC	=	International Electrical Commission
intrinsically	=	measured without collimator
kcps	=	10^3 counts per second
kcts	=	10^3 counts
LE	=	Low Energy
LSF	=	Line Spread Function
lead ring mask	=	ring covering the edge of the crystal
Mcts	=	10^6 counts
ME	=	Medium Energy
NEMA	=	National Electrical Manufacturers Association
PLES-phantom	=	Parallel Lines Equal Spacing phantom
PMT	=	Photo Multiplier Tube
PSF	=	Point Spread Function
$R_{20\%}$	=	Counting speed with 20% loss.
SPECT	=	Single Photon Emission Computed Tomography
"system"	=	measured with collimator
U_{int}	=	integral uniformity
U_{dif}	=	differential uniformity
UFOV	=	Useful Field of View

11. Literature

Reports and commentaries

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Table 1: Summary of the primary checks (see Section 2).
The three key elements for checking the gamma camera are: uniformity, sensitivity and COR (Centre of Rotation). These elements should be checked frequently. The specific frequency is dependent on the circumstances (e.g. half the frequency if no discrepancy has been found on four occasions, see the General Recommendations on Equipment Checks, Section 3: Frequency). The remaining tests need only be conducted following (re) acceptance (installation, relocation or very extensive repairs or modifications), after major maintenance (or major repairs) or if there are problems.
In the column "criterion", the rationale for conducting the test is indicated:
S: Specification available from the manufacturer
B: determining Baseline value for uniformity test
C: Clinical action threshold value
U: informative for the User.
For some tests, it depends on the work carried out during the maintenance as to whether

the test must be repeated; this is indicated by conditional **(condit.).**
* The minimum frequency for performing the COR verification must first and foremost be well grounded in the routine work, such as every week before starting work. In so doing, the different configurations (180/90/different collimators) can be checked alternately.

Test	Collimator	Explanation	Criterion See note table header
Planar per detector			
Intrinsic uniformity Tc	none	Alternate with system	C, S
System uniformity Co	alternate	Alternate with intrinsic	C, S
Intrinsic uniformity	none	other radionuclides	C, S
Energy-resolution	none		S
Background radiation	all		B, U
Shielding	HE,LE		S, U, C
Sensitivity (Constancy)	none/LE	together with uniformity	B, C
Sensitivity NEMA	all		S
Pixel size (quantitative)	LE (HR)		(S),C
Multi-window coregistration	LE (HR)		S, C
Count rate	none		S, U
Spatial resolution System (Constancy)	LE	Spatial resolution combine if necessary with COR	B
Spatial Resolution System (Quantitative)	all		S
SPECT			
COR ^{99m}Tc 180 and/or 90	LE	alternate configurations*	S
COR remaining isotopes	All		S
Spatial resolution	LE(HR)		S, B
Homogeneity/ contrast	LE(HR)		U
Whole body			
Scan speed	N/A		S
Homogeneity	LE(HR)		S
Spatial resolution	LE(HR)		S, U

	Frequency of performance			
	On (re)acceptance, all tests must be performed			
	adaptive frequency?		after major maintenance	Responsible minimum
		Start frequency		
	yes	Daily	yes	Alternating weeks (after the weekend)
	yes	Daily	no	
	yes	before every investigation with the radionuclide	yes	Depending on camera use
	no	No	condit.	(re)acceptance (major maintenance)
	no	N/A	no	major maintenance
	no	N/A	no	Acceptance
	see uniformity		yes	major maintenance
	no	N/A	no	(re)acceptance
	no	N/A	condit.	(re)acceptance
	no	N/A	no	(re)acceptance
	no	N/A	no	(re)acceptance
	no	N/A	yes	major maintenance
	no	N/A	no	(re)acceptance
	yes	several times per day	yes	e.g. weekly (after the weekend)*
	yes	depending on use	yes	depending on use
	no	N/A	no	(re)acceptance
	no	N/A	no	(re)acceptance
	no	N/A	condit.	(re)acceptance
	no	N/A	no	(re)acceptance
	no	N/A	no	(re)acceptance

Table 2: Cross-reference NEMA NU 1-2001 and Recommendations for Nuclear Medicine

NEMA NU 1-2001		**Recommendations for Nuclear Medicine:**
2.1	Intrinsic spatial resolution	Spatial resolution and linearity
2.2	Intrinsic energy resolution	Energy resolution
2.3	Intrinsic flood field uniformity	Uniformity
2.4	Systemspatial resolution without scatter	Spatial resolution and linearity
2.5	System alignment	Centre of Rotation COR
2.6	SPECT reconstructed spatial resolution without scatter	SPECT spatial resolution
2.7	Whole body system spatial resolution without scatter	Whole body spatial resolution
3.1	Intrinsic spatial linearity	Supplementary to spatial resolution and linearity
3.2	Multiple window spatial registration	Multi-window coregistration
3.3	Intrinsic count rate performance in air	Count rate performance
3.4	System count rate performance with scatter	Supplementary to Count rate performance
3.5	Intrinsic spatial resolution at 75000 cps	Supplementary to spatial resolution and linearity
3.6	Intrinsic flood field uniformity at 75,000 cps	Supplementary to Uniformity
3.7	System spatial resolution with scatter	Supplementary to spatial resolution and linearity
3.8	System planar sensitivity and penetration	Sensitivity
3.9	Detector shielding	Shielding
3.10	Detector-sensitivity variation	Planar sensitivity in action thresholds
3.11	SPECT reconstructed spatial resolution with scatter	Supplementary to SPECT spatial resolution
3.12	System Volume sensitivity	Supplementary to Sensitivity.
3.13	Reconstructed image uniformity	Transversal uniformity