Planar gamma camera

Uniformity

1. Introduction and rationale

The uniformity of the gamma camera is a measure of local variation in sensitivity of the detector surface. The uniformity directly determines the quality of the recorded images. If the uniformity is not correct, small abnormalities can be missed or artefacts may be regarded as abnormalities. The uniformity is very sensitive to almost all abnormalities which can occur in the camera, and is therefore the most important check of the gamma camera.

The basic check is the intrinsic uniformity check (without collimator) with ^{99m}Tc or ^{57}Co. Because the uniformity correction may depend on the energy and the number of energy peaks, additional intrinsic checks must be done with other radionuclides if these are used clinically. Checking the system uniformity using a ^{57}Co-flood source provides information about collimator damage.

On acceptance, it is recommended that the complete NEMA procedure be followed, if necessary in cooperation with the manufacturer. For frequent checks, a simplified procedure is described below.

2. Frequency

The uniformity is generally stable, but may, in some circumstances, deteriorate quickly. This is particularly the case in new or very old systems, with increased flood adjustments for radionuclides with multiple energy peaks. So, other than on acceptance and after maintenance, the frequency of uniformity checks can be adapted.

After delivery, a daily check is recommended. Based upon practical experience and given the high level of importance of good uniformity for image quality, the minimum frequency is weekly. In so doing, the checks for intrinsic uniformity and system uniformity may be alternated. Collimators may also be alternated with each uniformity check.

3. Method

Measurements of uniformity are performed by irradiating the scintillation crystal evenly with a point source without collimator (intrinsic) or with a flood source with a parallel collimator (system).

In all modern cameras, there is a built in protocol for the uniformity check, and the manufacturer's instructions may be followed. No further checks are required to ascertain whether the calculation of the uniformity has been carried out as described by NEMA (see NEMA NU 1-2001).

4. Required equipment, phantoms and sources

For intrinsic uniformity: point source ^{99m}Tc or ^{57}Co, approximately 10 MBq (if necessary also ^{67}Ga, ^{111}In, ^{123}I, ^{131}I, ^{201}Tl).
For system uniformity: planar source ^{57}Co, 100-400 MBq (near the lower limit, the counting time will become uncomfortably long).
Maximum permissible count rate is approximately 20 kcps (depending on the manufacturer's specification).

5. Procedure

Mount the desired collimator (system uniformity), or remove the collimator and, if indicated by the manufacturer, mount the lead ring mask (intrinsic uniformity).
Use the manufacturer's protocol (but verify that this complies with the NEMA: matrix 64x64, energy window 15% for ^{99m}Tc) and collect at least 5 Mcts. If time permits, collection of 10 or even 30 Mcts is recommended: this reduces the chance of coincidentally divergent results.

6. Analysis and interpretation

Use the analysis software supplied by the manufacturer (provided that it complies with the NEMA prescriptions: 9 points smooth). Calculate the uniformity in an area of at least the size of the CFOV, though preferably slightly larger, so the area which is most used clinically is covered.
Create an image with increased contrast, so areas with slightly reduced or increased numbers of counts become more visible. For this purpose, choose a fixed setting for the colour scale, e.g. between 80% and 120% of the average. Inspect the image for irregularities, i.e. cold or warm areas (sharply or vaguely demarcated), regular patterns of stripes or spots. Also check for edge effects.
The uniformity is determined by the quality of the detector and of the collimator. The uniformity of the entire system (including the collimator) is called system uniformity; that of the detector alone is called intrinsic uniformity. If the collimator shows no errors, i.e. if the holes and the septa are perfectly regular and very small, or alternatively very thin, the system uniformity approaches the intrinsic uniformity. Significant differences between the two parameters indicate collimator errors (see Additional checks, point e).

7. Action thresholds and actions

If, upon visual inspection, patterns are visible or a photomultiplier tube is clearly divergent, the manufacturer must be alerted immediately. Edge effects should be reported to the manufacturer, though they generally do not impede clinical use.
Upon (re)acceptance and after major maintenance, the camera must meet factory specifications. During the frequent checks of adaptive frequency, the uniformity (integral uniformity) in the (broad) CFOV may not exceed 4%. Experience shows that above this value the image quality begins to deteriorate noticeably in clinical use.
If this value is exceeded, a new correction table must be recorded. If these values are persistently exceeded, repair must take place as soon as possible. Modern equipment remains trouble-free (for ^{99m}Tc) well within 4%. In case the uniformity is systematically better (=lower) than 4%, stricter limits should be adapted (but not

so strict as to necessitate a new correction table). Here again, the balance between costs and benefits should be used to determine the optimum.

8. Pitfalls and comments

a. Immediately after recording a new uniformity table, the uniformity should be excellent (approximately 2%). However, if the camera is not entirely stable, this can quickly deteriorate. Therefore, a further check is required a day later.

b. When using a planar source, the uniformity of the source must be excellent: the coefficient of variation of the activity per cm^2 must have a minimum of <1%.

c. The distance of the source when determining the intrinsic uniformity must be at least 200 cm (3x the camera diameter: at that distance the difference in distance between the centre and the edge contributes at most 1% to variation in uniformity). Correction for the geometry can be made, and this will inevitably be necessary if it is not possible to mount the source sufficiently far away as, for example, when using a triple-head camera. This correction must be done analytically. If a fit procedure is used for this, non-uniformities with the same drift as caused by the geometry may remain undetected.

d. The use of flood sources or moving line sources filled with water and a radionuclide is not recommended: bulge, adhesion of the radionuclide to the wall, inadequate mixing and radiation exposure of the employees are disadvantages which do not outweigh the theoretical advantage. The collimator or the front of the crystal may become radioactively contaminated. This can be checked using a baseline measurement or sweep test. ^{57}Co sources may have become contaminated with ^{99m}Tc. This can also be checked using a sweep test.

e. Inhomogeneity in the visual assessment of uniformity can also be caused by errors in the display or in the print-out.

f. When the count rate is too high (>20 kcps) artefacts may arise.

g. When using a planar ^{57}Co source with excessive impurities in the high-energy isotopes ^{56}Co, ^{58}Co and ^{60}Co (especially with a new source) artefacts may arise. In such a case, a source-collimator distance of at least 50 cm should be used.

h. In SPECT images, large inhomogeneities in the area outside the CFOV along the central axis may nonetheless lead to clinically disturbing ring artefacts.

i. It may happen that a manufacturer requires the uniformity correction to be re-recorded frequently. In such a case, it is recommended that at least some intermediate checks be made to verify that the camera is stable. Furthermore, the user will have to weigh up whether the time and radiation exposure expended on this is justified and if necessary discuss this with the manufacturer to adjust the procedures.

9. Additional checks

a. Uncorrected uniformity. With most cameras, optimum uniformity is achieved by software correction using a uniformity correction table. Every time a new uniformity table for ^{99m}Tc is recorded, the uniformity should also be checked without the correction table. An increase in uncorrected uniformity leads to ever-increasing uniformity corrections. If large corrections are required, the corrected uniformity is likely to deteriorate rapidly over time.

b. High count rate. If the camera is used clinically for higher count rates, the procedure should also be done with a high count rate, e.g. at 75.000 cps. Sometimes factory specifications are available for this value. If factory specifications are not available, a visual assessment will need to be made as to whether the camera can be used for high count rates.

c. Off-peak. By default, the uniformity is checked with the energy window centred at the photopeak (on-peak). Shots off-peak, i.e. with the energy window set approximately 10% too low and thereafter 10% too high are particularly susceptible to poor adjustment or faulty linearity correction. All multipliers become visible. In addition, this method allows local broadening of the photopeak due to crystal defects (particularly moisture in the crystal) to become visible as spots in the image. Moisture in the crystal is essentially an issue of previous generations of cameras, but it is useful to test for this, especially towards the end of the camera's lifetime during major maintenance.

d. Dependence on the position of the detector. If the uniformity depends on the position of the detector, artefacts may arise in the SPECT studies. If this is suspected, a planar ^{57}Co source is used for relatively simple determination of the system uniformity at different angles. However, this is a time-consuming matter. The uniformity must be within the action thresholds at all angles.

e. Collimator angle errors. Angle errors in collimators (tilt of the septa) can lead to non-uniformity and errors of linearity. This is particularly the case in SPECT, where ring artefacts are then caused, especially if the errors occur near the collimator axis which lies parallel to the axis of rotation. A simple quality control of angle errors in parallel hole collimators consists of a series of point source images, where the point source (^{99m}Tc, approximately 100 MBq) is held at a great distance (several metres) in front of the mounted collimator. Multiple images (with at least 5 Mcts) at positions evenly distributed over the field of view are required. The resulting point spread functions are visually assessed for rotational symmetry. An isocontour look-up table is a useful aid in this. Abnormalities in rotational symmetry or in the profiles (no equilateral triangles with a regular outline) indicate angle errors. In order to quantify the error, two point source images should be made of the appropriate position(s) at various radii.

10. Literature, see also general literature

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Energy resolution

1. Introduction and rationale

The energy resolution is a measure of the ability of the detector to distinguish photons of different energies from each other. This is important in order to distinguish the radiation which is not dispersed within the patient or the detector, and which therefore should be used for the imaging, from scattered radiation which is not intended to contribute to the image. The energy resolution is expressed as the FWHM value of the relevant photopeak divided by the energy of this photopeak.

2. Frequency

The energy resolution must be measured after (re)acceptance and major maintenance because it can change when the PMTs are adjusted.

3. Method

Spectrum measurements are performed under the same conditions as the ^{99}mTc intrinsic uniformity check (see Uniformity protocol). Exact execution according to NEMA is generally not possible without the cooperation of the manufacturer. A simplified procedure is described below.

4. Required equipment, phantoms and sources

Source: bottle or syringe of ^{99m}Tc, approx. 10 MBq, point source ^{57}Co (at least 1 MBq).

5. Procedure

- Remove the collimator. Position the ^{99m}Tc source in a centrally position in front of the detector at a distance of at least 200 cm (see Uniformity: Pitfalls and comments). Count rate preferably less than 10 kcps. (When measuring according to NEMA, the lead ring must be mounted, and at least 2 mm of copper must be placed between the source and the detector).
- Record the spectrum. Measure half width of the peak. This can be done quickly and accurately by means of a (digital) photo, but if careful account is being taken of parallax, it can also be done directly on the screen. It is laborious but very precise to measure a successive series of narrow windows.
- Now also place the ^{57}Co source in front of the detector. Record the distance between the two photopeaks.
- Repeat the measurement five times.

6. Analysis and interpretation

- Calculate the FWHM. The distance between the peaks of ^{99m}Tc and ^{57}Co corresponds to 18,4 keV.
- Calculate the energy resolution, defined by the ratio of the FWHM value and the peak energy of ^{99m}Tc (141 keV).
- The gamma spectrum, as recorded by the detector, is composed of the gamma spectra registered by the individual photomultipliers. The FWHM of the detector is thus determined by the FWHM of the various photomultipliers and by the amplification factors of the photomultipliers. A broadened photopeak usually

indicates that one or more of the photomultipliers is disrupted.
- Calculate the standard deviation of five measurements.

7. Action thresholds and actions

If there is a significant broadening of the photopeak (reliably measured using the standard deviation) the manufacturer should be contacted. In agreement with the manufacturer a full NEMA audit can be performed.

8. Pitfalls and comments

a. The baseline of the pulse height analyser may have shifted (unequal to zero). This must be checked with source(s) with multiple gamma energies, e.g. with ^{67}Ga.

b. If the count rate is too high (>20 kcps) 'pulse pile-up' can occur, resulting in distortion of the spectrum. To exclude pile-up effects, it is advisable to use a count rate of less than 10 kcps for this test.

9. Additional checks

If specifications of the manufacturer are available, the energy resolution of other radionuclides should be checked.

Background radiation

1. Introduction and rationale

Gamma camera images may undergo interference by the so-called null effect which originates from background radiation and/or detector noise. Background radiation is usually slightly dependent on the orientation and position of the detector. Elevated background radiation may be due to contamination with radioactive material or increased detector noise.

2. Frequency

In principle, background radiation restricts the measurement of low activities. However, NEMA has set no requirements in this regard, nor is it specified by manufacturers. In general, background radiation is so low, that it is negligible compared to the diffuse background radiation within the patient. Knowing the baseline background radiation is useful, for detecting and removing radioactive contamination. Background radiation should therefore be determined on (re)acceptance and the measurement should be repeated if contamination is suspected.

3. Method

Measure the background radiation for all detectors of the gamma camera without collimator and with all available collimators as well as at different energy settings of common radionuclides (e.g. ^{99m}Tc and ^{131}I).

4. Required equipment, phantoms and sources

None

5. Procedure

- Remove all radioactivity from the chamber and surrounding areas.
- Mount the desired collimator.
- Choose a standard orientation and position for the detector.
- Choose a 15% energy window for ^{99m}Tc (follow the manufacturer's recommendations for other radionuclides).
- Measure for 10 min and record the total number of counts.

6. Analysis and interpretation

Check the image for hotspots. If there is no possibility of contamination (upon acceptance) then hotspots are indicative of a defect. If contamination is suspected, the site of contamination can be determined in this manner.

7. Action thresholds and actions

Remove any contamination.
If there are hotspots which are not caused by contamination, as with an unexplained increase in the total number of counts by more than 20% (empirical value), the manufacturer must be alerted.

8. Pitfalls and comments

Any source of ionising radiation (e.g. X-ray equipment) in adjacent spaces, including above and below can disrupt the measurement.
Contamination can occur on the floor or on the table, both front and back of the collimator or on the crystal itself.
Background radiation depends on the collimator used and the direction of the detector, these should be standardised.

Shielding

1. Introduction and rationale

Only gamma radiation from the field of view of the camera must be recorded. Hot sources outside the field of view (e.g. PET patients in another room or the bladder of the patient him/herself) should be adequately shielded by lead in the camera housing. With high energies (e.g. 364 keV of ^{131}I), the lead shielding may be inadequate and the manufacturer's specifications (if available) must be checked.

2. Frequency

Perform this check on acceptance.

3. Method

Measure the background radiation with and without source at various positions around the detector. According to NEMA NU 1-2001 two situations are simulated:
high uptake in the patient, and interference from other sources near the camera.
For (ii), NEMA specifies a distance of 2 metres around the camera, but this necessitates the use of a very strong source of ^{131}I. Therefore, this protocol recommends performing

measurement at 50 cm, where (if abnormalities are found) the check is repeated, if necessary with a stronger source.

4. Required equipment, phantoms and sources

Source: bottles or syringes of ^{99m}Tc (approx. 300 MBq) and ^{131}I (approx. 10 MBq; if necessary, another high energy radionuclide such as ^{67}Ga, ^{111}In). According to NEMA, the count rate must be between 1000 cps and 30.000 cps at 20 or 50 cm in front of the camera, respectively.

5. Procedure

Record the number of counts for 5 min or count about 20.000 counts, and create an image.

Simulation of locations with high uptake in patients

- Use the energy window of ^{99m}Tc with a width of 15%. Take care that when measuring in front of the camera, no pixel overflow occurs.
- Position the detector with LE-collimator 20 cm above the table pointing downwards.
- Take a measurement without source.
- Place the source with ^{99m}Tc centrally under the detector at 10, 20 and 30 cm outside the edge of the FOV (NEMA).

Simulation of interfering sources

- Use the source with ^{131}I and the HE-collimator.
- Take the measurement as for the energy window of ^{131}I with width as recommended by the manufacturer.
- Measure with the source at 50 cm on all four sides of the detector and at 50 cm in front of and behind the detector. The freedom of movement of the detector will determine whether it is easier to move the source or to rotate the detector.
- Measure background radiation at all the (usable) detector positions.

6. Analysis and interpretation

Correct the obtained measurements for background radiation. Determine the relationship between the measurements by comparing the shielding in relation to the measurement right *under* the detector and in relation to the measurement *in front* of the detector. Visually inspect the images for unexpected problems. If unexpectedly high values and clear irradiation are found in test, there may be an excessive gap between the detector and the collimator. It is possible that by chance the source is positioned exactly in front of this gap which is almost always present but when a collimator is positioned properly, minimal movement of the radiation source is sufficient to eliminate this radiation.

7. Action thresholds and actions

If possible, compare to factory specifications (apply the inverse square law if a distance of 50 cm is used instead of 200 cm). Ensure that the user is aware of any limitations in the shielding. Discuss any gaps between the collimator and the detector with the manufacturer.

8. Pitfalls and comments

a. Pinhole collimators are usually designed for use with ^{99m}Tc. If using ^{131}I with a pinhole collimator, background radiation can be increased as transmission from the cone of the collimator is too large for this energy.

b. Some radionuclides, e.g. ^{123}I, can transmit a relatively high percentage of high-energy photons, in particular due to radionuclide contaminants. If there is a lot of radioactivity just outside the field of view, this may contribute to the counts within the field of view.

c. When ^{67}Ga is used, only the highest energy peak will contribute substantially and the user must take into account the (low) efficiency in this peak.

9. Additional checks

Aim for gap-free mounting of collimators against the detector. Visual inspection for a gap will generally suffice. If not, all collimators should be checked for gaps using a similar quality control as described above.

Sensitivity

1. Introduction and rationale

Sensitivity is a measure of the total count yield of the gamma camera. To obtain statistically reliable pictures at low sensitivity, recording will need to go on for a longer period of time. The sensitivity is expressed as the number of photons per second detected and accepted through the energy window from a source with a certain activity (in MBq), i.e. in cps/MBq. This value depends on the radionuclide used, the collimator, the thickness of the crystal and width and position of the energy window. The sensitivity can deteriorate over time, e.g. if the photopeak broadens (poor adjustment of the photomultipliers, discoloration of the crystal).

2. Frequency

The sensitivity of a camera can deteriorate slowly, resulting in images that slowly develop a worse signal to noise ratio. Because this process takes place gradually, the user may not notice it. It is therefore important to check the sensitivity regularly. This need not be done with very high accuracy as long as clear changes are observed. Adapt the frequency as required. Sensitivity must be checked after any major maintenance or major repairs because changes cannot be excluded after such events have taken place. This measurement can be easily combined with the uniformity measurement (see points 3 and 8) and can then be performed very frequently with almost no extra work.

3. Method

According to NEMA, the system sensitivity is measured by placing a source of fixed geometry and known intensity on the collimator and counting for a specified amount of time. Since scattered radiation is also measured in the energy window, the same geometrical conditions must always be used for comparative measurements. The measurement is performed for all collimators and detectors.

The target precision of the measurement is 1%. This means high demands are made on all parameters to be determined during the process: amount of activity, counting time and number of counts.

As a measurement of constancy, the sensitivity can also be derived from the uniformity measurements or the COR measurements if in so doing the strength of the source is determined with sufficient accuracy and the source is always mounted in the same geometry.

4. Required equipment, phantoms and sources

According to NEMA:

The source consists of a round plastic (acrylic) container with an inner diameter of 150 ±5 mm and a base thickness of 5 mm (and a lid of 5 mm), filled with approx 10 mm of water with ^{99m}Tc (approx 10 MBq, count rate <30 kcps). Ensure that the activity is mixed well with water and measure the empty syringe. Other radionuclides may also be used. In practice, for example, a petri dish or beaker with an inner diameter of 100 to 150 mm may be used.

Simultaneously with uniformity:

Ensure that the strength of the source being used is determined with sufficient accuracy (within approx. 5%).

5. Procedure

According to NEMA:

- Mount the collimator to be tested and point the detector upwards. Strictly there should be 5 mm of acrylic between the water containing the activity and the collimator. In practice, however, it is sometimes much easier to point the detector downwards. If, using this method, the detector almost meets the specifications, the measurement can still be repeated according to NEMA.
- Fill the container with a well-calibrated quantity of ^{99m}Tc. Place the container at a distance of 100 mm from the collimator but avoid absorbing and scattering material.
- Use a 15% energy window for ^{99m}Tc. Follow the manufacturer's recommendations for other radionuclides. (Note that some manufacturers use a different energy window than described by NEMA.)
- Collect at least 1000 kcts.
- Accurately determine the counting time, check the clock on the camera against a stopwatch.

Simultaneously with uniformity:

- On acceptance, ascertain the conversion factor between the measurements according to NEMA and the value determined during the uniformity check. Do this separately for the intrinsic check (using a point source of ^{99m}Tc) and for the system check with the collimator (using the ^{57}Co flood source).

6. Analysis and interpretation

According to NEMA:

Calculate the amount of activity in the container adjusted for the residue in the syringe. Correct the counts obtained against the background radiation and correct for decay with respect to the moment when the calibration takes place. Take the centre of the measurement time interval as the time of measurement. Calculate the sensitivity, expressed in cps/MBq.

Simultaneously with uniformity:

Correct for decay. Using the conversion factor, the measured source intensity, the measurement time and the number of counts, calculate the sensitivity, expressed in cps/MBq.

7. Action thresholds and actions

According to NEMA:

Compare to specifications during acceptance. If the camera is already in clinical use, an experience-based guideline for repair is a sensitivity >20% (to obtain the original image quality, the patient would be given 20% more activity, or the recording would take 20% longer). Too high a value (>20%) may be an indication of other problems (e.g. too low a maximum count rate) and should be discussed with the manufacturer.

Simultaneously with uniformity:

Simultaneously checking the uniformity allows for a quick determination without any high degree of accuracy and is intended as an early warning of potential problems. If the value is more than 10% lower, the NEMA check must be repeated.

8. Pitfalls and comments

a. This absolute measurement is vulnerable to errors in all parameters specified, such as an incorrectly calibrated dose calibrator, errors in the determination of counting times or too long a counting time. Precise correction for decay during the measurement (see NEMA NU 1-2001) is possible. However, if the centre of the measuring period is used as the measurement time, the error in the final result is less than 0,3%.
b. Each radionuclide must be measured with its associated collimator (septal penetration).
c. To avoid contamination with radioactive material, it may be useful to seal the top of the phantom with a lid or with self-adhesive foil.
d. When simultaneously determining the uniformity, the source intensity must be carefully measured in order to avoid unnecessary follow-up.

9. Additional checks

a. High count rate.
   If the camera is used at high count rates for quantitative measurements, the sensitivity must also be checked at a relevant high count rate (see Count rate protocol).
b. Septal penetration.
   If the septal penetration is specified by NEMA, it should be checked upon acceptance by determining the sensitivity according to the complete NEMA procedure (this involves determining the sensitivity at various distances from the collimator).
c. Angle and detector dependence.
   If the camera is used for SPECT measurements, the difference between the detectors may not exceed the manufacturer's specifications. NEMA indicates that, the angle dependence of the sensitivity in a SPECT recording is determined and the maximum difference specified. Angle- or detector-dependent variations may lead to reconstruction artefacts. As a rule of thumb, these should not be greater than 5%.
d. Volume Sensitivity (SPECT)
   According to NEMA, the volume sensitivity in SPECT cameras can also be determined. This value is a direct derivative of the planar sensitivity, but if the SPECT recording is used quantitatively, the determination can be useful as a baseline and calibration value.

Pixel size

1. Introduction and rationale

The pixel size is important if one is looking at dimensions in the image, as is done in multimodality matching, attenuation correction, when using the images to determine radiation fields in radiotherapy or when the size of an organ needs to be followed up in a single patient over time. Only parallel collimators are tested in this manner. With other collimators (pinhole, convergent or divergent), the image size is also dependent on the distance between the collimator and the patient.

The pixel size can depend on the energy of the photon. This dependence is monitored using the Multi-window co-registration protocol.

2. Frequency

The pixel size be checked upon (re)acceptance and after major maintenance (see also Pitfalls and comments).

3. Method

Using the gamma camera with a parallel collimator, an image is made of two point sources positioned not too far apart from each other (e.g. 300 mm). Next the distance in pixels between the two is determined and the pixel size is calculated (in both the X and the Y-directions).

4. Required equipment, phantoms and sources

The phantom may consist of a disk or plate with 2 or more point sources of ^{57}Co or ^{99m}Tc (approx 5 MBq) or, if necessary other radionuclides. Alternatively, a lead plate with two or more holes in combination with a planar source of ^{57}Co (or if necessary ^{99m}Tc), approx 300 MBq can be used.

The measurement must be made in both the X and Y directions. A phantom in which the sources or the holes have been placed in both directions is useful so only one recording needs to be made.

5. Procedure

Mount the collimator with the best possible spatial resolution. Place the phantom (point sources) directly on the collimator (but see 8. Pitfalls and comments) and make an image.

- Choose a 15% energy window for ^{99m}Tc and follow the manufacturer's recommendations for other radionuclides.
- The matrix should be as large as possible.
- Collect at least 1000 counts in the peak pixel of the Gaussian count-profiles (profile width 30 mm) in X- and Y-direction (line or point source).

- Often the image can be enlarged using zoom modes. If this option is used, then the image size must be checked both with and without zoom modes.

6. Analysis and interpretation

Calculate the pixel size using the camera software.

7. Action thresholds and actions

When performing multimodality matching, the SPECT images are combined with MRI and CT images. The image sizes of the two latter generally have a deviation of less than 1%. This corresponds to a deviation of 3 mm over 30 cm and is thus small compared to the resolution (PSF) of the gamma camera, which in practice is not better than 5 mm FWHM. If the deviation in the pixel size is greater than 1%, the pixel size should be recalibrated. Other clinical applications may give rise to the adjustment of this action threshold.

8. Pitfalls and comments

a. The precision with which the magnification factor and/or the pixel size are determined depends on the spatial resolution of the system, i.e. of the collimator used. It is therefore important to use the collimator with the best spatial resolution.
b. In a collimator with thick septa, interference patterns can occur if the source is directly in front of one of the lead dividers. In that case, the source may also be placed at some distance from the collimator.
c. In some cameras, the software to change the calibration of the pixel size is part of the normal user interface thus the calibration can be "accidentally" changed. This will usually give rise to a large deviation. A quick check is sufficient to detect this error (for example, by measuring the total width or length of an arbitrary planar recording), but if the chance of this error is high and the image sizes are of clinical importance, frequent monitoring is recommended.
d. Ensure the magnification factor/pixel size is indeed independently checked. The magnification factor found may not automatically be retained as the new conversion factor.

Multi-window co-registration

1. Introduction and rationale

Energy independence from pixel size is primarily important for the image quality of recordings of radionuclides with multiple photopeaks when these photopeaks are added together. If the co-registration is poor, the PSF increases, and the image becomes blurred. Furthermore, the co-registration determines the accuracy of the pixel size for radionuclides with an energy other than ^{99m}Tc (see Pixel size).

2. Frequency

This check is recommended at (re)acceptance.

3. Method

A number of ^{67}Ga point sources are spread out over the surface of the detector and an image is made in several energy windows. Subsequently, it is noted whether the registrations of all sources in the different windows coincide. According to NEMA, the protocol is carried out without collimator, but this requires a special collimator pot which is placed upon the bare crystal. Therefore, the test described below is with a collimator.

4. Required equipment, phantoms and sources

Nine ^{67}Ga sources are required for the full NEMA protocol. This protocol is carried out at 5 points; it is possible to carry out the test with only 1 point source, but this is more time-consuming. The source will then need to be moved repeatedly, preferably while the recording is briefly stopped. Source intensity 1-10 MBq.

5. Procedure

- The LEHR (Low Energy High Resolution) collimator is preferred (as this generally yields more accurate results).
- The sources are placed in the middle and on both sides along the X and Y axes at 80% of the detector's diameter. Place the point sources directly onto the collimator (see 8. Pitfalls and comments).
- Use the default energy window for ^{67}Ga. Measure all photopeaks simultaneously (93, 184 en 300 keV). If only two energy windows are available simultaneously, 184 keV may be dropped. If the maximum pixel size is exceeded, successive measurements are required.
- The pixel size must not exceed 2,5 mm.
- Ensure at least 1000 cts at the maximum pixel setting at all photopeaks (about 5 min at 10 MBq).
- Record an image.

6. Analysis and interpretation

Calculate the maximum shift of all pairs of point source images in the X and Y directions (in mm), measured at different energies (if required, consult NEMA for the mathematical formulation).

7. Action thresholds and actions

Upon acceptance, the specifications may not be exceeded.

If the specifications are not met measurements must be repeated, in accordance with the full NEMA protocol (that is: without collimator using collimated ^{67}Ga source). Preferably, this is done in agreement with the manufacturer. If the specifications are stipulated with very high precision, the methods described are not adequate. The complete NEMA method must be followed if more than one check of the clinical criteria (see below) is deemed necessary.

If the specifications are exceeded during use or if no specifications are available, the following clinical criteria may be used:

For planar images whereby multiple energy peaks are added together, the differences in position between the different photopeaks must be small relative to the PSF. Half the PSF is used as a rule of thumb.

In making SPECT images with multiple photopeaks, it is very important where the shifts occur. Specifically, if the shift is found in the centre, it will lead to artefacts (see COR).

If the images are used for MRI/CT matching, the criterion of the Pixel size protocol (3 mm) may be used.

8. Pitfalls and comments

a. Note the maximum count rate. If the count rate is too high, pulse pile-up can occur, thus through coincidences, information from the two lowest energy peaks can end up in the relatively higher energy peak. As a result, this becomes disproportionately strong and broadened.

b. In a collimator with thick septa, moiré interference patterns can occur if the source is directly in front of one of the lead dividers. In that case, the source may also be placed at some distance from the collimator.

Count rate

1. Introduction and rationale

The camera's behaviour at high count rates is determined by the extent to which successive pulses can be distinguished. The manufacturer usually specifies the maximum achievable count rate and the count rate at which there is a 20% loss, i.e. at which 20% of the incident photons are not registered ($R_{20\%}$). For clinical purposes, a high maximum count rate is only significant under exceptional circumstances, such as in the investigation of patients who have had a therapeutic dose of radionuclide and in first-pass cardiac studies for shunt evaluation.

2. Frequency

This check must be carried out upon (re)acceptance as a check of the manufacturer's specifications. Only if precise quantitative measurements are required at high count rates, must the sensitivity at the relevant count rates be checked more frequently (see 9. Additional checks).

3. Method

The method described in these protocols is a simplification of the full NEMA protocol. If questionable abnormalities are found, the full NEMA procedure must be followed in cooperation with the manufacturer.
The camera's count rate is determined as a function of count rate offered, without collimator.
The count rate offered can be varied in several ways:

- In the decay method, measurements are taken whilst a source decays at a fixed distance. This method yields the smallest chance of measurement error, but it takes a considerable amount of time to measure a sufficient range.
- Using a dilution series of sources. This method requires an accurate method of dilution, and careful placement of the sources at a fixed distance.
- By varying the distance from the source. This requires a precise determination of the distance and a one-time calibration for changes in geometry as the distance grows smaller (by departing from the inverse square law).

4. Required equipment, phantoms and sources

One or more point sources of ^{99m}Tc (or ^{57}Co), depending on the method chosen. The source intensity should range from a minimum that yields a count rate < 20.000 cps to a maximum count rate which no greater than 40% higher than the calculated rate. With the aid of the factory specifications, the count rate measured at low source intensity (see Uniformity), can be used to determine at what source intensity a loss of 20% is to be expected. Tripling this intensity will often give you approximately the maximum source intensity.

- *Decay method:*
  A source with the maximum intensity.
- *Dilution method:*
  An exponential/logarithmic series of sources starting at the minimum intensity (1, 2, 4, 8 etc.) such that by simultaneously combining several sources, the intermediate values can be generated. A combination of the dilution method and the decay method is also possible.
- *Distance variation:*
  A source of about 10 MBq. The desired source intensity depends on the distance to be varied.

5. Procedure

1. Remove the collimator and mount the source centrally in front of the detector. The same position as for the uniformity check may be used. However, the distance may be smaller for this test, meaning less activity is required.
2. Use the peak position associated with a low count rate and do not adjust this at high count rates.
3. Energy window for ^{99m}Tc with a width of 15%.
4. Collect at least 10.000 counts per measuring point (measuring error <1%).

- *Decay method:*
  Measure the count rate of the maximum intensity ^{99m}Tc source until the source has decayed to the minimum intensity. The measurements should be taken every three hours, although measurements at the beginning and end of the working day will suffice. Always note the time. Some cameras can take these measurements automatically, e.g. on weekends.
- *Dilution series:*
  Measure the count rate for all source intensities from minimum to maximum intensity with stepwise increases of approximately 25% intensity.
- *Distance variation:*
  Start with the source at a distance that yields a count rate of 20.000. In steps of around 10%, bring the source closer to the point where the count rate is 40% lower than would be expected according to the change in distance.

6. Analysis and interpretation

Determine the graphical the relationship between the offered count rate and the actual count rate. Then determine the point at which the count rate measured is 20% lower than the count rate curve extrapolated linearly from the origin.

Decay method:
Calculate the actual source intensity by using the half-life of ^{99m}Tc.
Dilution series:
Take into account any decay of the sources during the measurements.
Distance variation:
For accurate results, correct for the change in geometry.

7. Action thresholds and actions

If $R_{20\%}$ is more than 10% lower than the factory specification, the full NEMA test must be repeated in agreement with the manufacturer. Based on experience, it is to be expected that these simplified methods will deviate no more than 5% from the full NEMA check. If the sensitivity at a low count rate complies with the specifications, a deviation in $R_{20\%}$ is not usually clinically discernible (see Additional checks). Inform the user of the way in which the sensitivity decreases at high activity if the camera is used at very high count rates such as for the investigation of patients in therapy.

8. Pitfalls and comments

a. Dilution series: careless dilution, non-reproducible placement of the sources.
b. Distance variation: errors in determining the distance or in the geometric correction.
c. Unintentional collimation effects of the source holder.
d. When the PMTs are exposed to high count rates for extended periods of time, the efficiency temporarily decreases and the sensitivity drops. In addition, the noise can increase. Recovery from this may take days. Keep this in mind whenever other tests need to be performed.
e. Take care that there are no objects nearby which could emit scattered radiation onto the detector. In multi-head cameras, it may be impossible to move the other detector(s) sufficiently far.

9. Additional checks

a. Other radionuclides
If the camera is used for patients who have received a therapeutic dose of a radionuclide, this check should be done more frequently. Use an adaptive frequency for the relevant radionuclide.
b. Quantitative studies at high count rate
Whenever quantitative studies are done at high count rates, the relevant range of the count rate should be checked more frequently. The sensitivity protocol can be used for this purpose by adjusting the source intensity.
c. SPECT at high count rate
When SPECT studies are done at high count rates, artefacts may arise if there is a difference in count rate performance between the detectors. See the Sensitivity protocol.
d. Count rate in the presence of scattered radiation
If specified, the count rate including scattered radiation can also be checked in similar fashion (see NEMA).

10. Literature, also see general literature

- Adams R. Dead time measurement in scintillation cameras under scatter conditions simulating quantitative nuclear cardiography. J Nucl Med 1978;19:538-44.

Spatial resolution and linearity

1. Introduction and rationale

Spatial resolution or three-dimensional resolution capacity is a measure of the sharpness of the image. It represents the ability of the gamma camera to observe individual point or line sources as distinct from each other. A good spatial resolution is important for good image quality, i.e. for a detailed image of the radioactivity distribution within the patient.
The clinically relevant system resolution is primarily determined by the intrinsic spatial resolution of the detector (without collimator) and the spatial resolution of the relevant collimator. Amongst other factors, the system resolution depends on the distance from the collimator and on the photoenergy.
The linearity determines whether straight objects are also depicted as being straight.
This is usually less clinically important, but indirectly determines the quality of the images (uniformity). The system linearity is determined by the intrinsic linearity and the quality of the collimator.

2. Frequency

The specifications should be checked quantitatively upon acceptance.
Changes in the spatial resolution and linearity will generally be visible as changes in the uniformity. In addition, the constancy should be checked qualitatively after major maintenance at the very least.
If the spatial resolution is suspected to be inadequate for clinical use, either of the two aforementioned tests can be repeated. Additionally, a semi-quantitative constancy measurement of spatial resolution can easily be combined with the Centre of Rotation check.

3. Method

NEMA quantitative method (spatial resolution):
The spatial resolution is expressed as FWHM and FWTM of the profile that is measured with a line source. These parameters are expressed in mm.
Semi-quantitative method:
When doing the COR checks, a recording is made of a point source under controlled conditions. If the PSF broadening of this image is determined in a standardised manner, a simple check of the constancy of the spatial resolution is possible.
Qualitative:
A measure of the resolution is the minimum distance at which two sources can still, only just, be perceived as separate. This parameter can be determined using a lead plate with holes or slits. The phantom is placed on the detector and irradiated with a planar source. The minimum visible distance is expressed in mm. A qualitative impression of the linearity is also obtained.

4. Required equipment, phantoms and sources

Quantitative method:
Line phantom: a capillary tube or pipe (e.g. of an infusion system, clamped or stretched into a slot in a perspex block), maximum internal diameter 1 mm, minimum length 30 mm.
Filled with e.g. ^{99m}Tc, approximately 100 MBq/ml.

Semi-quantitative method:
Point sources: ^{57}Co or ^{99m}Tc, see COR-determination.
Qualitative method:
Lead bar phantom (PLES-phantom, e.g. with 4 quadrants, bar distance e.g. 2, 3, 4, 5 mm) or BRH phantom.
The lead bar phantom consists of a Perspex plate with parallel lead bars, the width of each being equal to the distance between the bars. This phantom contains mostly quadrants or tracks with different widths/distances between the bars, the smallest of which ought not to be distinguishable to the camera. An alternative with a larger number of different distances is the BRH phantom (a lead plate with 2,5 mm holes, with on one side a fixed distance of 2,5 mm between them, and on the other side an increasing distance of 1 to 8 mm in steps of 0,5 mm).

5. Procedure
Quantitative method:

- The system resolution is measured for each collimator with a radionuclide relevant for the collimator.
- 15% window width for ^{99m}Tc; for other radionuclides see the manufacturer's instructions.
- Maximum count rate 20.000 cps.
- Place the line phantom or the point sources at a distance of 100 mm above the collimator (avoid absorbing and scattering material).
- Choose a matrix size large enough that at least 10 pixels fall within FWHM (if necessary use zoom mode, see further analysis).
- Collect at least 1000 cts in the maximum profile (profile width 30 mm), measure in both directions (X and Y). The two measurements may be combined.

Semi-quantitative method:
see COR determination
Qualitative method:

- Place the lead phantom directly on the collimator with the ^{57}Co flood source on top of it.
- Use maximum matrix size (and if necessary zoom mode, see analysis and interpretation)
- Use the energy settings for ^{57}Co with an energy window of 15%.
- Register at least 5 Mcts.
- Repeat the measurement after the phantom has been turned 90° and use a rotation plan so the entire crystal is periodically tested.

6. Analysis and interpretation
Quantitative method:

- Generate a 30 mm wide profile, perpendicular to the direction of the line source.
- Determine the maximum. If at least 10 pixels fall within FWHM, the maximum value measured may be used. If the number of pixels is insufficient, a fit (e.g. parabolic or Gaussian) must be carried out to determine the maximum.
  Calculate FWTM and FWHM with linear interpolation on both sides.

Semi-quantitative method:

- Generate a 30 mm wide profile in X en Y directions. Determine the width at half height. If the PSF follows a Gaussian distribution, this value is equal to the LSF. For other distributions, the value determined may still be used for a constancy measurement.

Qualitative method:

First assess the quality of the image. Estimate the FWHM by taking 1,75 times the minimum visible distance. Too large a pixel size gives rise to poor results; repeat the recording as necessary with maximum zoom mode (although only part of the detector can then be tested). Examine the image/images for irregularities; these indicate collimator defects. As a check, make a recording with a slightly displaced lead phantom. Determine the minimum distance which is still visually distinguishable and compare to the original recording.

7. Action thresholds and actions

Quantitative method:

If the factory specification has been exceeded, contact the manufacturer.

Semi-quantitative method:

If an increase is suspected, carry out a quantitative measurement (a).

Qualitative method:

If there is a suspected increase in the minimum distance where two sources are still distinguishable from each other, carry out a quantitative measurement (a).
If there are irregularities or suspected collimator defects, contact the manufacturer (see also ''Uniformity'' other checks point e).

8. Pitfalls and comments

a. At count rates above 20 kcps excessively high FWHM values may be measured.
b. When using a lead phantom with collimator, take account of interference patterns (moiré effect). Move/ rotate the lead bar phantom; in order to record patterns that are at a 45° angle to the X and Y axes.
c. Always use the lead bar phantom in the same position: some phantoms do not have an equal layer of Perspex on either side.
d. Use radionuclides with higher gamma energies (above 140 keV) in combination with the slit or lead bar phantom only if the lead plate or the lead bars are sufficiently thick (increased transmission shows broadened lines). Assume that the transmission in the lead must be less than 1%. Lead thickness required: 2 mm for ^{99m}Tc, 6 mm for ^{111}In and 10 mm for ^{67}Ga.

9. Additional checks

a. Intrinsic spatial resolution and linearity.
Quantitative intrinsic linearity and the quantitative spatial resolution measurements are a normal part of the adjustment of a gamma camera. These standard NEMA tests require specialised (PLES) phantoms and specific software for the calculations. This check should be carried out in agreement with the manufacturer and in accordance with NEMA standards. Clinically relevant changes in resolution and linearity are indirectly detected as inhomogeneities (Uniformity protocol) and by the qualitative

checks of the resolution and linearity.

b. Spatial resolution at 75.000 cps.
If specifications are available for 75.000 cps, these can be checked upon acceptance. If the uniformity at 75.000 cps and the $R_{20\%}$ are within the specifications, deviations are unlikely.

c. Spatial resolution in the presence of scattered radiation.
Carry out this check if specifications are available for the spatial resolution measured in the presence of scattered radiation (see NEMA). It is unlikely, however, that on doing this check abnormalities will be found if the spatial resolution without scattered radiation complies with the specifications.

10. Literature, see also general literature

- Hart GC. Moiré interference in gamma camera quality assurance images. J Nucl Med 1986;27:820-3.