Quality Control of Scintillation Cameras (Planar and SPECT)

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The purpose of quality control (QC) is to detect changes in the performance of a gamma camera system that may adversely affect the interpretation of clinical studies. Clearly, there are a large number of factors that contribute to the final image quality, including uniformity, resolution (both intrinsic and energy), collimation and the hard copy device. In addition, for certain types of studies, other factors such as count rate capability come into play. With the addition of tomographic imaging, comes an additional suite of parameters that can influence the clinical images - these include system center of rotation, gantry and collimator hole alignment, rotational stability of the detector head and the integrity of the reconstruction algorithms. On a day-to-day basis, there is a limited amount of time that can be reasonably devoted to system QC. Hence the main goal of a QC program should be to monitor those parameters that are a) most sensitive to changes in system performance and b) most likely to impact clinical studies. This review will focus on some of the more critical areas in the quality control of gamma camera systems.

QC of Planar Imaging Systems

Quality control for planar systems is based on measurement of system uniformity and resolution on a daily and weekly basis respectively. Additional, but less frequently performed QC measurements include checks of collimator integrity, multiple window spatial registration and for some systems, wholebody uniformity.

System Uniformity

The most sensitive parameter to changes in system performance is system uniformity. Changes in photopeak location, photomultiplier tube (PMT) performance, energy and linearity correction, etc all affect image uniformity. Hence this is probably the single most important QC test that can be performed on a gamma camera system and one that should be performed on a daily basis. While the acquisition of the uniformity image is a relatively straightforward matter, a number of issues need to be considered: how many counts should be acquired, should the acquisition be performed intrinsically or extrinsically, what isotope should be used? The answer to these questions depends on the type of system, and whether or not the system is being evaluated for its ability to perform planar or tomographic acquisitions. Irrespective of whether the acquisition is performed intrinsically or extrinsically, the system should be checked to ensure that the photopeak is centered within the energy window. The acquisition should contain between 1-3 Mcts and the final image should be inspected visually to ensure that the uniformity is adequate for clinical studies.

Uniformity measurements can be performed intrinsically on most gamma camera systems using a small (< 100 uCi) point source of Tc-99m. Ideally, the point source should be placed at a distance of four times the detector field of view, in order to ensure uniform irradiation of the detector. This technique is inexpensive with a low radiation burden to the technologist. In addition, the system is evaluated with the isotope that will be used for the majority of clinical studies. There are a number of disadvantages to such a

measurement. First, the collimator is not evaluated. On older gamma camera systems, the absence of pressure sensitive panels on the collimator face often results in collisions between the collimator and ancillary equipment such as the imaging table or collimator cart. Such collisions can result in damage to the collimator that can appear as cold spots on clinical images. Intrinsic measurements may be impossible on some systems due to detector geometry. On many of the new dual-head systems, it can be very time-consuming to orientate the detector heads to the proper position for an intrinsic measurement. On some modern systems, gantry limitations or the presence of safety devices makes it difficult to rotate the gantry once the collimators are removed. Finally, whenever the collimator is removed there is increased risk of damage to the exposed crystal.

Extrinsic measurements can be performed using either a solid disk of Co-57 or a refillable plastic source containing a mixture of Tc-99m and water. The Co-57 disk source has the advantage of convenience in that the collimator need not be removed. In addition, on many opposing dual-head systems, it is possible to simultaneously acquire uniformity images on both heads, thereby reducing the time needed to perform QC. Co-57 sheet sources have two major drawbacks. They are expensive and need to be replaced every 1-2 years. New Co-57 sheet sources usually contain small amounts of Co-56 and Co-58 (1). These radionuclidic contaminants have a shorter half-life (70-80 days) than Co-57 and emit high energy gamma rays (> 500 keV). Visual inspection of the energy spectrum from a recently manufactured Co-57 sheet source will often show a significant amount of high energy contamination. During the first few months of use, this contamination may adversely affect the performance of the gamma camera (2), unless measurements of uniformity are performed with a medium or high energy collimator. Some gamma cameras are particularly sensitive to high energy contaminants and may show non-uniformities in the flood images when the quality control is performed with a low energy collimator. The use of a medium energy collimator, in place of a low energy collimator, can significantly reduce the impact of these contaminants on image quality. In situations where use of a medium or high energy collimator for QC is impractical, the effects of these high energy contaminants can be minimized (but not completely eliminated) by moving the sheet source away from the detector face.

As an alternative to a Co-57 sheet source, a Tc-99m sheet source can be prepared by the addition of several millicuries of Tc-99m to a liquid filled plastic sheet source. The disadvantages of such sources are the time taken in preparing the source and the consequential radiation exposure to the technologist. In addition refillable sources are prone to a number of other problems. These include distortion of the sheet source (3), presence of air bubbles inside the source, poor mixing of the isotope within the source, and clumping or adhesion of the isotope to the walls of the plastic container. The last problem is often the result of using Tc-99m bound to colloidal particles (e.g. Tc-99m sulfur colloid) or in some chemical form that facilitates aggregation of the Tc-99m. All of these problems can be avoided by careful preparation of the sheet source and by routine inspection of the source to check for warping, leakage or distortion of the plastic.

Resolution / Linearity
Measurement of system resolution and / or linearity is generally performed on a weekly basis and can be performed using either intrinsic or extrinsic techniques, each

with its own advantages and disadvantages. Intrinsic measurement involves removal of the collimator with the attendant risk to the crystal. Extrinsic measurement may show Moiré patterns due to interplay of the bar or hole pattern and the lead septa of the collimator (4). This has always been a problem with medium or high-energy collimators and, with the improvements in intrinsic resolution, it can also be a problem with some low-energy collimators (5). Hence, under most circumstances, intrinsic measurement is preferable to extrinsic measurement. To evaluate the spatial resolution of a gamma camera, a wide variety of test patterns have been developed over the years. The most common test pattern is the four-quadrant bar phantom, which accounts for over 80% of all resolution patterns used in nuclear medicine (6). Other commonly used test phantoms are the BRH phantom (7), the parallel line equal spacing phantom (8) and the Hine Duley phantom (9). All these patterns provide a qualitative index of resolution. The primary reason for this is that in all cases the hole size or the slit width is of the order of 2-5 mm. This is comparable to the intrinsic resolution of a gamma camera. Hence, the image produced is a convolution of the gamma camera intrinsic resolution and the slit width or hole spacing. Small changes in intrinsic resolution simply alter the modulation of the high and low count areas in the hole or bar pattern image and reduce image contrast. The consequences of this are that the same bar or hole spacing may still be discernible over a range of values of intrinsic resolution (10). Correct use of these phantoms requires that all images be compared with a reference image. This reference image can be obtained during acceptance testing or when a quantitative measurement of intrinsic resolution is being performed on the system.

Experience in our laboratory has shown that of these two parameters, system resolution tends to be a very stable parameter and will often remained unchanged even in the presence of significant changes in image uniformity. System linearity is more sensitive to changes in PMT performance. Fortunately, such changes are also generally manifest as changes in system uniformity. While the 4-quadrant bar phantom is the most commonly used phantom for measurement of system resolution, it is not ideally suited to the assessment of system linearity. Hence, test patterns such as the orthogonal hole pattern or the parallel line equal spacing phantom are preferable to the four-quadrant phantom as they allow assessment of both linearity and resolution.

Multiple Window Spatial Registration
Multi-peak imaging with isotopes such as Ga-67 and In-111 assumes that images acquired at different energies are directly superimposable. In conventional gamma cameras, the magnitude of the positioning signals generated by the pulse arithmetic circuitry increase with gamma ray energy. These signals are normalized to some reference energy to insure that the position of an event and, consequently, image size is independent of gamma ray energy. The accuracy to which this correction is achieved is termed the multiple window spatial registration (MWSR), and is usually of the order of 1-3 mm. Larger values for the MWSR will result in poor co-registration of images acquired at different energies and lead to degradation in image resolution. In modern gamma cameras, the use of energy and linearity correction maps has significantly improved the MWSR. However, as a consequence, errors in the correction map or inappropriate use of a correction map for a given energy may lead to more subtle errors in clinical studies. If a large number of studies are being performed with isotopes such as In-

111 and Ga-67, the MWSR should be checked on a 1-3 month basis. Measurement of MWSR is performed intrinsically by imaging a number of collimated point sources of Ga-67 using the method described by the National Electrical Manufacturers Association (NEMA) (11). This method while quantitative, is very time-consuming. An alternative, which we have found useful in our laboratory, uses a set of 4-8 collimated point sources of Ga-67 as per the NEMA method. Images of these sources are acquired at 93 keV and 296 keV. Subtraction of the 93 keV image from the 296 keV image provides a simple visual indication of the co-registration of the two images. If a significant difference is seen in the subtraction image, quantitative analysis can then be performed using the NEMA method.

Collimators

While gamma camera collimators are often extremely heavy, their robustness is not in proportion to their weight and the modern low energy high resolution collimator is very fragile and easily damaged. A small dent in the collimator will result in an apparent cold spot in the uniformity image. This type of artifact should not be confused with that due to damage to the crystal and can be distinguished by the absence of a bright rim around or adjacent to the cold spot. While routine inspection of the collimator surface was possible with many older types of gamma camera systems, newer systems often make it difficult to inspect the collimator due to the presence of patient crush protection pads attached to the front of the collimator. In such cases, damage can be deduced by comparing flood images obtained with different collimators.

Collimators are manufactured by one of two methods, either in a mold (cast collimation) or by gluing together corrugated strips of lead (foil method). With the latter technique, mechanical stress or inadequate bonding of the adhesive may lead to a slight separation of the lead foils. The result is a crack along the length of the collimator, which will be evident as a line of increased activity on the uniformity images. Depending upon the degree of radiation leakage through this crack and its location in the field of view, it may require replacement of the collimator.

Other potential problems include poor mating of the collimator to the detector head, or gaps between the collimator frame and the collimator itself. Hence, all collimators should be inspected by the technologist on a 1-2 month basis, to check the integrity of the collimator retaining bolts and collimator fit to the detector head. Most collimator related problems can be detected in the extrinsic uniformity images, a point in favor of extrinsic measurement of uniformity rather than intrinsic.

Whole Body Imaging

Whole body imaging with the older generation of gamma cameras (40 cm field of view), required 2 passes along the length of the body. These 2 passes were then aligned to give a complete whole body image. Incorrect alignment of these two passes resulted in the well known vertical "zipper" artifact. The field of view of modern whole-body imaging systems is generally large enough (> 50 cm) to permit acquisition of a whole body image with a single pass down the body. While this eliminates the potential for the zipper artifact, it still requires movement of either the gantry or imaging table, with the acquisition of a series of static views, or a continuous acquisition over the length of the body. With a series of static images, there is always the potential for incorrect alignment

of the images resulting in a similar type of "zipper" artifact orientated horizontally across the whole body image. With continuous mode acquisition, electronic timing errors or erratic motion of the gantry or patient table may result in banding artifacts in the whole body image. With both these types of problems, the conventional flood images will fail to indicate any problem with the system. Hence, wholebody uniformity should be checked every 1-2 months. This can be done by placing a sheet source on the lower detector (moving gantry system) or on the imaging table (moving table system) and acquiring whole body flood images (11).

QC of SPECT Systems

While it is well recognized that tomographic systems are more complex than planar systems, the disparity in complexity between the two modes of operation has increased in recent years with the advent of multi-detector systems. It is likely to further increase as new advances such as scatter correction, attenuation correction and coincidence imaging move from the research environment into routine clinical use. Comprehensive quality control in a modern tomographic gamma camera and computer system may involve the performance of a large number of sophisticated tests of system function, many of which require specialized test equipment and are beyond the capabilities of most small laboratories. This section will review the most common and useful procedures for modern SPECT systems.

Uniformity

One of the major sources of artifacts in tomographic imaging is non-uniformity in the flood image. The degree of non-uniformity in the response of a gamma camera to a uniform field of radiation can be defined in terms of the global and local variations in uniformity over the field of view (integral and differential uniformity, respectively) (11). Integral uniformity is defined as the largest variation (maximum - minimum) in counts over the useful field of view, while differential uniformity is a measurement of the worst case rate of change of uniformity over a limited distance (~5 pixels). Modern gamma camera systems typically have integral and differential uniformities of between 4-7%. Non-uniformities of this magnitude can generate ring artifacts in tomographic data (12), hence all tomographic systems apply an additional correction to the raw image data, called "uniformity", "flood" or "sensitivity" correction, before data reconstruction. Following uniformity correction, a tomographic system in good working order will have values of differential uniformity in the range 1.0-2.5%, with values of integral uniformity a little higher at 1.5-3.5%.

In order to understand the magnitude and type of non-uniformity that can create a ring artifact, it is necessary to understand the mechanism by which ring artifacts are generated. The reconstruction process assumes that the gamma camera has perfect uniformity. During back-projection, all pixels are assumed to have equal weight and are back-projected with equal intensity. If the counts in one pixel of the image are artificially reduced (e.g. due to a dent in the collimator), then information at that location will be back-projected at that reduced level. The result in the reconstructed image will be a ring artifact, with the radius of the ring equal to the distance of that pixel from the center of rotation (13). In practice, no system demonstrates perfect uniformity and there will always be minor changes in uniformity from one pixel to the next, even with uniformity correction. Each and every one of these minor changes in uniformity will result in a ring

artifact. However, they are only of concern when their magnitude exceeds the noise level in the transaxial image and they can be perceived above image noise. Because ring artifacts are the result of rapid changes in uniformity from one pixel to the next, a parameter that measures changes in uniformity from pixel to pixel will be the most sensitive to the detection of ring artifacts. Hence measurement of differential uniformity is the most useful indication of the suitability of the system for SPECT. Unfortunately, measurement of differential uniformity is not available on many gamma camera systems and the user must resort to measurement of integral uniformity in its place.

How good (or low) the values of differential uniformity must be to ensure the absence of ring artifacts in clinical studies depends on the clinical study. The purpose of uniformity correction is to reduce system non-uniformities to a low enough level so that any ring artifacts generated from residual non-uniformities in the system are less than image noise and hence are not visible in the reconstructed data. However, image noise in the reconstructed data will vary significantly with the type of study, hence a low count In-111 SPECT study will be far noisier than a high count Tc-99m liver SPECT study. Therefore a ring artifact that may be clearly visible in the Tc-99m liver SPECT study, may not be visible in the In-111 SPECT study. This implies that greater non-uniformities can be tolerated for some types of clinical studies than for others (14). Rather than estimating the level of system uniformity required for different types of studies, it is simpler to correct system non-uniformities to a level that will ensure no visible ring artifacts in even the highest count clinical studies. In general, it has been found that a 30 million count flood image provides sufficiently good correction of system non-uniformities for all current clinical studies. This correction should result in a value for differential uniformity of less than 3% (14). It should be noted that this level of correction might not be adequate for some types of phantom studies. For example, a Jaszczak phantom with 10 mCi Tc-99m may give 50-70 million counts over a 30 minute SPECT acquisition, and in such studies ring artifacts may be noted even though the system uniformity is adequate for clinical studies.

For routine QC of a SPECT system it is necessary to quantitate the degree of non-uniformity in the system. In order to obtain adequate counting statistics, significantly more counts must be acquired in the flood image compared to what is acquired for planar QC. Practical considerations usually limit the number of counts in the uniformity image to between 5-10 Mcts. With total counts less than 5 Mct, measurements of integral and differential uniformity are significantly altered by image noise (15). The values for differential uniformity should be tracked on a daily basis and action taken (e.g. acquire a new uniformity correction map) when the values exceed 3-4%.

Center of Rotation

Accurate center of rotation (COR) correction is important for high quality tomography. Errors in COR of as little as 0.5 pixel in a 128 x 128 matrix can lead to degradation in image quality (16). COR is measured by performing a 360 degree acquisition around a point source of Tc-99m. Most manufacturer's have software designed to analyze the acquisition and determine if the COR is within acceptable limits. Not only is it important to use the correct value of COR, it is also essential that this value remain constant as a function of angle. When measured on a gamma camera system, at a radius of rotation of 20 cm, both the X and Y values for the COR should show less than a

2 mm variation over a 360° orbit. COR is normally a very stable parameter of modern gamma camera systems and a weekly check is adequate to ensure proper correction.

Tomographic Resolution

An overall assessment of system performance can be obtained by imaging a suitable tomographic phantom. These are usually circular phantoms containing a variety of rods or spheres that can be filled with a mixture of water and Tc-99m. The usual purpose of this phantom is to determine optimum system performance. Hence the phantom is imaged under ideal conditions, i.e. minimum radius of rotation, high resolution collimation, 128 x 128 matrix with at least 120 views and high total counts (30 - 50 Mcts). The phantom should be placed on the headrest of the imaging table. Reconstruct transaxial images of the phantom with minimum smoothing. Single pixel thick slices through the uniform section of the phantom can be used to evaluate uniformity. Thicker slices through the resolution elements can be used to determine tomographic resolution. Note that because of the high counts present in such an acquisition, it is often necessary to acquire a high-count uniformity correction map (~100 Mcts or more) in order to provide adequate uniformity correction for this study. This test of tomographic resolution and uniformity should be performed every 6 months.

Rotational Uniformity

On most SPECT systems, the "uniformity" correction map is generated from a flood image acquired with the detector head facing up. It is then assumed that this correction map can be applied to images acquired at all angles of rotation. There are a number of instances when this assumption may not be valid. The photomultiplier tubes within the detector head are heat sensitive; hence heat generated by the electronics within the head may alter their characteristics. If the heat distribution within the head changes as a function of angle, then so too can the performance characteristics of the detector. Another likely cause of variations in uniformity with angle of rotation, is poor optical coupling of a PMT to the light guide or crystal. This can cause the tubes to decouple slightly at certain angles, leading to a significant change in uniformity. Photomultiplier tubes are also sensitive to the earth's magnetic field. Their performance characteristics can change with their orientation to the earth's magnetic field, leading to changes in uniformity with rotation (12). This may be a problem in older SPECT systems with inadequate magnetic shielding. A simple test for the assessment of rotational uniformity is to securely tape a lightweight Co-57 sheet source to the collimator face and perform a high-count tomographic acquisition over 360°. In order to obtain sufficient counts, this acquisition can take several hours and is often best performed overnight. The raw data can then be played back in cine mode to check for significant changes in uniformity with rotation. Note: many modern systems have pressure sensitive cover plates on the collimator face. In such cases, this test can only be performed if this feature of the system can be bypassed. Measurement of rotational uniformity should be performed once or twice a year, or whenever a significant upgrade or repair has been made to the detector head.

Collimator hole-alignment

Parallel-hole collimators are assumed to have the orientation of the holes perpendicular to the surface of the crystal. In reality there can be considerable variation in collimator hole angle both locally and globally. These variations directly affect the center of rotation and a poorly manufactured collimator may have considerable variations in COR across its surface. These variations cannot be corrected for by the standard COR correction method, and their presence cannot be determined by inspection of planar image quality. While such collimators will often produce acceptable planar images, the quality of SPECT images will be inferior. Unfortunately the only solution for this type of problem is replacement of the collimator. A simple way to check a collimator is to perform multiple measurements of COR along the length of the collimator, and check that all measurements essentially give the same result (16). Maximum variations in COR should not exceed $\pm$ 1.0 mm over the length of the collimator (17,18). Larger variations than this indicate local hole angulation errors. Furthermore, the average COR value for the collimator should be similar to those for the other collimators on the tomographic system. Measurement of collimator hole alignment need only be performed once for each collimator, as it is solely a function of the physical characteristics of the collimator.

Gantry alignment (single head system)

For a tomographic acquisition in single headed SPECT systems, the gantry is usually set to 0° and the detector head is leveled prior to an acquisition. Setting the detector head level is based on the assumption that the axis of rotation of the detector head is horizontal. This axis of rotation is determined by the alignment of the gantry. Misalignment of the gantry can be caused by a number of things. In many older SPECT systems, sagging of the detector arms can occur. This is particularly true in cantilevered systems as compared with counterbalanced systems. The gantry itself may not be level on the floor, either due to incorrect shimming of the gantry, or irregularities in the surface of the floor. Whatever the cause, the consequences are that leveling the detector head results in data being acquired obliquely rather than perpendicular to the axis of rotation. For example, a 1° gantry misalignment with the detector head at a 20 cm radius of rotation will cause a 3.5 mm displacement of image data along the axis of rotation. Variations in gantry alignment will be visible in the analysis of the weekly COR measurement as variations in the Y-position of the point source. Gantry alignment and its stability with rotation can also be easily checked using a small bubble level. Level the gantry at 0°, then rotate the gantry through 180° and check that the gantry is still level. Alignment should be checked once or twice a year and after any major upgrade or modification to the gantry.

Head alignment (multi-head systems)

Many multi-detector systems do not permit tilting of the detector head and hence if the gantry is not vertical, it is not possible to level the head and misalign the detector relative to the gantry. However a new concern with multi-detector systems is the alignment of a given detector to itself at different radial positions and the alignment between the different detectors.

A simple method of simultaneously checking radial alignment, inter-head alignment and collimator hole alignment is to acquire tomographic acquisitions of a point source. Assuming that we are evaluating a dual-head 90° system, then the following two

acquisitions need to be performed. With the point source located close to the center of rotation of the gantry, acquire a 360° acquisition of the point source with head #1 at the minimum radius of rotation. Now acquire a second acquisition with head #2 at the maximum radius of rotation. Reconstruct both studies in an identical manner. The only difference between the two sets of transaxial images is the loss of resolution in head #2 data due to the increased distance from the point source. Now subtract the transaxial images from the head #1 from those of head #2. If there is no misalignment, the resulting images should show a doughnut shape indicating perfect co-registration of the two heads. Any misalignment of the two heads will be readily apparent on the subtracted images. This is a very simple but useful test that will work on dual-head 90° systems, as well as conventional dual-head and triple-head systems.

This test need only be performed on a 6-month or yearly basis. It should be repeated if any changes in COR are noted in the weekly QC

Fan-Beam Collimators

Fan-beam collimators are coming into widespread use for brain and cardiac studies. The cause of artifacts associated with this type of collimator is often difficult to determine, as the raw data is in a distorted form and difficult to interpret. The primary factor of interest with a fan-beam collimator is focal length. A number of techniques have been described that allow the user to determine both the true focal length of the collimator and an estimate of the variation in this focal length over the collimator field of view (19,20). The main disadvantage of these techniques is that they require either special software or multiple acquisitions and reconstruction of point sources at different radii of rotation and collimator focal lengths. Fortunately, this process need only be performed once on each collimator to accurately characterize it.

Conclusions

As the complexity of modern systems increases, it becomes more important for both the technologist and physician to be able to recognize the various types of artifacts that can occur in gamma camera systems and their potential impact on clinical studies. A thorough evaluation of the system at installation and a comprehensive quality control program will detect the majority of problems that can occur. With the improved stability of modern systems and the latest generation of "smart" detector systems that have streamlined and automated much of the image acquisition and analysis, it is easy for the user to become complacent and assume that the system will "take care of everything". The failure of a system component can occur at any time, and in modern systems, may be subtle and difficult to recognize. In such an environment it becomes imperative that any unexpected finding in a clinical study be questioned with respect to a possible malfunction of some aspect of the acquisition and analysis of the data.

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