Acceptance Testing and Quality Control of Gamma Cameras, Including SPECT

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The measurement of several performance parameters of a scintillation camera at the time of installation and thereafter at regular intervals is necessary to ensure that the camera is operating within specifications and to detect changes over time that can initiate a request for service. There are varied opinions on what constitutes a satisfactory acceptance test and quality control program. Few individuals would disagree that either an acceptance test or routine quality control measurements are necessary, yet agreement on the contents and frequencies of these tests is lacking. This paper discusses the performance parameters of scintillation cameras that are usually measured for planar imaging and also for SPECT with rotating cameras.

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An acceptance test is verification following installation that a gamma camera meets the specifications of performance that were agreed upon at the time of purchase. Following acceptance, periodic checks on the constancy of selective operating characteristics are necessary to ensure adequate performance and constitute the quality control program (*1–5*). When the camera is also used for SPECT imaging, additional parameters must be included in both the acceptance test and the quality control program (*6–8*). There is no universal agreement on a protocol for camera acceptance testing or a quality control program (*9–11*). Opinions vary widely on what are the minimum necessary tests and their frequency.

Possibly the most widely recognized set of camera performance tests is that proposed by the National Electrical Manufacturers Association (NEMA) from the Nuclear Imaging Section of the Diagnostic Imaging and Therapy Systems Division (*12,13*). They describe how a manufacturer arrives at the specifications of his camera and how these are standardized between manufacturers (*14*). The NEMA standards do not set minimum performance requirements. They are not intended for acceptance testing or quality control of scintillation cameras. Special equipment is necessary to make the NEMA measurements and therefore they are not intended for all camera owners. Although there are critics of the NEMA standards for "Performance Measurements of Scintillation Cameras" and implementation of these standards by users is difficult and sometimes impossible (*15*), familiarity with them does give insight into the underlying parameters of camera performance.

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PLANAR IMAGING

For planar imaging, the most important operating parameters are spatial resolution, flood field uniformity, spatial linearity, energy resolution, count rate response, multi-window spatial registration, and sensitivity.

Spatial Resolution

Spatial resolution is a measure of an imaging system's ability to detect two closely spaced objects as two separate entities. The resolving limit of an instrument is the minimum distance that two objects can be separated and still be distinguished as two objects. For example, historically the resolving power of a telescope was described by the minimum angular separation of two stars that could be distinguished as two objects. For a scintillation camera, related parameters that are often used as surrogate measure of spatial resolution is the full width at half maximum of the point spread function or the line spread function. This information can be extended one step further by calculating the modulation transfer function (MTF). The MTF is a measure of the contrast transfer from object to image as a function of spatial frequency, i.e., object size.

The NEMA specification for spatial resolution is the full width at half maximum and full width at tenth maximum of line spread functions at multiple positions within the central and useful (collimated) fields of view of the camera. The central field of view is defined as the central region having linear dimensions 75% of those of the useful field of view. The resolution should be measured along both the X and the Y axes of the camera to evaluate any orientational variation in the spread functions. The NEMA protocol requires a special slit phantom and acquisition into a digital matrix for which there is at least 10 pixels distributed over the full width at half maximum of the line spread function. Most nuclear medicine computers do not have a sufficiently large matrix for this unless a magnification (zoom) mode is used. However, zoom mode limits evaluation to a small region of the useful field of view.

A more common and less quantitative approach is the visual evaluation of the image of a resolution phantom. The quadrant bar phantom is most often used. The minimum perceptible bar spacing in a transmission image is used as an index of camera spatial resolution. This can be performed either with or without collimation. An estimate of the full width at half maximum of the line spread function at the same energy can be obtained by multiplying the smallest resolvable bar spacings by 1.75 (*3*). With collimation on modern cameras, particularly medium or high energy collimators where the intrinsic resolution may approach the collimator hole size, there is the potential for generating Moire patterns that can complicate image interpretation. Moire patterns can also be observed on an intrinsic bar phantom image if it is collected in a digital matrix where the pixel size is close to the intrinsic spatial resolution. Generally, for routine quality control a resolution test pattern is used to evaluate intrinsic resolution at least weekly to ensure that there has not been degradation of resolution in comparison to a benchmark image that was acquired at time of acceptance. At time of acceptance the resolution is also measured with the collimators in place in order to verify that the collimators comply with agreed upon specifications.

Intrinsic Uniformity

The intrinsic flood field uniformity of a scintillation camera is the ability of the camera to produce a uniform image when exposed to a homogeneous spatial distribution of gamma rays. Most modern cameras are not designed to be intrinsically uniform because gains in spatial resolution can be obtained by sacrificing intrinsic uniformity. Therefore, these systems require some mechanism of uniformity correction. Typically, the uniformity correction involves computer corrected registration of regional photopeak Z signal and X and Y coordinate position signals. The monitoring of camera uniformity is probably the most sensitive indicator of camera performance and should be performed daily prior to patient studies. Most nuclear medicine facilities perform daily uncorrected (when possible) and corrected flood images that are subjectively evaluated. For a more quantitative evaluation, the flood image can be digitized and numerically or graphically analyzed. The NEMA protocol for intrinsic flood field uniformity analyzes both differential and integral uniformity over the useful and central fields of view. The integral uniformity represents the maximum pixel count rate change over the indicated field of view expressed as a percent. The differential uniformity is the maximum change over a five pixel distance in either the X or Y directions thereby representing the maximum rate of change of the regional count rate.

Flood field images should be evaluated under the same energy conditions used for patient imaging. If off-peak technetium-99m (^{99m}Tc) imaging is performed then the flood should be checked for uniformity at this pulse height setting. Also, the user should verify that floods obtained with gamma ray energies other than those used for uniformity correction are acceptably uniform for clinical studies. This is particularly true for thallium-201, gallium-67 (^{67}Ga), and iodine-131. If these floods do not appear adequately uniform then a correction flood of the same energy is indicated.

Linearity

Spatial linearity is one of the parameters that influence flood field uniformity. In the ideal system, a straight line source of gamma rays should yield a straight line in the image. Any deviation from a straight line represents distortion. Because of the finite number of PM tubes in scintillation cameras there is a wave-like distortion in the image of a line source. Quantitative linearity correction is accomplished by many manufacturers by storing in a microprocessor a correction algorithm that shifts the positions of scintillation events the appropriate direction and distance to yield a straight line.

The NEMA protocol for measuring linearity involves the acquisition along the X and Y directions of an image from a multi-slit phantom, the same one used for the spatial resolution measurement, followed by an analysis of the line spread peak positions. Deviations of the peak position from the true location of the center of the slits is a measure of the deviation from linearity. Typically, most departments do not measure linearity separate from either spatial resolution or flood field uniformity. A subjective evaluation of linearity is obtained when a bar phantom or an orthogonal hole phantom is imaged.

Energy Resolution

The energy resolution of a scintillation camera is a measure of its ability to separately distinguish the energies of two gamma rays that differ only slightly in energy. Traditionally the parameter that is measured is the full width at half maximum of the photopeak expressed as a percentage of the photopeak value. Since Compton scatter in soft tissue is so dominant at the energies used for gamma-ray imaging, the ability to discriminate against these, which reflects the energy resolution of the system, has a substantial impact on image quality. Energy resolution is a function of gamma ray energy and therefore the energy at which it is measured must be specified. The NEMA protocol suggests measurement at 140 keV with uniform irradiation of the useful field of view, without a collimator. Most modern cameras have energy resolution for ^{99m}Tc in the range of 10–12%. Energy resolution is not routinely measured as part of a quality control program. If possible, it should be measured as part of an acceptance test. For an accurate measurement a multichannel analyzer is usually required so that, as suggested by NEMA, at least 50 channels are distributed over the full width at half maximum of the photopeak. In some cameras the energy pulse is not readily accessible so the measurement may be impracticable.

Count Rate Performance

Following the interaction of a gamma ray in a scintillation crystal, a finite period of time is necessary for the scintillation event to evolve to the output "count". During this time interval the camera cannot process other scintillations as distinctly separate events. The minimum time required between two events for the events to be processed as distinct events is the deadtime. This limits the maximum processing rate and results in increasing data loss as the input rate increases. For quantitative image analysis it is important that the percentage data loss due to camera deadtime be known and corrected. This is usually a problem only during very high count rate studies such as first-pass cardiac scintiangiography. It is only during this type of study that a large amount of radioactivity (possibly 10–30 mCi of ^{99m}Tc) is simultaneously within the field view of the camera. In this situation the input rate to the collimated detector can exceed several hundred thousand gamma rays per second. Under most other imaging situations the radioactivity is distributed throughout the body and that in the field of view results in much lower input rates to the detector. The NEMA protocol suggests specifying the count rate performance as the input rate that results in a 10% data loss and also as the maximum observable count rate. NEMA defines a technique for measuring the deadtime of the camera under the assumption that the system behaves as fully paralyzable in the range where a 20% data loss is expected. Few laboratories measure either camera deadtime or the count rate response of a scintillation camera as part of a routine quality control protocol. It is, however, an appropriate parameter to measure during acceptance testing and it is one of the specifications quoted by most camera manufacturers.

Multi-Window Spatial Registration

The number of light photons incident onto a photomultiplier tube in a scintillation camera is determined by how close the photomultiplier tube is to the interaction site in the crystal and how much energy is deposited in the crystal and, therefore, the total number of light photons emitted. Thus, the signal from a photomultiplier tube reflects some combination of spatial location and energy deposition. The signals from all of the photomultiplier tubes are analyzed in order to derive positioning voltages for the scintillation event. If these positioning voltages are not normalized for the energy of the gamma ray, or equivalently the window setting of the pulse height analyzer, gamma rays of different energies originating from the same location would be recorded at different locations on the image. Therefore, correction circuits are necessary to ensure that images of different energies spatially coincide when the gamma rays originate from the same locations. This is most important when summed images from multi-energy emitters are used. For example, if two or three of the ^{67}Ga peaks are summed to form a single image it is important that the images derived from each window are spatially coincident. The NEMA approach for measuring this multi-window spatial registration consists of imaging a point source of ^{67}Ga at two locations on each of the X and Y axes and analyzing the displacement in the location of the image of these point sources for each of the windows. This procedure is usually performed during an acceptance test but rarely as part of a routine quality control program.

Sensitivity

The sensitivity of a scintillation camera is measured as the number of detected counts per unit time per unit source activity for a specified energy window and geometry of measurement. The intrinsic sensitivity is typically tens of thousands times higher than that through low-energy, parallel hole collimators. Since the camera is never used for imaging without a collimator it is the sensitivity of the total system that is of interest as well as the relative sensitivity between the available collimators for that particular camera. Manufacturers of collimators label sets of collimators quite differently. What is called a high resolution collimator by one manufacturer might be a general purpose collimator to another. Therefore, it is important to know the relative sensitivity of the available collimators. The NEMA approach to measuring sensitivity is to measure the count rate per microcurie for a small source of known activity in a 10 cm diameter flat dish. This should be done through each collimator so that the relative sensitivities can be calculated. It is usually done once during acceptance testing but not routinely as part of the quality control program. The activity should be low enough so that data loss because of camera deadtime is negligible. It is possible to monitor the sensitivity of the camera over time as part of the quality control program if the amount of activity used each day for the flood image or for the bar phantom image is known. By standardizing the geometry for the acquisition of either of these images and noting the time for acquisition of a preset number of counts, a measure of relative sensitivity can be obtained by dividing by the activity.

Other Important Parameters

There are several very important performance characteristics of scintillation cameras that are not addressed by the NEMA standard which should be included in either acceptance tests or routine quality control tests. These include:

1. High count density flood images obtained through each collimator for evaluation of any defects in the collimator construction. This should be done during acceptance testing and at any time thereafter when there is a suspicion that the collimator has been damaged.

2. On cameras capable of acquiring whole-body images by scanning either by moving the detector or the patient bed, spatial resolution and alignment of the zipper between multiple passes should be checked. This can be done by scanning a quadrant bar phantom set at a diagonal to the direction of motion. Comparison of the image with and without scanning will indicate resolution loss or misalignment of the interface between multiple passes. Also the speed should be calibrated periodically.

3. If a formatter is used, the fidelity of image quality over all areas of the film should be checked. This should be studied for all of the standard formats that are used clinically by recording a flood image at each film location and evaluating the images for constancy of intensity and shape.

4. When the camera is used with a computer the camera/computer interface must be tested to ensure that information is not being lost or distorted during this transfer. The X-Y gains of the interface should be checked by imaging an object of known dimensions and calculating the gains along the two axes. Also the count rate recorded at the camera console should coincide with that recorded by the computer.

5. Most cameras have built-in safety switches to deactivate the system, particularly with respect to motion of the detector. Some of these are manually operated ("panic buttons") and others are supposed to be automatic, such as stopping the detector motion in whole-body scans. These safety switches should be tested at installation and periodically thereafter.

There are other special accessories on some cameras that should be included in a quality control program, but will not be discussed here. Table 1 summarizes the parameters previously discussed with common techniques and suggested frequencies for monitoring. It is emphasized that the selection of parameters measured routinely as part of a quality control program are very subjective. If there is lack of universal agreement on what should be measured and there is even less agreement on how often these should be measured. In the majority of nuclear medicine departments a minimum quality control protocol consists of flood field uniformity measured daily and spatial resolution measured at least weekly.

SPECT

A great deal of attention has been given in the past few years to quality control protocols for SPECT. The substantial increase in the number of publications on artifact formation and quality control procedures for SPECT are not without justification. It is now well known that there are significant problems with respect to accurate presentation of the spatial distribution of radioactivity in transverse sections and slight degrees of "sloppiness" in data acquisition or processing can have substantial adverse effects on the results. In fact, poorly performed SPECT can be more detrimental to patient care than no SPECT at all, particularly if SPECT images are used in lieu of planar images. The potential advantages of tomography over planar imaging can be achieved only by emphasizing the strict adherence to proven acquisition protocols and by understanding what the processing protocols are doing to the data. This means that the physician and technologist must be familiar with options of data acquisition, available filters, and attenuation correction techniques. They must know where each is most appropriate, i.e., different filters may be indicated for different clinical studies. The appropriate processing is a function of the spatial frequencies in the object and the count density in the planar images. Filters should be evaluated under clinically meaningful conditions, not from high count phantom images. With this increased demand for attention to detail in SPECT, the need for more sophisticated training of technologists and physicians and frequent reviews is obvious. In addition to the camera performance parameters discussed previously, the following must be considered in a SPECT system acceptance test and quality control program.

Camera/Collimator Uniformity

Because the spatial orientation of the camera and object changes during a SPECT acquisition, isolated areas of nonuniformity are spread throughout the data set and therefore into the reconstructed image during back projection. For 360° data acquisition the most common presentation are rings of increased or decreased intensity suggesting a bull's-eye appearance.

Over and above the camera's built-in uniformity

TABLE 1
Acceptance Test and Quality Control Parameters

Performance parameters	Acceptance test protocol	Quality control protocol	Frequency
Spatial resolution	Full width half maximum and full width tenth maximum of line spread function for ^{99m}Tc along X and Y axes. Also bar phantom images as bench mark.	Resolution phantom (quadrant bar phantom, rotate 90° between acquisitions)	Weekly
Uniformity	Integral and differential over useful field-of-view and central field-of-view. Flood images for bench marks. Offpeak and other energies.	Intrinsic or extrinsic flood evaluated qualitatively	Daily (before first patient)
Linearity	Line sources or orthogonal hole phantom evaluated subjectively.	No separate test, subjective evaluation from bar phantom resolution test and intrinsic to the uniformity measurement	—
Energy resolution	Full width at half maximum of ^{99m}Tc photopeak expressed as percent.	Same	Annual
Count rate response	Twenty percent data loss, resolving time, maximum count rate for 20% window.	Same	Annual
Multi-window registration	Two ^{67}Ga point sources imaged along X and Y axes with individual windows and summed windows. Measured displacements on individual window images.	Same	Annual
Sensitivity	Count rate per μCi through all collimators with 20% window, calculate absolute sensitivity and relative sensitivity for available collimators.	Same	Annual
High count density collimator floods	Ten million count floods through each collimator for evaluation of collimator defects.	Same	Annual or when suspicious of damage
Formatter	Flood images at all locations and for all image sizes.	Same	Annual
Whole-body accessory	Scan bar phantom along diagonal and compare to stationary image, calibrate speed.	Same	Annual

correction scheme (linearity and energy correction), a high count correction flood is also necessary for SPECT imaging. The temporal and spatial stability of the uniformity is very important. The high count density correction flood is collected in one camera orientation and at one point in time. Data acquisition for SPECT results from multiple camera orientations which could change the uniformity, for example, due to effects of environmental magnetic fields changing orientation with the axes of the photomultiplier (PM) tubes, slippage of PM tubes, shift of the collimator, etc. The stability of the uniformity over time should be checked for each camera to determine the necessary frequency of collecting the high count density correction flood. Most camera manufacturers have a recommended protocol for SPECT uniformity correction but this should be verified with respect to frequency of application.

Center of Rotation

In the reconstruction of images from projections it is assumed that the image matrix, representing the activity distribution in a section, has a constant relationship to the data acquisition matrix. If one matrix shifts with respect to the other for different angles of data acquisition, then the image reconstructed from back projecting the data will be blurred because of the relative motion of the two matrixes. The simplest example is that of a point source. For 360-degree acquisition the count rate versus pixel number of the point should be a straight line along the axial direction and should have the shape of a sine wave along the other camera axis. The amplitude of the sine wave is the distance of the point source from the center of rotation. Deviation from this suggests that the center of rotation is moving during the acquisition and the reconstructed image of the point source will be blurred, resulting in loss of resolution. Since activity distributions other than points can be considered as an assemblage of many point sources of various intensities, the reconstructed image of an extended source will be blurred (over and above the blurring due to the resolution of the camera) if the center of rotation is not centered in the image matrix.

There are several ways to measure the center of rotation and apply corrections to the data after acquisition or apply off sets to the ADCs before data acquisition. Each camera manufacturer supplies a recommended protocol for their systems, including software.

As with the uniformity correction flood image, the location of the center of rotation must be checked frequently and the data retained if future reconstructions from the original projections are anticipated. It is the value of these parameters at the time of data acquisition that is relevant, not the condition of the camera at a future time when the original data set is reconstructed, i.e., you should not correct projections acquired last month with this month's uniformity or center of rotation values.

Alignment of Camera with Axis of Rotation

With parallel hole collimators the plane of the detector must be parallel to the axis of rotation. If the camera head is angled with respect to the axis of rotation, the projections will not be orthogonal to the object, and the slice volume will vary from this effect over and above that due to changes in camera resolution with depth. For this reason it is extremely important that the camera stand be level and perpendicular to the floor, and that the camera head be parallel to the floor in the detector up or down orientation. During camera installation the leveling of the detector stand and the patient pallet should receive close attention from the manufacturer's service representatives. Prior to each data acquisition, the operator must level the detector head. There are various ways to do this including use of a spirit level on the detector and this can be checked by acquisitions of images of point sources of 180 degree opposed views. Misalignment results in resolution loss in the reconstructed images similar to misalignment of the center of rotation. By aligning the camera head with the axis of rotation, it is assumed that the collimator holes are perpendicular to the detector and thus the axis of rotation.

Adjustment of X-Y Gains

The gains in the X and Y directions, i.e., over the two axes of the detector, should be matched so that pixel cross sections are square and distance factors in both axes are equal. The gains can be measured by imaging point or line sources separated by known distances along each axis. The separation of the peaks of the count profiles should be the same number of pixels along the X and the Y axes. Note, this is important for both the camera X-Y gains and at the camera/computer interface. Pixel dimensions in the third direction of the reconstructed image, i.e., the Z axis, can be determined from the measurements in the X-Y plane but this pixel dimension should not be confused with the slice thickness. The slice thickness can be defined by a line spread function obtained along the Z axis and expressed as a full width of half maximum of this line spread function.

In summary, the thorough characterization of a scintillation camera's performance immediately after installation is important for at least two reasons: (a) as a mechanism to verify that the system performs as designated by the manufacturer's specifications and agreed upon in the purchase order; and (b) to serve as a bench mark against which future measurements can be compared. The camera quality control protocol should be designed to verify acceptable performance of the camera prior to each patient study or at least daily. Exactly what constitutes the specific test within a quality control program is still very much a matter of personal preference. The recommendations presented here are those of the author and certainly do not represent a consensus by any organized group within nuclear medicine.

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