

Performance and Acceptance Testing of Scintillation Cameras for SPECT

Robert J. English and Robert E. Zimmerman

Brigham and Women's Hospital and Harvard Medical School, Boston, Massachusetts

This is the third in a series of four continuing education articles related to the characteristics of the scintillation camera. Upon completion of this article, the reader should be able to: 1) understand the principles and the necessity of performance testing; 2) have the basic information to establish and conduct a routine testing program; and 3) effectively ensure the installation and performance of a SPECT system.

In the last two decades, the scintillation camera has evolved from a small field of view competitor with the rectilinear scanner to a more sophisticated instrument which is the backbone of nuclear medicine imaging. The major concerns of detector consistency and performance, which plagued the buyer in the past, have been somewhat relieved by uniformity, energy and linearity correction, along with other improvements. However, there still exists a twilight zone of doubt (particularly with SPECT) that confronts the novice customer. This doubt is associated with the burden of determining which particular vendor's approach to camera imaging optimization is best, and basic questions such as: Does the instrument perform as claimed? Is the support from the vendor reliable? It remains, therefore, for the user to take the responsibility of verifying the vendor's claims of a reliable, quality instrument.

Some scintillation camera manufacturers adhere to a standard code of performance specifications established by the National Electrical Manufacturer's Association (NEMA) (1), and the set of performance measurements they have established. These measurements provide uniform guidelines that assure the customer of state-of-the-art equipment. Items such as differential and integral uniformity, linearity, spatial and temporal resolution, energy resolution, dead time, etc. are all calculated with reproducible methodology that allows the purchaser a reliable technique of comparison shopping.

The manufacturer has the responsibility of testing each instrument, not just a sampling, for certain of these standards prior to shipping and after installation. The failure of the vendor to provide this verification demonstrates a lack of service that may violate the purchase agreement. The post-installation performance measurement is the critical difference between the vendor's promises and actual product performance. Many variables may enter into an instrument's clinical reliability during and after the shipment of the instrument.

For reprints contact: Robert J. English, CNMT, Nuclear Medicine, Brigham and Women's Hospital, 75 Francis St., Boston, MA, 02115.

PURCHASING THE SCINTILLATION CAMERA

The camera of today is a sophisticated mass of electronics, assembled to carry out an extraordinary task: changing the invisible energy of radiation into visible images of diagnostic value. And as such, one can not always expect it to work as well as a vendor would have one believe. This is true of automobiles, home appliances, and probably even medical facilities. However, in the case of cameras, the consumer is in a position to select from a number of various manufacturers, with varying prices, service contracts, and additional options. Prior to the contract signing, the buyer should carefully compare characteristics and features of various camera vendors that meet these parameters in their literature, and narrow down the selection process to a particular manufacturer with the best price, service record, and customer support system. Evaluating equipment service and customer support requires the buyer to seek out institutions that have the instrument of choice and to talk informally with those individuals responsible for its daily operation. Once the purchase has been made, hopefully meeting the satisfaction of the vendor and consumer, it is then the responsibility of both parties to test, verify, and document the purchased system's performance. If the performance characteristics of the instrument are taken from the manufacturer's own literature and placed in the purchase contract, then installing a dependable instrument with mutually agreed upon performance characteristics should be achievable.

Once a particular manufacturer's instrument has been selected, the buyer should ensure the vendors printed claims by simply appending the purchase order with these stated characteristics. The following, for example, is a typical appendix added to one purchase order, which is taken exactly from the vendor's own advertising literature.

"The system shall meet or exceed the following specifications as outlined in the NEMA method of measurement, at 140 keV in the central field of view (CFOV):

1. Intrinsic uniformity—Integral	± 3.0%
Differential	± 4.0%
2. Intrinsic resolution—FWHM	4.0 mm
FWTM	8.0 mm
3. Intrinsic energy resolution	11.0%
4. Intrinsic spatial linearity—Absolute	1.0 mm
Differential	0.4 mm

5. Intrinsic count rate performance
 - 20% loss (normal mode) 75 kcps
 - 20% loss (high count rate mode) 110 kcps
 - Maximum count rate 200 kcps
6. Intrinsic spatial resolution at 75 kcps (FWHM) 5.0 mm
7. Multiple window spatial registration 2.0 mm
8. Intrinsic flood field uniformity
 - Integral at 75 kcps $\pm 7.0\%$
9. Point source sensitivity $\pm 4.0\%$
10. Extrinsic spatial resolution (Low-energy collimator)
 - FWHM (air) 10.5 mm
 - FWTM (air) 17.8 mm
 - FWHM (10 cm H₂O) 11.2 mm
 - FWTM (10 cm H₂O) 22.9 mm
11. System sensitivity 330 cpm

The buyer of such an instrument now has to assume that the manufacturer will deliver and install an imaging device that meets and/or exceeds their literature claims. When this is not the case (2), the user should then, upon delivery, request and receive a copy of the performance characteristics of their purchased instrument, as measured prior to shipment. Upon completion of the installation procedure, the service or installation team should repeat the testing and issue an updated copy of the installed unit's measured parameters, preferably prior to further payments. This detail should, of course, be included in the initial purchase agreement. The repeated testing process results in a small amount of inconvenience for the vendor and a large degree of reassurance for the consumer. In addition, the buyer now has a set of documented performance parameters upon which to base daily, monthly, and quarterly quality control protocols.

The remainder of this text is a guide for conducting routine testing or establishing baseline performance characteristics should the vendor fail to do so.

PERFORMANCE TESTING

The bulk of performance testing of rotating cameras involves the instrument's basic planar characteristics. Any discrepancies inherent to the camera's static imaging process will be amplified in SPECT, through the reconstruction process, into significant artifacts. Thus, the optimal planar performance of a SPECT system generally occupies the greatest attention. Performance testing must include both intrinsic and extrinsic measurements.

Intrinsic Measurements

Flood Field Uniformity. Evaluation of intrinsic field uniformity should be a daily function that insures the detector's ability to produce a uniform image from a homogeneous source. A 200–800 μCi $^{99\text{m}}\text{Tc}$ point source is placed a minimum distance of five crystal diameters from and perpendicular to the center of the detector, with the energy window(s) set

to those limits used in patient data acquisition. Upon completion of loading the uniformity and energy correction reference flood, a 5–10-million count evaluation flood should be analyzed. A number of manufacturers offer software that calculate differential and integral uniformity (Fig. 1). However, lack

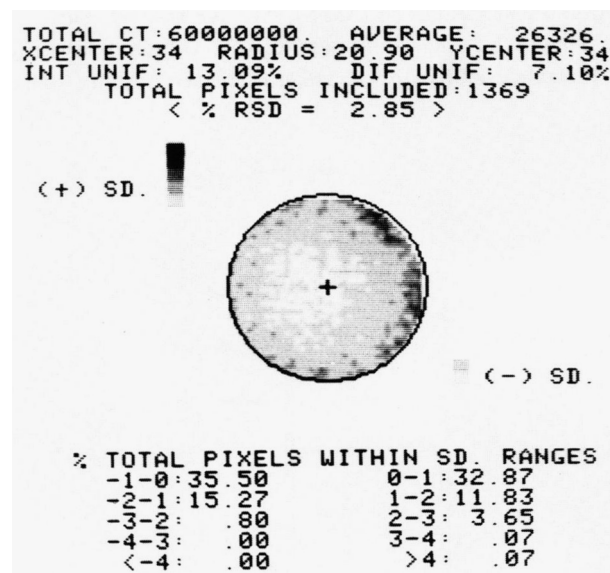


FIG. 1. Vendor provided software calculating integral (13.09%) and differential (7.10%) uniformity from a pixel searching routine.

of this luxury should not prevent the user from evaluating visual discrepancies and possibly even analyzing integral variations from the systematic placement of profiles or histograms, a feature common to even the least sophisticated computer systems.

Integral uniformity represents the maximum pixel count rate change over the indicated field of view, expressed as a percent, and may be calculated from basic profile software available on most nuclear medicine computer systems. To best simulate NEMA protocols, the user should apply a nine-point smooth to a 10,000 count per pixel, 64×64 flood image, to reduce the effects of random fluctuations in the data. The smoothed image is then analyzed by systematically searching for the maximum and minimum counts and inserting the results in the following formula:

$$\text{Integral Uniformity} = \frac{(\text{max} - \text{min})}{(\text{max} + \text{min})} \times 100.$$

Differential uniformity is the maximum change over a five-pixel distance in either the X or Y directions in every row and column, presenting a task too time consuming for manual determination. Many vendors provide software packages that implement a search routine to apply the formula:

$$\text{Differential Uniformity} = \frac{(\text{hi} - \text{low})}{(\text{hi} + \text{low})} \times 100.$$

Spatial Resolution Testing. As a measure of the system's ability to image two closely spaced sources as separate entities, spatial resolution should be conducted immediately upon completion of installation and at least quarterly thereafter. This may be performed using a NEMA slit mask, for calculations of full width at half maximum (FWHM), full width at tenth maximum (FWTM), and in sophisticated circumstances, modulation transfer function (MTF). The NEMA slit mask is a lead sheet with nine 1-mm parallel slits, 30 mm apart (Fig. 2). Placed carefully on the detector surface, a point source

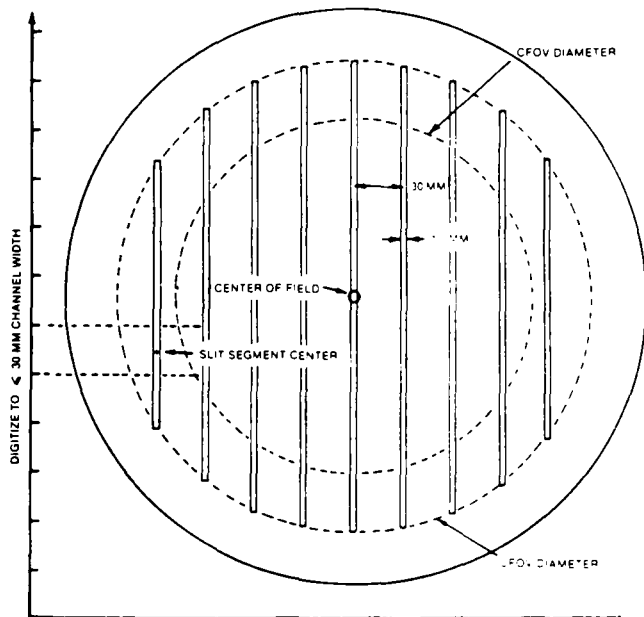


FIG. 2. Design specifications of the NEMA slit mask.

is collimated into an image of nine line sources of equal width and separated distance. A profile across the image will yield a series of curves that may be converted from pixel width to effective millimeter separation. From this data, quantitative indices can be calculated and recorded for future comparison. If the slit mask is not available, the routine use of bar phantoms will at least provide a visual index to a system's resolution performance, but a pair of straight, thin, well collimated capillary tubes, parallel and 10 mm apart will yield workable profiles.

Again, using profile software, a histogram is placed through the line source image acquired from two capillary tubes, generating two curves (Fig. 3). The number of pixels separating each of the peaks is determined and recorded with this actual distance separating the parallel tubes. The FWHM in pixels is calculated by determining the number of pixels separating the ascending and descending points that are half of the maximum count of the peak. The FWHM in millimeters may be determined by converting pixels into millimeters by dividing the recorded pixels separating the peaks by the true distance between the tubes. This factor is then multiplied by the pixel

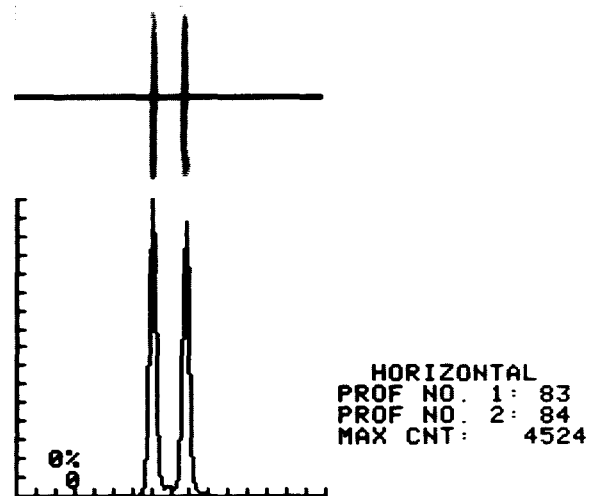


FIG. 3. Using profile algorithms, line spread functions are generated from two imaged capillary tubes for analysis of FWHM and FWTM by determining the number of pixels separating those points at half the maximum counts of the peak.

FWHM to yield a FWHM in millimeters.

Spatial Linearity. The ability of the system to convert a straight line source into a straight line image is considered spatial linearity. If the NEMA slit mask is used, a simple collection of an image in the X axis, and repeated in the Y axis will provide a series of straight lines across the field of view in two directions. An adequate length of butterfly IV tubing, filled with ^{99m}Tc , and stretched to a straight line will also provide some quantifiable index to spatial linearity should the slit mask not be available. The pixel variance of a line from right to left and from one end to another may be quantified and recorded (Fig. 4). Deviations of the peak position from

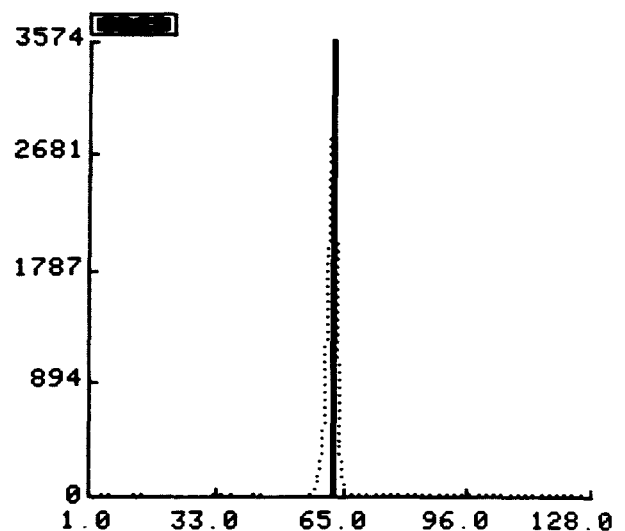


FIG. 4. Spatial linearity of a camera system determined by calculating the pixel shift of a straight line source from one end to the other.

the true location of the center of the line source is a measure of the deviation from linearity. Subjective evaluations may be conducted with a bar phantom.

Energy Resolution. Energy resolution is a measure of a system's ability to separately distinguish the energies of two gamma rays that differ only slightly in energy. It is calculated in % FWHM. Most modern cameras provide an energy spectrum display that allows the user to distinguish the acquired radionuclide's energy peak and spread. If the spread, in keV, at half the maximum of the peak is determined, divided by the energy of the collected source, and multiplied by 100, the % FWHM will be available for recording. For example, this may be done manually for ^{99m}Tc by plotting the counts from the ratemeter as a function of a one-channel window starting at 120 keV and continuing through 160 keV, then calculating a FWHM from the maximum and half maximum points of the curve. This result is then divided by 140 keV and multiplied by 100 to yield a % FWHM.

Count Loss Versus Count Rate. Also called dead time, this parameter is a measure of the system's ability to complete processing of one event and move on to another. A useful test to perform at the time of installation, it is of little practical value for routine studies employing standard patient doses. For example, it may be of some importance in testing equipment designed specifically for first-pass cardiac studies using a 30-mCi bolus of activity.

Extrinsic Measurements

System Sensitivity. The measure of the number of detected counts per unit source activity is an extrinsic test that evaluates the count rate performance of individual collimators. A known amount of activity is placed in a small volume of water, just covering the bottom of a culture dish, and the count rate is observed and recorded as cps/ μCi .

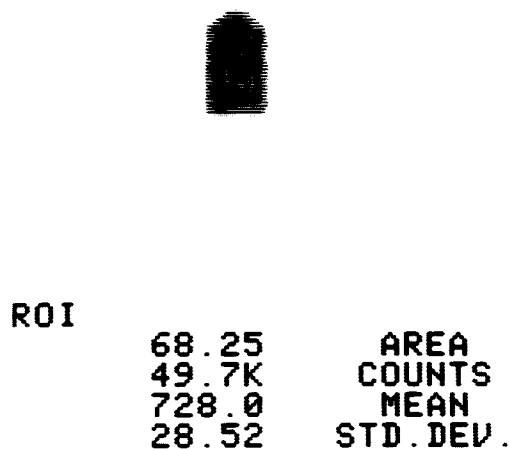


FIG. 5. Sensitivity variations as a function of acquisition angle may be calculated by monitoring the count variations of a sealed source (usually a ^{57}Co flood source) collected at four consecutive 90° angles. If a ^{57}Co source is not available, a ^{99m}Tc source may be used as demonstrated above.

Sensitivity Variation versus Angle. Variation of the angle of the camera detector should not result in sensitivity alterations. A test to verify this may be conducted by measuring a uniform, sealed source taped to the collimator face and imaged at four consecutive 90° angles. A measure of count variation will provide an indication of the system sensitivity as a function of angulation (Fig. 5).

Resolution versus Distance. Quarterly acquisition and analysis of line sources at varying distances from the collimator will provide a time related index of possible resolution degradation. This measurement is of particular importance in SPECT, for the greatest detriments to acceptable resolution studies are distance and attenuation.

A 1-mm diameter capillary tube is filled with high specific activity of ^{99m}Tc and imaged at 0, 2, 5, 10, and 20 cms in air and water. Profiles are placed through the line sources and resultant FWHMs determined. Figure 6 demonstrates the

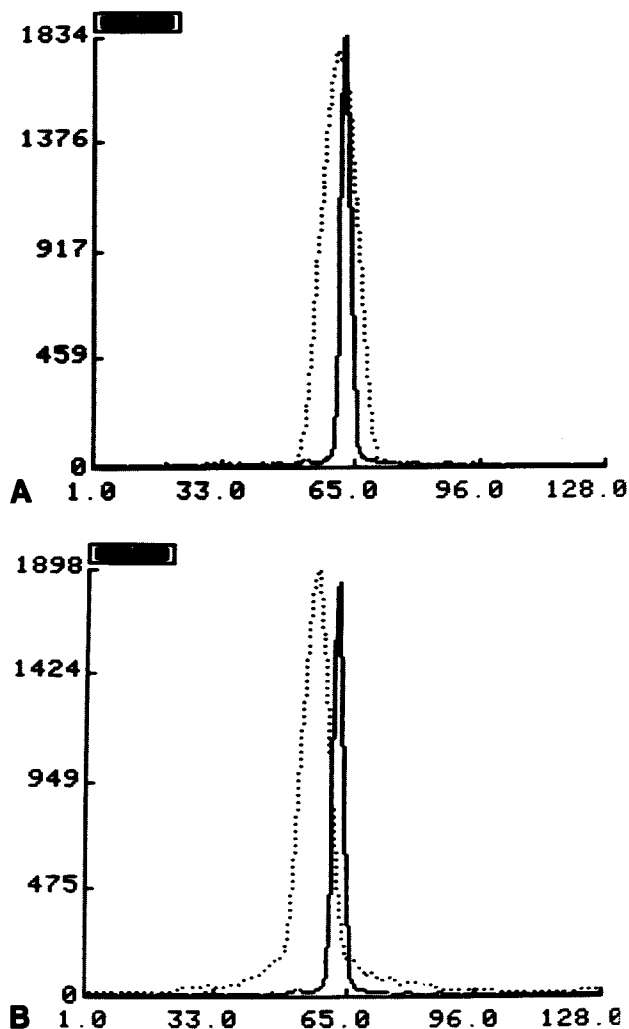


FIG. 6. Line spread functions (LSF) showing effects of (A) distance, in which solid line represents LSF at detector surface and dotted plot represents LSF at 20 cm, and (B) attenuation on resolution where solid lines represent LSF in air and dotted line is LSF in 10 cm depth of water.

broadening effects of distance and attenuation on the line spread function as a result of distance and attenuation.

Positional Variations versus Angle. The reconstruction process of SPECT is dependent on a reproducible image independent of the detector acquisition angle. Verification of this characteristic may be conducted by placing five point sources on the collimator surface in an appropriately spaced cross fashion and monitoring their positional variances as a function of the rotation process. This may be accomplished by reviewing the complete set of projections in a cinematic mode, reviewing the sinogram available on many systems during the image reconstruction process, or determining the pixel location, and resultant shift, from the individual projections using

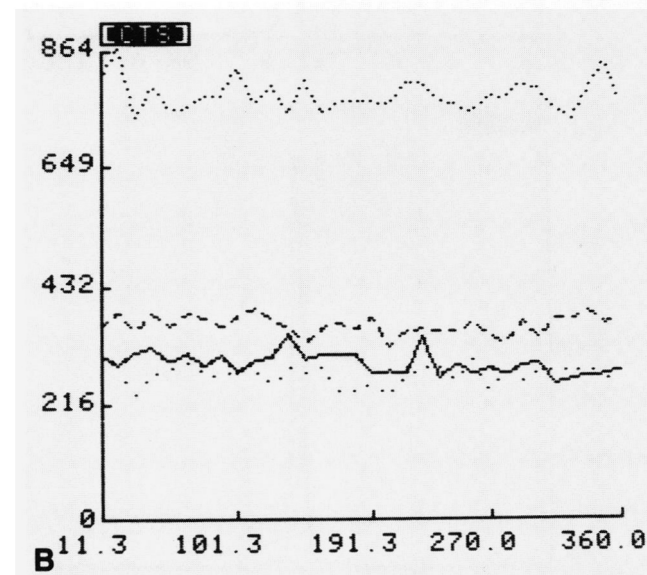
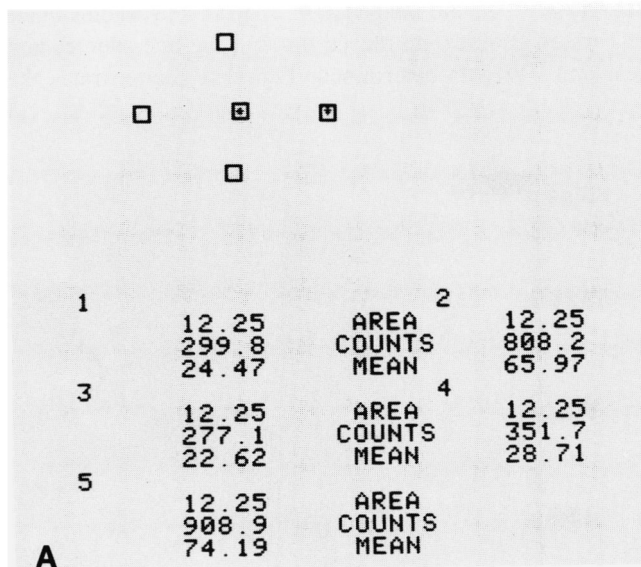


FIG. 7. (A) Position variations as a function of acquisition angle determined from the SPECT collection of five point sources taped to the collimator face. (B) Shifts in position may be calculated from the curves generated from standard dynamic analysis software. If ROI is smaller than the point source and the source varies, the counts in the curve will drop to zero.

pixel location software. Positional placement as a function of angle may also use a curve generating routine plotting activity as a function of angulation (Fig. 7) and should be recorded and conducted quarterly.

Reconstructed Spatial Resolution. Cross sectional images produced with SPECT have an inherently poor resolution due to many factors, including distance, attenuation, energy resolution, and the reconstruction process. Recording a base line FWHM at the time of installation, by collecting and analyzing a line source (Fig. 8), will allow the user to monitor any changes in this parameter over a period of time. This procedure should be repeated quarterly with identical collection parameters and recorded for changes that might warrant a service call.

Collimator Leakage. Any discrepancy in the planar image will cause significant artifact generation as a product of the reconstruction process. Damaged collimator septa will produce areas of discrete increased or decreased activity that will be reproduced in a circular pattern on the reconstructed image. The physical examination of the collimator, its mounting, and the detector's general rotational movement will provide early warning signs to potentially poor reconstructed images. Visual study of the 30-million count flood image used in SPECT uniformity correction may also provide information on otherwise camouflaged problems (Fig. 9A) that will amplify through the reconstruction process into serious artifact (Fig. 9B).

Collimator Alignment. In the ideal SPECT system, opposing projections should be exact mirrors of one another. A number of factors prevent this from being so, the least of which is the fact that the detector assembly is simply a massive amount of weight to move around in 360°. Thus, the possibility of a given collimator septa being in exact alignment with itself in an opposite view are extremely small. Small variances may be effectively dealt with using center of rotation (COR) corrections. Software provided by the manufacturer will effectively

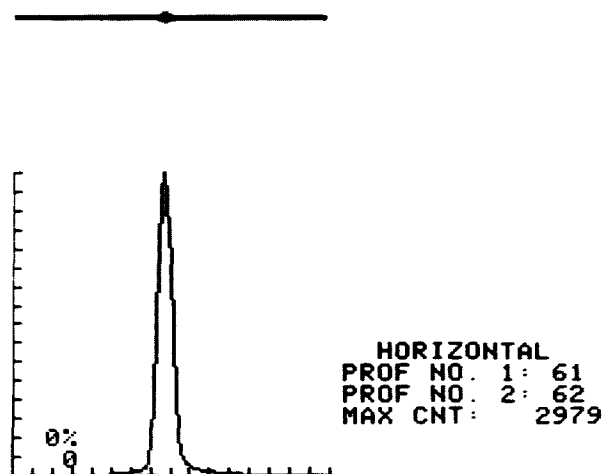


FIG. 8. Line spread function of a reconstructed SPECT acquired line source. Resultant FWHM is recorded for future comparison.

calculate and correct for these alignment discrepancies, provided that they are within a workable range. If routine monitoring of COR data reveals a gradual shift in acquired source placement, service should be notified, as mechanical and/or electronic problems have arisen. Sudden or one time erratic COR errors are probably indicative of poor collimator mounting, or more likely, point source movement during the COR collection process.

Reconstructed Image Quality. The final product of any SPECT acquisition and processing procedure is subject to a

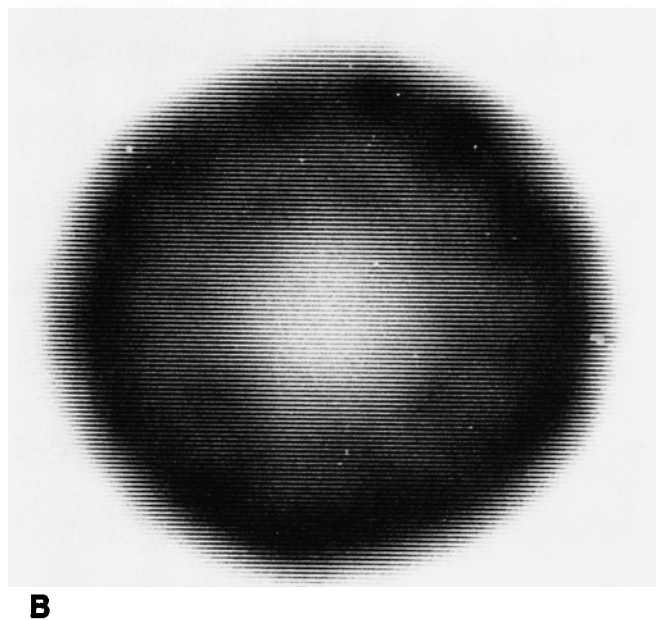
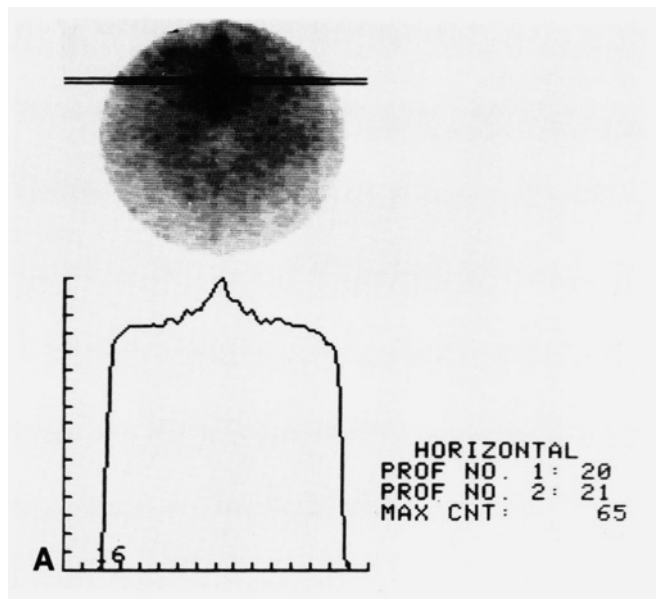


FIG. 9. (A) Image and histogram study of a 30-million count extrinsic flood revealing a vertical linear source of increased activity, and (B) the resultant reconstructed cold artifact in the transaxial view of a uniform source, corrected with the flood source in Fig. 9A.

host of potential problems and errors. Upon completion of installation, the user should perform two phantom studies (any number of commercially available cylindrical phantoms with hot and cold rods will do), under both ideal physical conditions and realistic clinical conditions. This overall phantom test should be conducted quarterly, with the results of resolution, contrast, and uniformity compared and recorded. Figure 10A demonstrates the resolution capabilities of a five-year-old rotating camera system, whose input acquisition parameters were at the extreme of ideal. The rotational arc was as close as physically possible to the target. The acquisition time was as long as necessary to collect millions of counts per projection, and a high resolution matrix with a maximum number of projections was instituted. The resultant transaxial image was logged for future comparison. Figure 10B reveals the impact of clinical distances, collection times, and reduced matrix sizes. Again, these transaxial images are saved for later reference.

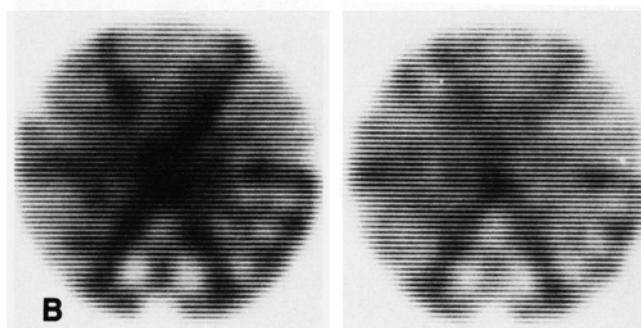
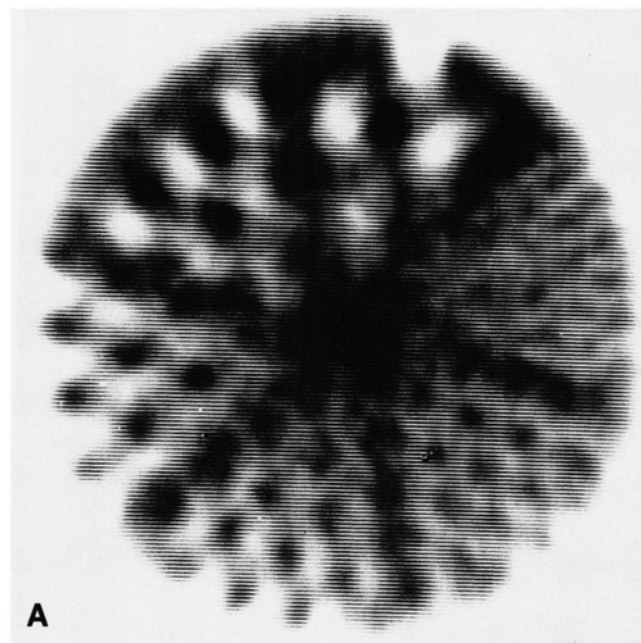


FIG. 10. (A) Reconstruction of a cylindrical phantom with cold rods collected under ideal acquisition parameters, and (B) the same source collected with typical clinical parameters.

OVERVIEW

The degree of sophistication in today's nuclear medicine imaging systems has placed a great deal of trust by the user on the manufacturer. Holding the vendor to published claims remains the luxury of those consumers with the time and expertise to conduct lengthy, involved testing. Thus, the institution without the benefit of a physicist or advanced technologist, are at the mercy of their vendor. A number of articles in the literature have addressed the practicality of NEMA testing and routine quality control (3-7), but there is little solace to the user untrained in these protocols. It, therefore, is necessary for the nuclear medicine community to take the initiative and make the expenditures to ensure the proper operating performance of their systems. As described in this and other texts (8,9), the bulk of testing procedures for SPECT systems do not require advanced training and extremely expensive test instruments. The proper training, with the correct equipment, will place virtually any technologist in the position of monitoring a vendor's claim. The buyer with the apathetic approach to camera performance, simply reaffirms the old adage, "Let the buyer beware."

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