An Overview of PET Quality Assurance Procedures: Part 1

Patricia Keim

Downstate Clinical PET Center, Methodist Medical Center, Peoria, Illinois

Objective: In order to ensure reliable image creation from data provided by a PET system, a comprehensive quality assurance program should be adopted.
Methods: Minimum requirements for a quality assurance program should consist of a daily test of the scanner under normal working conditions and periodic recalibration of the scanner to guarantee correct normalization.
Results: Analysis of additional tests of spatial and axial resolution, count rate performance, counting efficiency, and statistical image uniformity will enhance the quality assurance program.
Conclusion: Quality assurance programs for PET scanners should be individualized to each site.
Key Words: Quality assurance, PET, quality control.

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To ensure good, reliable image creation from data provided by a PET system, a comprehensive quality assurance program should be adopted. Minimum requirements for the quality assurance program should consist of a daily check, to test the scanner under normal working conditions, and periodic recalibration to guarantee correct normalization. Additional tests to measure spatial and axial resolution, count rate performance, counting efficiency (sensitivity), and statistical image uniformity could be included in the program to ensure the scanner is performing within the manufacturer's specifications. These additional tests can be very time-consuming. Busy departments may have to limit the number and frequency of these tests.

The procedures described below for use with Siemens' ECAT 951/31 scanner (Siemens Medical Systems, Inc., Hoffman Estates, IL) can be adapted to any PET system to evaluate the functionality of the equipment. In the future, guidelines or standards may be developed to standardize requirements for PET equipment.

A thorough, comprehensive quality assurance program is ideal, but such a program is not always practical. Patient load and the variety of scans performed often determine how much time a site can commit to quality assurance. Therefore, quality assurance programs should be individualized to each site. This guide seeks to familiarize technologists with the quality control and acceptance testing specifications of PET, so that technologists may develop the best program for their sites.

For reprints contact: Patricia Keim, Downstate Clinical PET Center, Methodist Medical Center, 221 N.E. Glen Oak, Peoria, IL 61636.

SCANNER HARDWARE

Each generation of PET scanners has different detector hardware. Each plane consists of a continuous circle of crystals, while a ring is several crystals in width. Our single-ring scanner is eight crystals wide, with 256 crystals needed to form one plane. A single-ring system has eight direct planes and seven cross planes for a total of fifteen planes. Additional rings can be added to increase the field of view. Newer scanners have a larger number of planes and crystals.

DAILY QUALITY CONTROL

A daily quality assurance scan should test the scanner under normal, routine conditions of use (*1*). The scan should provide the operator with information regarding the system's operation and alert the operator to any developing problems. The scan data will be displayed in an image known as a sinogram (Fig. 1). The daily quality control sinograms are reviewed for nonuniformity. Through review and recognition of the abnormal defects in the sinograms, the technologist can help identify problems in hardware and software functions (*2*).

Each sinogram consists of numerous overlapping lines, called lines of response, which give the location of radioactivity. The lines are formed from the flight pattern of true coincident counts. A true coincident count occurs when two photons from the same annihilation reaction strike the opposing crystals within a specified time frame. The time frame is referred to as the coincidence window. A coincidence window is usually between 8 and 22 nsec. Our scanner has a fixed coincidence window of 12 nsec.

Direct planes are formed when a true coincident count forms a line of response directly within the same ring of crystals. A cross plane is formed when the lines of response

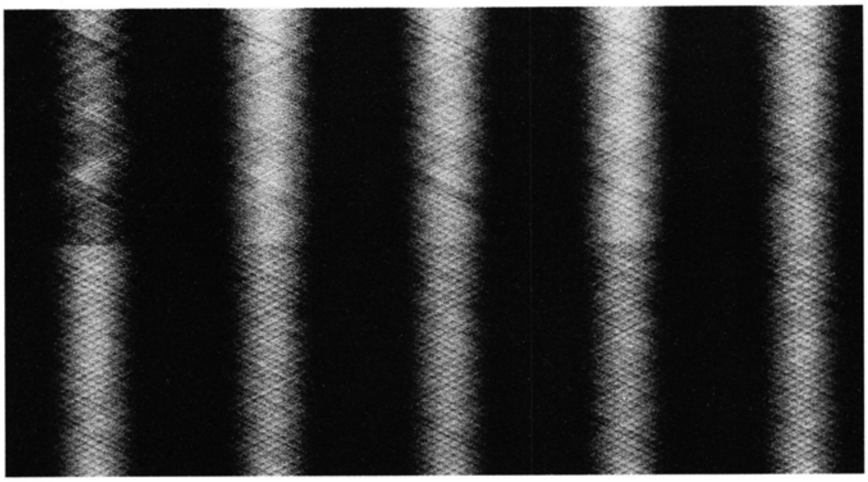

FIG. 1. Sinograms from a daily quality control scan. These are sinograms of first ten planes.

cross over to the neighboring ring of crystals (Fig. 2). A sinogram of numerous lines of response is created for each direct and cross plane (*3*).

Each true coincident count is represented by a line of response in the sinogram that is unique to each count. With the assistance of a computer software program, the pair of detectors that identified this photon can be identified (Fig. 3).

Daily quality control scans are acquired by using a long-lived radioactive source such as germanium-68 (Table 1). There are a number of different scanners and several different types of sources available for daily quality control scans. Our system uses a rotating plane source (Table 2) (Fig. 4). This source is mounted by brackets into the center of the gantry and automatically rotated during the entire length of the scan (Fig. 5). The rotation allows for even radioactive distribution to the crystals so that the detectors' response will be homogeneous and produce a uniform sinogram (*4,5*).

WEEKLY QUALITY CONTROL

A normalization scan is applied to all acquired scans. A lack of proper normalization can lead to serious artifacts in the images (*6*) if there are poor counting statistics. The operator can fine-tune the detector by acquiring system calibration, plane efficiency, and normalization scans (*7*).

System Calibration

System calibration sets the voltage of the photomultiplier tubes to adjust the gains and energy thresholds. This provides a uniform response in the crystals to the average pulse height of the 511-keV electromagnetic energy peak. The peak is centered between the lower level discriminator (LLD), which is set at 250, and the upper level discriminator (ULD), which is set at 850. Each bucket of detectors (four aligned detector units) calibrates independently of the others. Each detector block (a detector unit of four photomultiplier tubes) within a bucket, compares itself for a uniform

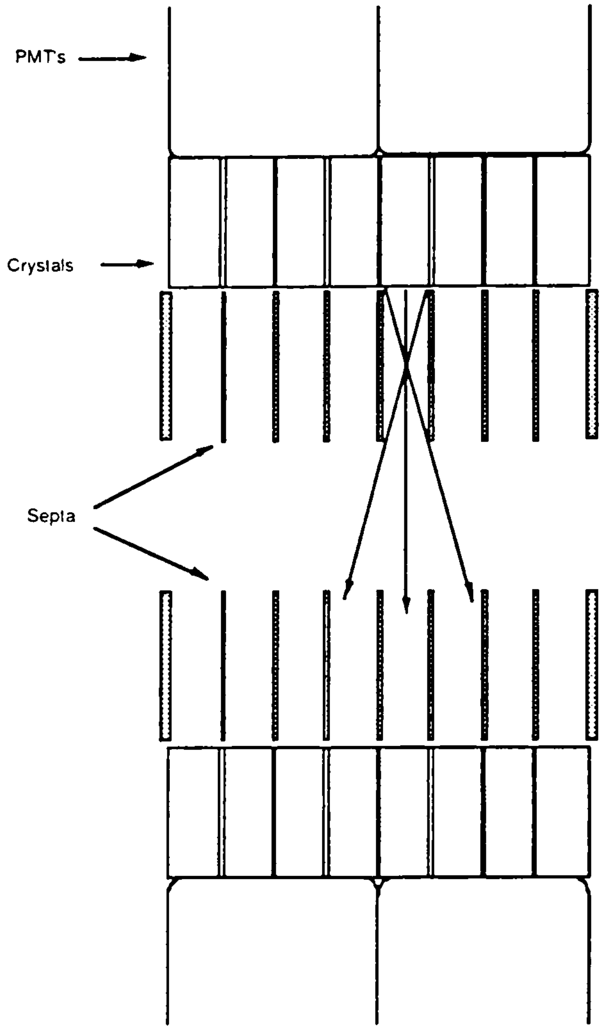

FIG. 2. Cross-over lines of response to neighboring planes. Reprinted by permission of Reference 4.

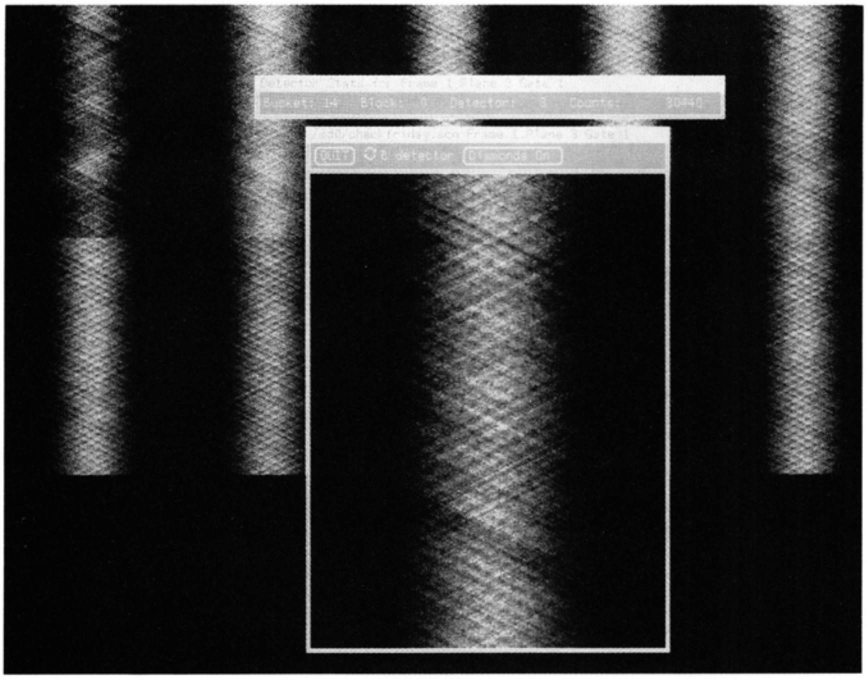

FIG. 3. Sinograms with special software to help locate a bad bucket or block.

TABLE 1. Quality Assurance Parameters

Procedure	Acquisition	Activity	Frequency
Daily	2000 cts/pl	^{68}Ge plane source	every working day
Normalization	total time 9 hr	^{68}Ge plane source	weekly*
Calibration	90 min†	^{18}F 0.2–0.25 μCi/ml (5–6 mCi) in the uniform phantom	monthly*‡
Plane efficiency	20 min†	^{18}F 0.2–0.25 μCi/ml (5–6 mCi) in the uniform phantom	monthly*‡
Spatial resolution	500,000 true cts/pl 0 and 10 cm × axis offset 5 min stationary† 20 min wobble†	^{18}F 500–1000 μCi in the line-source needle phantom	quarterly
Axial resolution	196 steps, 5-sec acq/step 0 and 10-cm offset 42 min†	^{18}F 200–500 μCi on cotton tip needle phantom	quarterly
Count rate performance	total time, 12 hr	^{18}F 5 μCi/ml (40–60 mCi) uniform phantom	quarterly
Counting efficiency	65,000 true cts/pl 20 min†	^{18}F 1–2 mCi in the uniform phantom	quarterly
Image uniformity	500,000,000 true cts 4 hr†	^{18}F 0.2–0.25 μCi (5–6 mCi) uniform phantom	quarterly

*Also after service or any change in hardware.

†Approximate amount of time scan will take.

‡More often if the system quality data sheet is outside of the s.d.

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TABLE 2. Radioactive Source Phantoms

Phantom	Description	Radionuclide
Uniform distribution phantom	Low absorption plastic, 20 cm long by 20 cm diameter, 0.5-cm wall thickness, holds 6283 ml of fluid, fillable.	Fluorine-18 is a positron emitter with a 109-min half-life. It is readily available for use in a phantom at most on-site PET facilities.
Plane phantom	Rectangular-shaped holder with an activity area 59.8 cm long by 7.7 cm wide and 6 mm thick, which holds 269.1 ml.	Germanium-68 is a long-lived positron emitter that is difficult to work with. The plane source comes as a sealed source from a manufacturer and is shipped to an on-site facility. It has 1–3 mCi of activity.
Line source phantom	Surgical needle of 14-gauge stainless steel that has one end sealed and the other end open with a screw cap to seal. The needle is 12.0 cm long and holds 0.135 ml.	Fluorine-18, which is used to fill the needle, is usually on-site and readily available.
Point source	14-gauge needle, open on both ends with a screw cap to seal one end. It is 12 cm long. A small amount of cotton is used in the open tip to absorb the radioactivity to make a small point source.	Fluorine-18 is used as the radioactive material.

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response and a physical distribution of the activity range with acceptable variation in the expected actual response ratio (*4*). If a detector in a block is bad, the entire block uniformity will be decreased, indicating a problem.

The system calibration scan (Table 1) requires that the uniform distribution phantom (Table 2), (Fig. 6) be placed in a phantom holder that slides into the patient head-holder bracket (Fig. 7). This allows for even attenuation around the phantom. The phantom should be in the center of the field of view.

Plane Efficiency

The plane efficiency scan may be acquired immediately after the system is calibrated because it also requires the uniform distribution phantom, located in the center of the field of view (Table 1). An acquisition is performed for 20–30 min. The plane efficiency procedure checks for plane-to-plane variations and efficiency. The computer applies a multiplication factor to average the plane's responses to decrease natural plane-to-plane variances. This results in a uniform image. Plane efficiency may be performed immediately after the system calibration using the uniform distribution phantom (Table 2).

Normalization

The normalization corrects for individual crystal sensitivity to the lines of response, within a block, from a source of radioactivity, thus balancing the efficiency of the detector pairs. Normalization measures the efficiency of each detector's line of response and applies the necessary multiplication factor to adjust each block and bring it into line with the average detector's response. This multiplication factor is applied to every scan after acquisition to minimize the discrepancy between the various detector pairs and to ensure that the reconstructed image contains as few variations due to hardware differences as possible (*6*).

Depending on the model of scanner used, the normalization scan can take from one hour to several hours to perform. For scanners that require a longer normalization, the

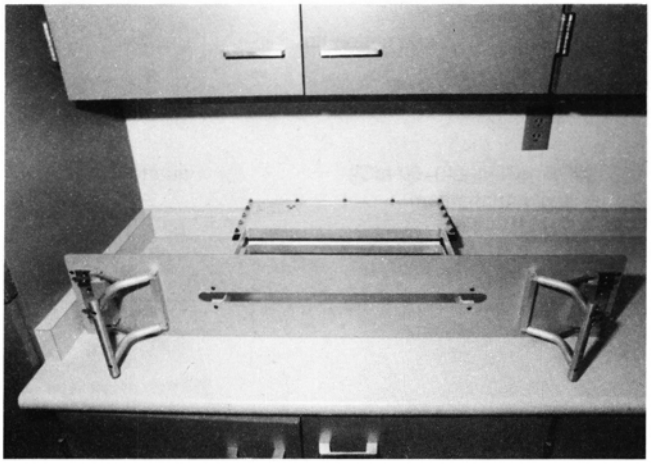

FIG. 4. Plane source of germanium-68.

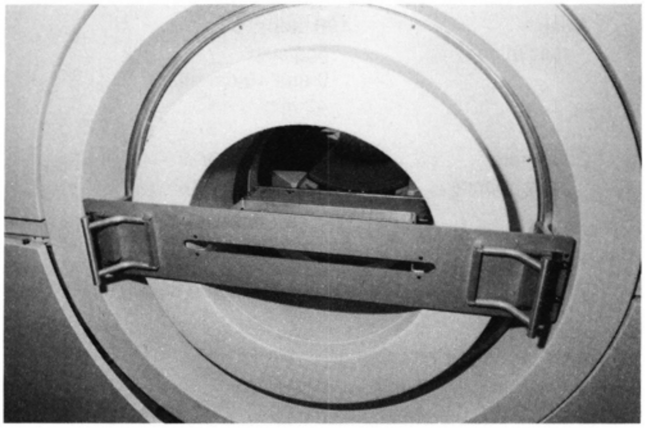

FIG. 5. Plane source mounted into field-of-view in scanner by brackets that are located on gantry.

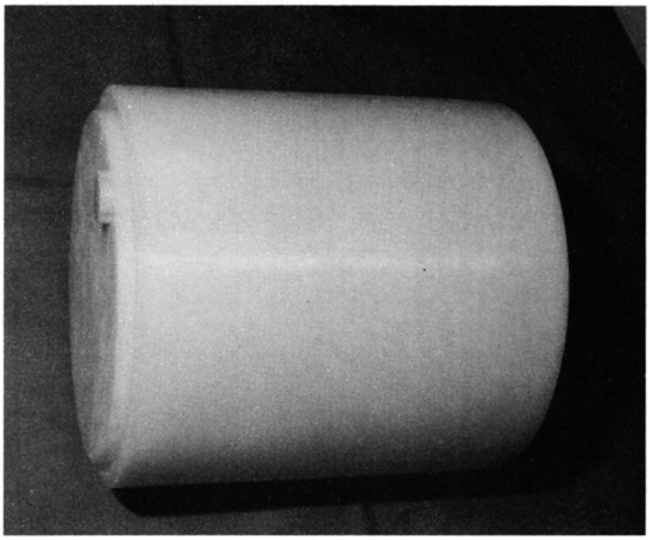

FIG. 6. Fillable uniform phantom.

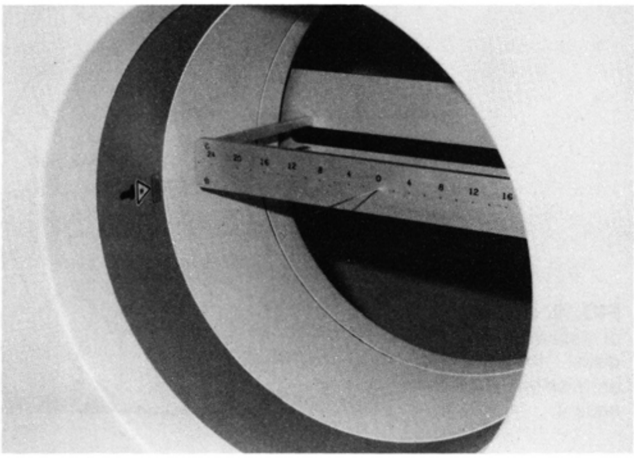

FIG. 8. Line-source needle is mounted into field of view in center of scanner in gantry. Source can be moved to other locations on X axis.

data may be acquired overnight so that each working day can be used to image patients (Table 2).

The calibration and plane efficiency scans do not have to be done weekly if the daily quality control results stay well within proper limits. These two procedures can be performed monthly. Normalization should be performed every week. If calibration and efficiency scanning are performed, a normalization scan must immediately follow. All three tests should be completed after any change in scanner hardware.

ACCEPTANCE TESTS

In order to authenticate the integrity of the scanner and assure compliance with the manufacturer's specifications, acceptance tests are performed after the scanner is installed. These tests may include measurement of spatial and axial resolution, counting efficiency, image uniformity, count rate performance, and repeatability. The results are then compared to the scanner's performance at the factory. These tests can be periodically performed and compared to the acceptance test results to ensure that the scanner is consistent in its performance.

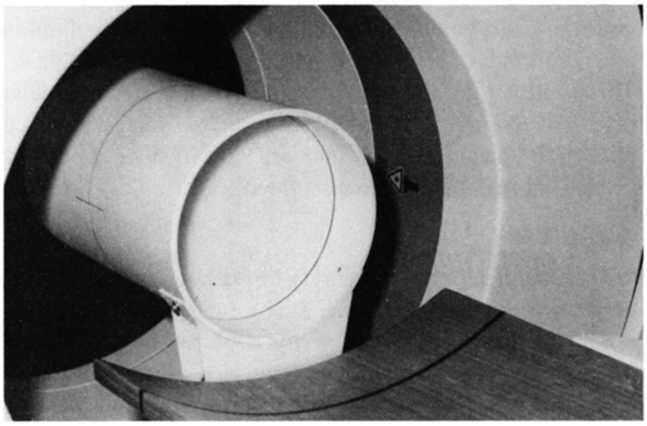

FIG. 7. Uniform phantom mounted into scanner's field of view in gantry in holder that allows even attenuation.

Spatial Resolution

Spatial resolution is a measure of the scanner's ability to accurately distinguish between two close objects and to observe their details (*8*). Spatial resolution is the primary limitation of PET imaging (*9*). A line-source needle (Table 1) filled with a positron emitter and placed axially through the field of view will allow calculation of the line spread function through all imaging planes (Fig. 8). A loss in spatial resolution will occur as the source is moved away from the center of the field of view (*6*). At least two scans are performed for the spatial resolution test, one in the center of the field of view and one 10 cm or more from the center in either the X or Y direction (Table 2). The full width at half maximum (FWHM) and full width at tenth maximum (FWTM) of the line-spread function is calculated by measuring the width of the curves at 50% and 10% of the peaks, respectively. The FWHM is the most important measurement since the count rate must fall to less than 50% in the area between two lesions before the scanner will be able to differentiate between the two lesions (*10*).

Axial Resolution

Axial resolution is a measure of the scanner's ability to resolve lesions in the Z axis direction. This test measures the FWHM response of the radioactive source and the position uniformity of each plane relative to the other planes. The important factors affecting the axial resolution are the geometry and material of the intrasepta (*6*). The septa are solid rings of lead or other attenuating material that fit between, and separate, each of the rings of crystals (Fig. 9). Septa reduce the in-plane and out-of-plane scatter, reducing the singles count rates and improving the ratio of coincident-to-noncoincident events (Fig. 10), (*11*).

To test axial resolution, a small point source of positron-emitting isotope is needed (Table 1). A minimum of two positions are acquired, at the center of the field of view and

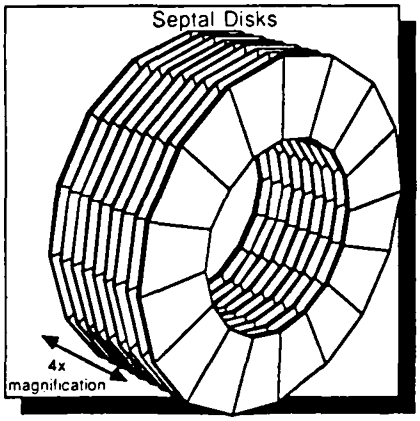

FIG. 9. Circular array of assembly of septal disks. Reprinted by permission of Reference 4.

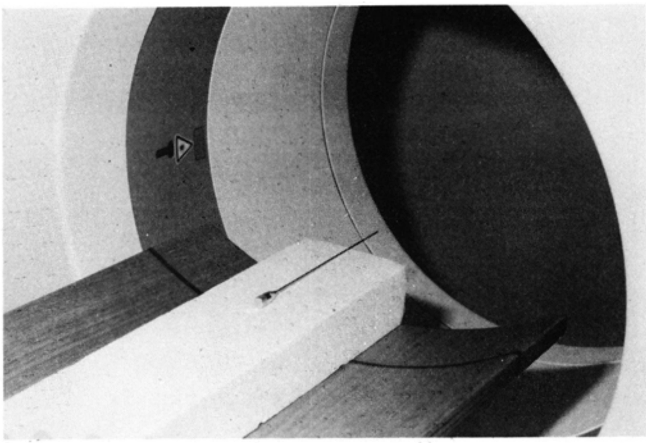

FIG. 11. Point source needle placed on patient couch for axial resolution test.

at a 10-cm to 20-cm offset (Fig. 11) (Table 2). The source is attached to the patient couch and stepped through the field of view in small (0.5-mm–0.7-mm) increments. A short scan lasting 5–10 sec is acquired in each position. Partial volume effects may be determined by averaging the peak-to-valley distance of the line-spread function for each point (*1*). A large partial volume ratio can result in an underestimation of the radionuclide concentration in a structure that is smaller than the width of the line-spread function on the reconstructed image (*12*). The line-spread function for the planes should cross the FWHM point (Fig. 12).

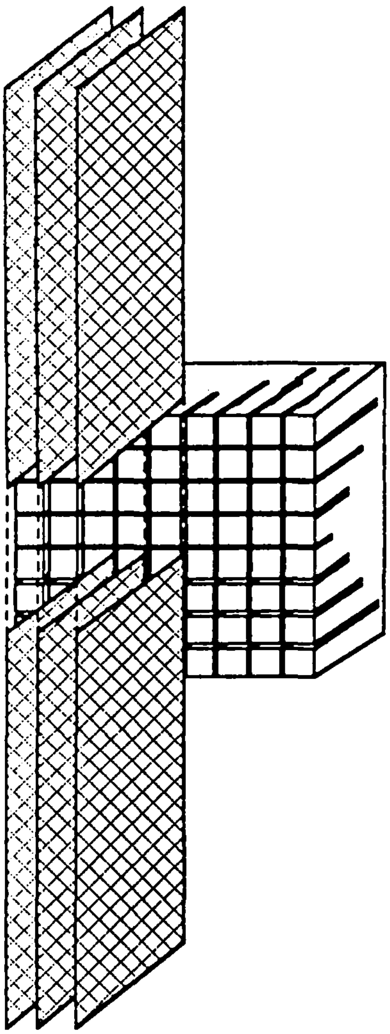

FIG. 10. Septal disks as they appear placed within crystal blocks. Reprinted by permission of Reference 4.

Counting Efficiency

The counting efficiency scan tests the scanner's sensitivity to the dual 511-keV gamma rays. A count of true coincident events, acquired over a known amount of time, must be obtained before a counting efficiency can be calculated (*12*). The efficiency scan uses the uniform distribution phantom filled with a known amount of activity (Table 2).

Image Uniformity

Image uniformity is the scanner's ability to accurately reproduce the activity within the entire field of view. Image uniformity is used to prove that the calibration and normalization procedures functioned correctly (*6*). Image uniformity uses corrections for normalization, dead-time, randoms, scatter, and attenuation to measure the deviation in the reconstructed image from a uniform response. These deviations are due to statistical fluctuations from the scanner's hardware and software (*1*).

The procedure for measuring image uniformity uses the uniform distribution phantom placed in the distribution phantom holder and centered in the field of view (Table 2). The results of the uniformity are based on a 15-cm circular region of interest inside the reconstructed image for each plane. The mean and the standard deviation of the pixels inside that region are then computed.

Count Rate

The count rate test measures the scanner's ability to accurately correct for dead-time over a range of radioactivity. A known amount of radioactivity is placed in the uniform distribution phantom and allowed to decay over a long period. The data are then analyzed to determine how well the scanner handles radioactivity from high to low concentrations.

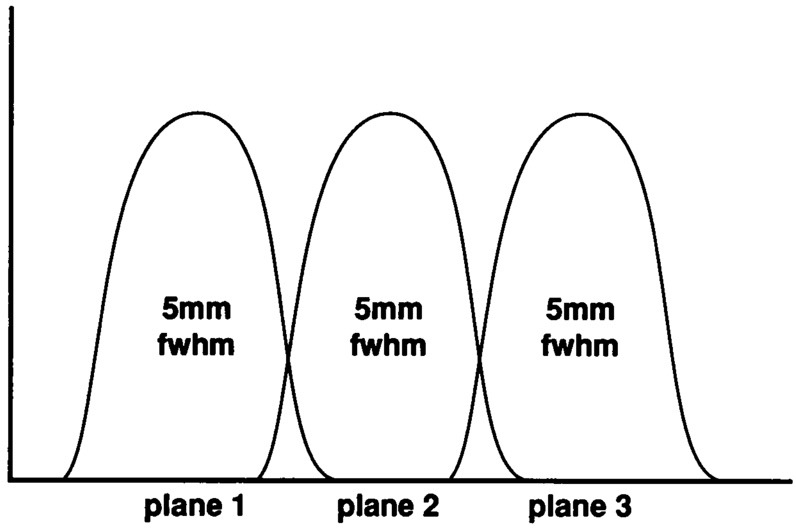

FIG. 12. Axial response curves for each plane.

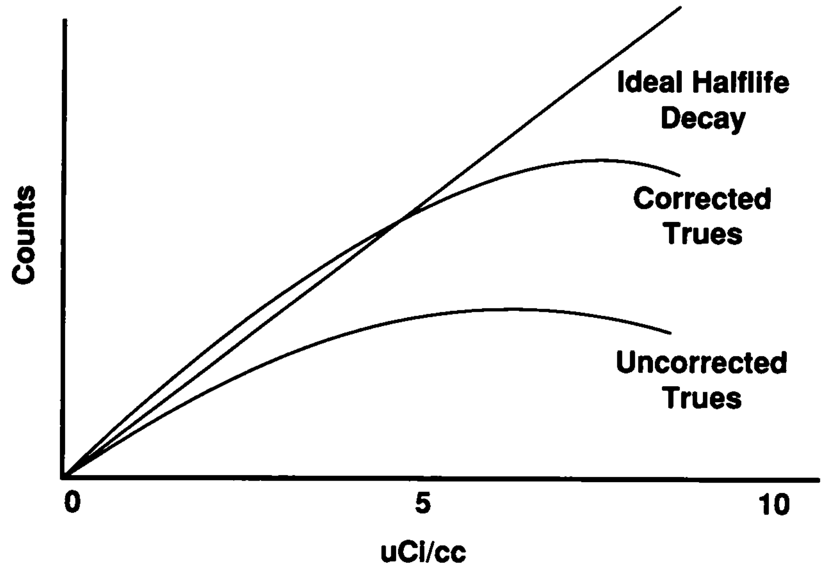

FIG. 13. Count rate test graph of counting statistics from zero activity to 10 μCi per cc.

The uniform distribution phantom is placed in the distribution phantom holder and centered in the field of view (Table 2). The count rate program will direct the scanner to begin a 5-min acquisition every 25 min for 12 hr. All true coincident counts are collected and recorded for each acquisition (Fig. 13).

CONCLUSION

This is the first part of a comprehensive overview of PET quality assurance procedures. These tests are mainly used on Siemen's Ecat scanners but serve as a very useful tool for all PET users. A daily quality control scan is necessary to check the equipment for problems before any patient scans are acquired. Additional tests for spatial and axial resolution, count rate performance, efficiency, and statistical image uniformity should be performed at set intervals and results reviewed to make certain the equipment is functioning at maximum expectations.

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GLOSSARY

Bismuth germanate oxide (BGO): material that comprised the crystals. Has a higher density and atomic number to provide better stopping power for the 511-keV gamma rays.

Block: a detector unit made up of four photomultiplier tubes with a square of sixty-four crystals.

Bucket: four blocks aligned together.

Coincidence detection: the time frame allowed for the PET scanner to detect and record two simultaneous photons travelling in 180° direction.

Cross plane: an image slice that is recorded from coincident detection from a neighboring concentric row of crystals.

Crystal: an individual resolution element. The crystals are made up of bismuth germinate oxide (BGO).

Direct plane: an image slice that is recorded from coincident detection from the same concentric row of crystals.

FWHM: is 50% of the isocount line from a point source.

FWTM: is 10% of the isocount line from a point source.

Intrasepta: is a ring of hardened lead or tungsten disks placed to align with the gaps between the rings of detectors.

Line of Response: the recording of the pathway of the two gamma photons from the same annihilation reaction.

Line-Spread Function: is the energy curve produced by radioactivity.

Multiples: gamma radiation striking the same crystals currently involved in detecting a true coincident count. This causes confusion as to which detectors recorded the correct event and which is the extra event. This results in the loss of the true count.

Photomultiplier tube: a tube in which small electron currents are amplified by a cascade process employing secondary emission.

Randoms: occur when gamma rays from two or more unrelated events are detected at the same time.

Ring: aligned buckets form a circular detector ring.

Scatter: radiation that is diverted from its original path by some type of collision.

Sinogram: the polar coordinate system used to store a line of responses' angular inclination and radial distance from the field-of-view central axis.

Stationary: the detector ring assembly in the gantry does not move during acquisition.

True coincident counts: gamma radiation from the annihilation reaction that strikes scintillation crystals 180° apart within a specified time frame.

Wobble: the detector ring assembly in the gantry is gently revolved in a circular pattern to double the spatial sampling frequency during acquisition.