SPECT: Quality Control Procedures and Artifact Identification

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Commercially available single photon emission computed tomography (SPECT) cameras require both new calibration and very careful routine quality control procedures. These procedures must be performed properly and regularly to produce artifact-free images. Calibration procedures include field uniformity, center of rotation, pixel size, and camera alignment. Of these, field uniformity is the most important because nonuniformities have a greater effect on tomographic images than on planar images. Calibration procedures for all these SPECT parameters are presented in detail as are quality control procedures that will ensure artifact-free, clinically useful images.

Commercially available rotating scintillation cameras for use in single photon emission computed tomography (SPECT) systems have placed new demands on both the technologist and the equipment to ensure high quality images. Equipment uniformity specifications that are adequate for standard planar imaging are far from adequate for tomographic systems. Likewise, new quality control procedures must be performed accurately and on a routine basis. It must be remembered that tomographic reconstruction algorithms greatly amplify the effect of any statistical or camera nonuniformities in the reconstructed image (*1–5*). This is also true for other camera miscalibrations such as pixel sizing and center of rotation (COR). We will discuss each of the quality control procedures developed at our institution to produce SPECT images that are free from artifact.

There are three etiological groups responsible for artifacts in reconstructed tomographic images: (1) errors in camera calibration and set-up, (2) errors in patient preparation and set-up, and (3) poor or improper choice of computer reconstruction parameters. Once the technologist is able to identify artifacts and their probable sources, he or she can correct the imaging error in future studies or the data processing error in the current study to obtain images that are free from artifact.

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Calibration of SPECT Cameras

Field Uniformity: A uniform camera field response is the single most important factor in obtaining high quality tomographic images. Tomograms obtained with a nonuniform camera will show concentric ring or "bull's-eye" artifacts (Fig. 1). The magnitude of these artifacts has been shown to vary inversely as the square root of the distance from the COR to the nonuniformity and directly with the diameter of the object being imaged (*6*). In other words, field uniformity defects at the COR will have a greater effect than those nearer the edge of the field of view and the bigger the object, the greater the effect.

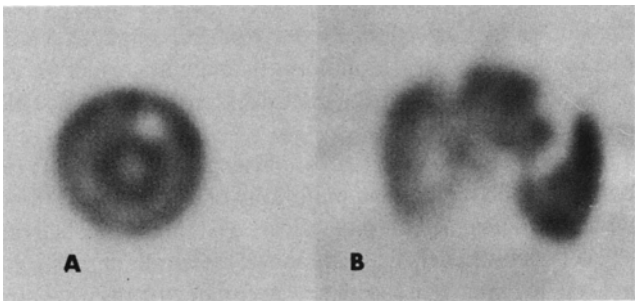

FIG. 1. (A) Bull's-eye or concentric ring artifacts. (B) These artifacts are readily seen on the transaxial liver image, making interpretation impossible.

To demonstrate this point, images of a 31-pixel (19.5 cm) and a 51-pixel (32.1 cm) diameter uniform cylinder were reconstructed from computer simulated projections. Each projection contained a 2% Gaussian nonuniformity with a FWHM of four pixels (i.e., a small, soft defect) located at the COR. The resulting tomograms (Fig. 2) showed a 10% defect in the small cylinder and a 15% defect in the larger cylinder. This implies that uniformity should be controlled to $\pm 0.5\%$ to keep artifacts under 5%. This example, however, does not take into account statistical noise. Assuming our most difficult imaging situation to be liver studies because of the large size of the liver and assuming one million counts per slice to be a reasonable statistical level, we feel that camera uniformity should

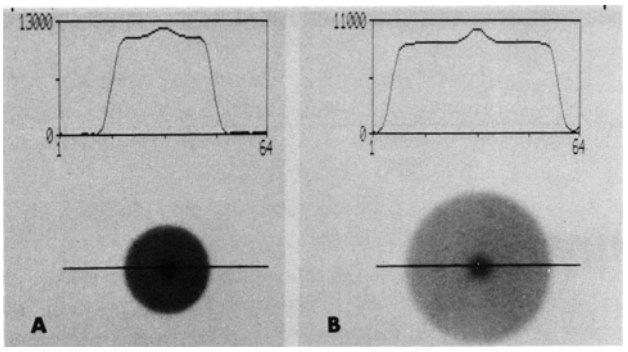

FIG. 2. (A) Computer simulation of 31-pixel diameter cylinder showing the effect of 2% Gaussian nonuniformity with a FWHM of 4 pixels. (B) Simulation showing the effect of the same nonuniformity on a 51-pixel diameter cylinder. Note that magnitude of bull's-eye artifact in reconstructed image increases with the diameter of the object being imaged.

be kept to ±1%. Artifacts caused by residual nonuniformities of response smaller than this will be less than the noise in the final tomograms and thus will not be detectable.

Factors affecting camera uniformity that originate at the detector include: (1) intrinsic nonuniformities of sensitivity and linearity, (2) extrinsic variations caused by the collimator, and (3) variations owing to the effects of local magnetic fields with rotation of the camera. Nonuniformities may also be introduced at the camera-computer interface; e.g., differential nonlinearities in the analog-to-digital converters (ADCs). Because there are so many sources of nonuniformity, we recommend a computer flood correction at the end of the imaging chain for uniformity correction. Properly performed, such a correction will assure ±1% uniformity and will correct for all of the causes of nonuniformity noted, except for magnetic field effects.

The most common source of artifact is inadequate field flood correction. To obtain field uniformity of ±1%, a field flood with a statistical accuracy of at least ±1% must be obtained (*6*). A circular camera face uses about 3000 pixels of a 64 × 64 matrix. To obtain ±1% statistical accuracy, you must acquire 10,000 counts/pixel:

$$\text{i.e.,} \qquad \frac{\sqrt{10000}}{10000} \times 100.$$

The total counts needed is thus equal to 3000 pixels × 10,000 counts/pixel or 30 million counts. A 30 million count flood image acquired using a high resolution collimator and 5-mCi Tc-99m requires 20–30 min to accumulate. However, this is one case where more is better. At the same time, it must be noted that to achieve a statistical accuracy of ±0.5%, a 120 million count flood must be obtained, which can take as long as 2 hr. We consider this too long to be reasonable.

The one case in which no amount of field correction will eliminate camera nonuniformities is when there are variations in field uniformity with rotation due to magnetic fields. Magnetic fields from the earth and nearby electrical equipment cause small, uneven shifts in photomultiplier tube (PMT) gain, which in turn cause the field uniformity to vary as the camera rotates. A field flood taken in one position cannot correct for varying nonuniformities. There are two contributing causes to this problem: (1) inadequate magnetic shielding and (2) improper PMT tuning. Cameras that have nonuniformities caused by inadequate magnetic shielding should not receive final acceptance from the manufacturer until the problem is corrected. Most manufacturers now recognize this problem and inadequate shielding should not be a problem with newer cameras. Some older cameras may, however, not have adequate shielding installed. If you are upgrading a camera to tomographic capability, be sure to check for this. Residual nonuniformity from this cause should be less than 5% and preferably less than 1% with adequate shielding.

The simplest method to prevent variation caused by improper camera tuning is to put the cameras on a regular maintenance schedule. In addition, each SPECT system has a specific method for tuning to ensure maximum performance. This may not be the same tuning technique used for standard gamma cameras, so be sure to inquire if problems persist.

Technique: Obtain a daily 30 million count field flood using a liquid-filled flood source with 5-mCi [^{99m}Tc] pertechnetate to approximate the count rates encountered in clinical studies. Enough of the liquid should be squeezed out so that there are no bulges left on the sides of the flood. To check for flood source bulging, place the flood on a flat surface. Pressure on one corner of the flood should not result in downward motion of the corner. If downward motion is present, it means that too much liquid is in the source. Liquid should be removed until there is no further motion on a flat surface. Our laboratory uses a Nuclear Associates liquid flood phantom with a 45-cm diameter. With the flood source open so that liquid may be added or removed, about 65% of the space should be liquid. The 35% that is air can then be pressed out to obtain a flat field flood. Be sure that all of the air is expelled. Air bubbles in the flood will cause apparent areas of decreased sensitivity, which will in turn create "ring" artifacts in the reconstruction.

It is also very important for the collimator to be in the same orientation for both flood and clinical studies and for the floods to be repeated for different collimators. Correcting a study done with one collimator with a field flood obtained with another collimator is not recommended.

Field flood correction factors are calculated according to the following:

$$F_i = \frac{\text{mean flood counts}}{C_i}$$

where F_i is the correction factor for the ith pixel and C_i the counts in the ith pixel. All projection data must be corrected with this formula before reconstruction begins. The flood correction programs provided by all manufacturers are based on this formula.

Camera uniformity may be checked by imaging a uniform cylinder phantom. We use a water-filled phantom with a diameter of 19 cm and a length of 25 cm containing 10 mCi of Tc-99m. The phantom is imaged obtaining enough counts per projection image to result in one million counts per reconstructed tomographic image (slice). The time required to obtain one million counts/slice is calculated by the following:

$$\frac{1 \text{ million counts}}{\text{slice}} \times \frac{1 \text{ sec}}{\text{counts}} \times \frac{\text{number of slices}}{\text{number of stops}} = X\frac{\text{sec}}{\text{stop}}$$

where:

number of slices = the number of slices necessary to encompass the entire phantom at 1 profile/slice.

number of stops = the number of projection images per 360°.

1 sec/count = the inverse of the counts/sec of the phantom.

After acquiring the data, each projection image is field corrected using a 30 million count flood. Data are then reconstructed using a high resolution convolution filter. Each reconstructed image is then reviewed for concentric ring artifacts. After the initial acceptance testing, this phantom test need only be done once a month, or when a problem is suspected, to check the continuing uniformity of the camera.

Center of Rotation: The COR is the computer's determination of the location of the camera's axis of rotation, which allows each projection image to be properly aligned for backprojection during the reconstruction process. A point source reconstructed with the wrong COR will look like a ring or a doughnut because it was misaligned in each backprojection (Fig. 3). Even small errors in COR determination will result in broadening of a point source. The effect on an organ image would be a loss of resolution or even the introduction of spurious structure. The COR may vary over time because of changes in camera tuning, ADC gain, and ADC offset. Large changes (greater than two pixels) may indicate possible technical errors in the determination or camera malfunction. The COR should be determined at least on a weekly basis and after every camera or computer adjustment or repair. Determining the COR to an accuracy of ± ¼ pixel or better will ensure that no measurable error will occur.

Technique: Place a point source off center and extend it over the edge of the imaging table. A point source off the COR will give a more accurate determination because the technologist will not be summing the same number each time. Extending the source over the edge of the table eliminates attenuation degradation by the table. Position the camera head for a tomographic study and level it using a bubble level. Image the source in two projections 180° apart. Determine the maximum pixel element for each image and calculate the COR according to the following formula:

$$\text{COR} = \frac{P_a + P_b}{2}$$

where P_a and P_b are the maximum pixel element in the two projections. This is another case where more is better. The greater the number of projections, the more accurate the determination. Most manufacturers have algorithms that will calculate this value for as many projections at the camera will acquire. Record the value and the date for each COR determination in a log book.

Pixel Sizing: Pixels (or voxels because in tomography they are really volume elements) may be given "real world" dimensions. These dimensions are needed for determination of the ray lengths in attenuation correction algorithms, for accurate image scaling, and for size and volume determinations. They are subject to drift and variation in the same manner and for the same reasons as the COR. Pixel sizing should be performed each time a COR calibration is performed.

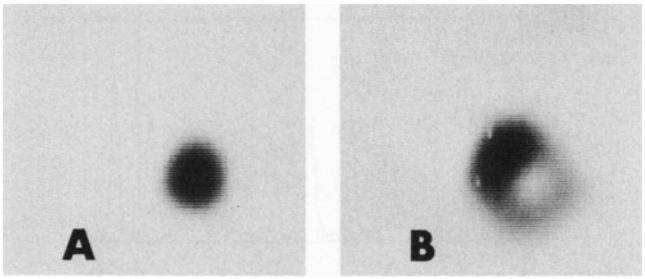

FIG. 3. (A) Reconstruction of a point source using correct center of rotation. (B) The same point source reconstructed using a center of rotation that was 2 pixels from the correct value. Note how incorrect value misaligned projection data causing decreased resolution.

Technique: The easiest method is to use a hole plate backed by a flood or two line sources a known distance apart. The most important factor is that the distances are known. The sources are then imaged for enough time so that well-defined profiles may be obtained (Fig. 4). Images should be acquired on the computer in the same matrix (64 × 64, 128 × 128 etc.) that will be used for tomographic data acquisition. The values of the profile curves should then be examined and the inclusive number of pixels from peak to peak should be determined. The mm/pixel is determined as follows:

$$\frac{D_m}{\text{number of pixels} - 1} = \text{mm/pixel}$$

where D_m is the distance in millimeters from centroid to centroid on the hole plate or from line to line on the line sources. This determination should be made in both the x and y axes and for several places on the camera. The x- and y-axes values should be equal.

Table-Camera Alignment: SPECT transaxial reconstructions assume that the image projections were obtained in planes perpendicular to the axis of rotation of the camera. If the camera head is not parallel to the axis of rotation (leveled) during data acquisition, this assumption is not met. The result of this error is that the reconstructed image is not transaxial but actually contains data from several planes. This problem is not easily detected in the reconstructed image and if it remains undetected, may seriously compromise image resolution (Fig. 5). Therefore, these parameters should be checked before imaging each patient.

Technique: The exact technique will depend on the type of equipment used. The following techniques are used at our institution and could easily be adapted to other systems.

(1) *Camera head parallel to the axis of rotation:* After setting up the patient, the technologist levels the camera using a bubble level. We recommend using this technique even on systems that have built-in head angle encoders; it is an inexpensive insurance against failure of built-in systems.

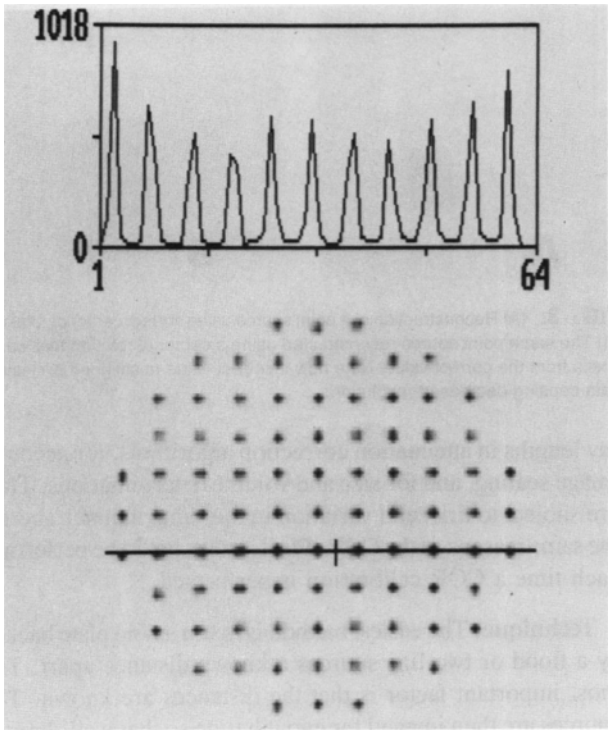

FIG. 4. Profile taken through the computer image of a hole plate. By printing out the values of the profile and counting the pixels from peak to peak inclusively, the pixel size may be determined.

(2) *Imaging table perpendicular to the gantry:* This should be checked by the manufacturer when the camera is installed. At that time, marks (we use adhesive arrows) should be put at the end of the table and the camera head for quick alignment. To check the accuracy of the alignment over a period of time, level the camera head and place it in a lateral or 90° position. Measure the distance from the edge of the table to the camera face. Rotate the camera 180° and measure again at approximately the same place. These values should be the same.

Artifacts in SPECT

In the course of our studies, we have found the liver to be the most difficult organ to image with SPECT because tomograms of large organs such as the liver that cross the COR will show camera nonuniformity artifacts more prominently

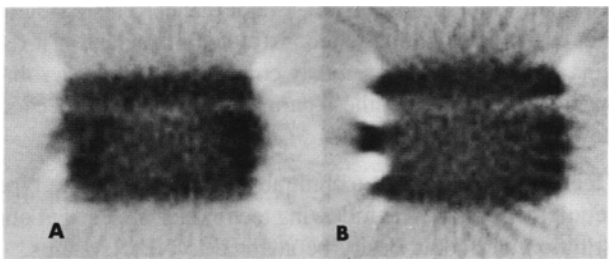

FIG. 5. Decreased resolution due to the camera not being parallel to the axis of rotation (or leveled). The two cylinder phantoms were imaged with (A) camera not level and (B) camera head level. The areas of decreased activity at the end of image (B) are two large metal bolts. They were not visualized at all in image (A) when the camera head was not level or parallel to the axis of rotation.

than small organs such as the heart located away from the COR (*6*). For this reason most of our examples that demonstrate artifacts will be liver images. An example of a normal, properly reconstructed tomogram of the liver is shown in Fig. 6 for reference.

Camera Calibration and Set-Up: The majority of artifact-producing errors in this category have already been discussed at length in the section on quality control procedures. These include (1) bull's-eye or concentric ring artifacts due to nonuniformities and (2) image blurring due to a camera head that was not leveled using a bubble level.

The final artifact in this category is image noise due to insufficient count density (Fig. 7). This appears as mottled areas within the liver, which are difficult to interpret and could be read as decreased liver function. This artifact may be eliminated by imaging for a longer period of time, administering a larger dose, or using a higher sensitivity collimator.

Patient Preparation and Set-Up: The two artifacts that arise during patient preparation and set-up are (1) the "starburst" and (2) arm shadows.

A starburst artifact (Fig. 8) will appear in the reconstructed transaxial image when a subcutaneous injection site is in the image field. The injection site appears as a starburst because it is not in the field of view for all projection images and because it is so intense. It is in some ways analagous to the artifacts seen in x-ray CT images that are caused by surgical clips and other metal objects. The artifact in Fig. 8, which was caused by residual activity in the antecubital fossa, could have been eliminated by positioning the patient's arms over his or her head for the duration of the study.

Arm shadow artifacts occur when the patient's arms are in the field of view during data accumulation. This artifact is most noticeable on liver images (Fig. 9). The arms are clearly seen and at first glance do not seem to cause a problem. The mottled area within the liver, however, is not due to disease but is actually due to the varying and uncorrected attenuation of the arms. This scan is difficult to interpret since one cannot say with any degree of confidence whether the mottling is due to attenuation or disease. For this reason, it is not advantageous to perform SPECT liver studies on patients who are unable to raise their arms over their head for the duration of the study. Although many patients will demur at raising their arms, given proper encouragement, assistance and instruction by the technologist, most patients can tolerate this position for the duration of a study. Given encouragement and instruction, 95% of our patients were able to raise their arms over their heads for the duration of this study.

Poor Choice of Computer Reconstruction Parameters: The large number of reconstruction parameters that are open to manipulation in most SPECT software packages makes it quite easy to introduce errors and produce artifacts during image reconstruction. The artifacts included in this category are image blurring, image noise, and an intense ring at the outer edge of an organ. Fortunately, artifacts that arise from a poor choice of reconstruction parameters may be corrected at any time unlike errors described in the previous two cat-

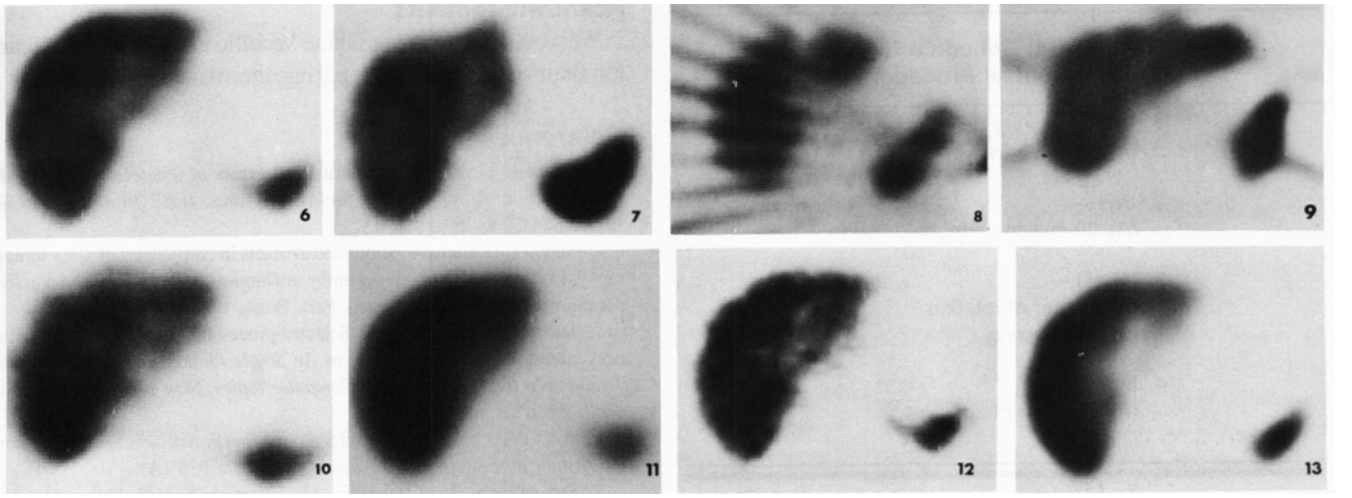

FIG. 6. Normal liver properly reconstructed; there are no artifacts. The areas of decreased activity in the medial portion are normal anatomy (ligamentum teres and portal structures). **FIG. 7.** Image noise due to insufficient count density appears as a mottled effect in interior portion of the liver. **FIG. 8.** Transaxial liver image with starburst artifact. An area of increased activity can be visualized on the right with rays of activity emanating from it. **FIG. 9.** Arm shadows can be seen on each side of this transaxial liver image. Mottling in the liver is due to the uneven attenuation caused by the arms; it is not disease. **FIG. 10.** Image blurring due to the wrong center of rotation. This was reconstructed from the same data as the normal image in Fig. 1. Note loss of resolution of the normal anatomy in medial portion of the liver. **FIG. 11.** Image blurring due to a convolution filter that was too smooth. This is the same image data as in Fig. 1 but normal anatomy is not visualized because the wrong filter was used. **FIG. 12.** Image noise due to a convolution filter that is too sharp. This is the same image data as Fig. 1. Note the presence of structured noise not only in the liver but also in background and the spleen. **FIG. 13.** Intense outer ring on an organ because of too little or no attenuation correction. This image data is the same as Fig. 1 but areas in medial portion of the liver are not visualized and outer edge is more intense.

egories that may only be corrected by reimaging the patient.

Image blurring arises from two sources: the wrong COR (Fig. 10) or a reconstruction filter that is too smooth (Fig. 11). If the wrong COR is used, the loss of resolution is due to the computer misaligning the center pixel in each projection image. This is readily corrected by frequent performance of the correct COR calibration, recording the value and using the correct value for each patient. Some manufacturers have reduced this source of error by making the COR a permanent part of the patient file. However, the COR calibration must always be performed before the patient study in order to record the proper value.

In choosing a reconstruction (convolution) filter, it must be remembered that convolution filters must be matched to the individual imaging situation. A filter that is too smooth will result in loss of resolution, much like over-smoothing a conventional image. Normal structures as well as disease may not be visualized (Fig. 11). Images that have high information density may be reconstructed with a sharper filter (higher spatial frequency) than those images with low information density, i.e., the greater the counts per transaxial image element, the sharper the reconstruction filter that can be used. This is important because sharper filters provide greater image resolution.

Conversely, image noise may be intensified by using a reconstruction filter that is too sharp. The appearance of structured noise not only in the liver but also in the background and spleen is indicative of this problem (Fig. 12). Once again, the convolution filter must match the imaging situation. Filters may be chosen by imaging phantoms that approximate the organ and using count rates used in the clinical situation. The phantoms may be reconstructed by using various filters and selecting the one that gives the best representation.

The last artifact in this category is an intense ring at the edge of an organ due to too little or no attenuation correction. If this occurs, areas in the medial portion of the liver will not be visualized (Fig. 13). This is due to the greater loss of photons that originate in the center of an organ as compared to those photons originating at the periphery. This is more prominent in large organs such as the liver than in small organs such as the heart. The solution is to perform attenuation correction on all images that show this type of artifact.

Conclusion

Conventional imaging methods are remarkably tolerant of poor instrument performance. Changes of $\pm 10\%$ in a two million count field flood are barely noticeable to most observers. This is not the case with SPECT imaging. Small changes in uniformity across the face of the camera will result in bull's-eye artifacts. Changes in COR and pixel sizing must be detected and recorded to prevent decreases in image resolution. The camera head must be leveled for each procedure to ensure projection images that will result in true transaxial images. Each one of these quality control procedures is the sole responsibility of the technologist performing the clinical procedures. By maintaining a set schedule of quality control procedures such as that outlined in Table 1, we have been able to obtain consistently high quality, reliable SPECT images.

Above all, SPECT imaging systems cannot tolerate sloppy technique or an "I'll do it tomorrow" attitude. This invariably results in images that are at best difficult to interpret and at worst misleading. By being cognizant of these facts and by recognizing artifacts and their origins, technologists will be

TABLE 1. Schedule for Quality Control Procedures

1. Before every procedure—
   (A) Level camera head
2. Daily—
   (A) 30 million count field flood
3. Weekly—
   (A) Center of rotation
   (B) Pixel sizing
4. Monthly—
   (A) Cylinder phantom

able to review their technique and correct imaging errors in future studies and data processing errors in the current study to obtain high quality, artifact-free images.

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