Optimal SPECT processing and display: Making bad studies look good to get the right answer

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Single photon emission computed tomography (SPECT) perfusion imaging of the heart is a sensitive and accurate method for the detection, localization, and risk stratification of patients with known or suspected coronary artery disease. However, in some situations SPECT suffers from relatively poor specificity often caused by image artifacts resulting from unique features of the patient's body and behavior during the acquisition, the distribution of the radiopharmaceuticals outside of the heart, and technical factors associated with image acquisition, processing, and display. In some situations these problems can be fixed by reimaging, waiting for changes in radiotracer biodistribution to occur naturally, attempting to induce changes by manipulations such as administering liquids, and finally, resorting to software processing and manipulation.[1] In some patients there may be multiple problems present that interact in such a complicated way that even Einstein could not figure the physics. In such a situation the poor interpreting clinician imager is lost, and reaching an accurate interpretation becomes challenging to say the least. Recognizing the problems, knowing the effects that they will have on the resultant perfusion images, and knowing the available methods of quality control and image processing to correct the problems go a long way to improving specificity and the overall accuracy of SPECT studies and, perhaps most importantly, knowing when to bail out and refer the patient for another study to make the diagnosis.

In general, recognition and correction are of the utmost importance, and if the patient has already left the nuclear laboratory and reacquiring the study is not an option, correction is the only method available to improve the studies. However, these techniques are also useful for onsite patients who cannot tolerate reimaging, such as those with heart failure, orthopnea, back pain, or other orthopedic problems; those with neurologic or mental illnesses who cannot cooperate; and in rare cases, an inadequately sedated child. Recognition of problems and knowing which techniques are available and applicable requires interaction, cooperation, and understanding between the technologist and the interpreting physician as they see the patient at different stages in the process. The first step of quality control is having the technologists, before the patient's departure from the imaging area, and the physician, before interpreting the perfusion slices, review the projection images in a continuous cine loop format. This enables the detection of motion, sources of attenuation, and extracardiac activity. Next, the orientation and defined axes and borders of the heart should be carefully reviewed on the aligned stress and rest images. Finally, the reconstructed slices and polar perfusion maps are assessed visually, semiquantitatively, and quantitatively.

This review will focus on the practical problems listed in Table 1 and describe how they are recognized and the methods used to overcome them to obtain optimal SPECT images and to achieve an accurate diagnosis.

PATIENT MOTION

Despite advances in cardiac SPECT hardware and software, patient motion remains a major problem. A requirement for accurate reconstruction in SPECT is that the heart remains in a constant position for each projection so that data are appropriately registered during image reconstruction. Patient motion during data acquisition may cause significant displacement of the heart and misregistration of projection data.[2] Motion may be lateral, vertical, or rotational (twisting). It may be abrupt or gradual and may occur once or multiple times. Front line prevention and recognition are done by the nuclear medicine technologist. He or she should inform the patient of the need to hold still and take regular average-sized breaths and let the patient know that he or she is being monitored. Every step should be taken to make the patient comfortable and the imaging time kept as short as possible, while still providing adequate counts.

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Table 1. Common causes of cardiac SPECT image artifacts

1. Motion
Detection of motion
Correction of motion
2. Attenuation
Breast tissue
Diaphragm
Lateral chest wall fat
3. Image processing and reconstruction
Selecting cardiac axes and polar map reconstruction
Selecting cardiac apex, base, and boundaries
4. Normalization and scaling
Narrowing upper and lower limits of reconstruction
Frame, series, and cardiac display scaling
Deletion of hot spots or extraction of heart
"Dial-a-lesion"
5. Filtering and ramp filter artifacts
6. Gated SPECT

Motion-induced perfusion defects are influenced by the type, amount, timing of motion, and number of detector heads.[3] Prigent et al[4] showed that the magnitude and timing of motion are the most important factors that determine whether image artifacts will ensue, whereas the direction and pattern of motion determine the location of artifacts. Cooper et al[5] found that motion of 0.5 pixel (3.25 mm) is usually not visually detectable; 1 pixel (6.5 mm) of motion was recognized but judged to be clinically insignificant, and 2 pixels (13 mm) of motion led to clinically significant artifacts in 5% of interpretations.

An example of how motion affects images is shown in Figure 1. Displayed are representative slices in a patient with normal perfusion (0 pixels). Subsequent columns show vertical shifting of 1, 2, and 3 pixels in 32 of 64 projections acquired with a dual-detector system. With a 1-pixel shift, the inferior wall on the short slice has a decrease in counts. With 2- and 3-pixel shifts, there is marked degradation of image quality on all 3 views that is most marked on the inferior wall and apex. With motion, normal perfusion may become false ischemia if motion was not present on the matched images.

Motion that occurs when the heart is close to the detector is more likely to introduce image artifacts, because the corresponding projections have better spatial resolution and contribute more information to the final reconstructed SPECT images. The number of frames with motion also determines the magnitude of image artifact; the greater the number of frames with motion, the greater the artifact.[6]

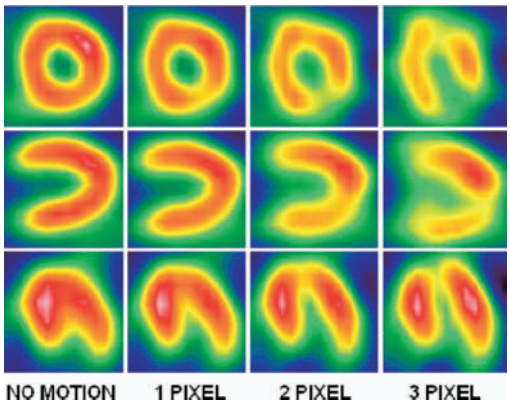

Figure 1. Representative midcavity slices in a normal stress perfusion study without motion (0 pixel) and subsequent shifting of 1, 2, and 3 pixels of vertical motion in 32 of 64 acquired projection images. Marked abnormalities are induced in the inferior wall and apex with increasing shifting.

Detection of Motion

Inspection of the projection data in a cine loop format is usually the best way to detect cardiac motion. A horizontal line may be placed just below the heart to serve as a frame of reference during review of the dynamic cine display of the projection images. Movement of the heart above or below that line can be easily detected and is indicative of abrupt vertical motion. Degree, direction, and frequency of motion can also be assessed. This technique allows detection of abrupt motion of several pixels but may miss gradual uniform motion that is more difficult to identify. With dual-detector camera systems, such gradual motion may be identified during cine review when the projection images from one detector are linked to the images from the second detector. The last projection from detector 1 shows the final position of the heart, and the first projection from detector 2 shows where the heart started. Spatially, these 2 images are adjacent, but temporally, the last image from detector 1 is at the end of the acquisition and the first image from detector 2 at the beginning of the acquisition. Detector or collimator misalignment or tilt may produce a similar effect and needs to be considered if the final images have motion-type artifacts but motion is not observed on the rotating projections.

Sinograms and cyclograms are derived from the raw projection data and are additional tools for detection of motion. Sinograms facilitate identification of horizontal motion, and cyclograms are more suitable for identification of vertical cardiac motion. A sinogram is created by displaying projected counts for a single row over all projection angles. For example, the fourth row of pixels of the first projection image forms the first row of the

Figure 2. Examples of a sinogram in a patient with motion and after correction and in a patient with inappropriate gating.

fourth sinogram; the fourth row of pixels of the second projection image forms the second row of this sinogram, and so on, until the fourth row of pixels of the last projection image forms the last row of this sinogram. An example is shown in Figure 2. Thus the number of rows in the sinogram equals the number of projections in the SPECT data set. A cyclogram is somewhat similar to a sinogram, but it uses pixel columns instead of pixel rows. Sinograms and cyclograms with no motion appear as smooth continuous images, whereas those with motion appear as images with breaks or discontinuities as shown in the left image of Figure 2. The middle image shows how the sinogram looks after correction, and the right image shows the effects of inappropriate gating. With inappropriate gating, there are varying counts per projection due to beat rejection.

Neither of these displays is optimal for detecting gradual continuous motion.[2] Another technique is adding individual planar frames to produce a summed cyclogram image in which the heart forms a horizontal stripe as it moves from left to right across the field of view. This is particularly useful for detecting abrupt vertical motion.[1] A useful method for identification and quantification of motion with multidetector SPECT systems is to place a point source on the patient's chest. Chest wall motion is detected by deviation of the point source. This does not detect cardiac motion that is independent of body displacement.[7] Although this technique is useful, it is seldom used in clinical practice.

Effect of Motion on Reconstructed Images

Motion may cause the following image artifacts on the reconstructed images: "hurricane sign," distorted ventricular shape, and discontinuity of the ventricular walls. The hurricane sign[8]—in which the left ventricle in the short-axis views resembles the National Weather Service symbol for a hurricane—is caused by motion-induced smearing of photon counts in opposing directions around the left ventricle.

Distortion of the ventricle so that the heart appears elongated or tilted, discontinuities of the left ventricular (LV) walls at the apex, nonanatomic defects, 12- and 6-o'clock defects, and hot spots are other characteristic patterns of motion artifacts. Anteroseptal wall defects are more frequently seen with downward motion, anterolateral wall defects are more frequently seen with upward motion, and inferior wall defects are usually seen with cardiac bounces.[4,6]

Motion Correction

Motion correction adjusts the projection data to compensate for patient motion. The projections are shifted vertically in an attempt to keep the heart in an equivalent motion-free trajectory, where the axial location is constant over all angular views and where the transverse location follows a sinusoidal path. Although shifting the projection data may compensate for translational motion, it cannot handle all possible types of patient motion (such as twisting) and is therefore only an approximate means of motion correction. Even so, in many cases motion correction can sufficiently compensate for patient motion and turn a seemingly unreadable study into a readable study.

Generally, detection and correction of axial or vertical motion are easier than those of lateral motion. Motion-correction algorithms are listed in Table 2 and include cross correlation, diverging squares, 2-dimensional fit, projection-reprojection, and manual shift approaches.[3,9-12]

In the cross-correlation function technique, summed profiles from successive projections are compared via a cross-correlation function. The magnitude of shift in profile count distribution is measured and used to perform motion correction on the projection data. This

Table 2. Motion detection and correction techniques

Cross-correlation function
Diverging squares
2-Dimensional fit
Projection-reprojection
Manual shifting

method is sensitive to sudden movement between projections but is less sensitive to gradual motion.[9]

The diverging-squares algorithm technique starts by placing a rectangular region of interest (ROI) around the heart for each projection image. The algorithm then aligns all projection images by shifting the center of the heart in each projection to follow a predetermined trajectory and maintain a constant position throughout the entire study.[10] This method is also useful in correction for center-of-rotation errors.

The 2-dimensional fit method[11] starts by defining a circular ROI that encloses the whole heart in the 45° left anterior oblique projection. An x-coordinate is assigned to the center of the circle at the 0° (anterior) projection, and a y-coordinate is assigned to the center of the circle at the 90° (left lateral) projection. Then the actual patient projection data of the x and y positions are compared against calculated data and adjusted for motion if needed.

The projection-reprojection technique iteratively reconstructs the heart and reprojects the image. A displacement vector, which maximizes agreement between the projection and its corresponding reprojection, is calculated. This vector is then used for motion correction.[3] This algorithm functions well with all types of motion.

Applicability of such automated algorithms may be limited if there is considerable liver uptake, which interferes with the detection of the myocardial borders. In such situations the manual correction technique is preferred. A reference marker—either a rectangular ROI or, more commonly, a horizontal line—is positioned just below the heart across a cine display of the raw data. The operator manually shifts the individual projections to align the heart position until the lower boundary of the myocardium lies on the reference line in consecutive frames. Most manual techniques use some type of masking, whereby regions above and below the myocardium are digitally removed.[2] Many manual interfaces for motion correction have a feature that when the image is shifted, all subsequent images are shifted by the same amount. This is very useful if there is a single instance of patient motion that is maintained over the entire scan. By placing the myocardium at the same reference point in each projection, motion is corrected. Manual motion correction is time-consuming, and operator performance may not be consistent and reproducible, but it may be the only option available in some cases.

Evaluation of the motion-corrected images can be performed by visual assessment of the corrected cine projection data and via bull's-eye maps of the reconstructed images to quantify residual motion artifact. On review of the short-axis slices and polar perfusion maps, if the results appear normal, then it is unlikely that the original data had true perfusion defects. However, if the results are still abnormal and the observer is unsure about the success of motion correction, then the study should be repeated.

Regardless of which method of motion correction is used, the corrected projection images need to be reviewed to make certain that the correction accurately repositioned the heart. It is best to reacquire the images if motion had been detected, but because of limited camera availability and the probability that the factors causing motion on the first acquisition are likely to be present on reacquisition, in many cases software correction methods are used.

ATTENUATION

Attenuation of photons resulting from travel through different tissue densities is the most common factor affecting the quantitative accuracy and visual interpretation of myocardial perfusion SPECT images.[13-15] Attenuation correction methods are available by use of emission line sources or computed tomography transmission data. The technical aspects of these methods are beyond the scope of this review, and we will focus on the use of the projection images and gating to differentiate between attenuation, infarction, and ischemia.

Breast Tissue

Breast attenuation artifacts depend on the position, size, and density of the breast, as well as the patient's body habitus and orientation of the heart within the thorax. In women with an average body habitus, the left breast usually overlies the anterolateral wall of the left hemithorax. In this position the anterior, anteroseptal, and anterolateral walls of the left ventricle are eclipsed by the breast. In women with large pendulous breasts, the left breast lies over the lateral chest wall and results in a lateral wall attenuation artifact. In young women with firm, dense breast tissue, attenuation usually occurs in the anteroseptal wall. In women with large breasts, the breast tissue may overlie the entire left ventricle, resulting in a more diffuse and commonly less discrete attenuation artifact.[1]

With regard to all of the previously mentioned artifacts, it is assumed that the patient is not wearing a

bra and is imaged horizontally. If the patient is imaged in any other position or is wearing a bra, attenuation artifacts will be located in other portions of the heart. If the patient is imaged in a sitting or recumbent position by use of one of the new dedicated cardiac small–field-of-view cameras, a pendulous right breast may attenuate the inferior wall. Allowing patients to wear their bras causes a greater distance between the detector head and the heart and tends to place the breast in a more central position over the heart.

The interpreting physician should always be aware of factors that may alter the position, configuration, and density of the breast. Breast implants and fibrosis after a mastectomy, for example, may be denser than normal breast tissue and thus accentuate attenuation artifacts. Breast attenuation may also occur in men with gynecomastia. This usually results in anterior wall attenuation artifact.

Inspection of the rotating projection images is very important for recognizing the position of the breast in relation to the left ventricle and the density of the breast tissue; any shift of the breast between stress and rest is important and needs to be considered. Efforts in patient positioning should be directed toward consistency in breast location between the stress and rest acquisitions. The use of lead or "hot" line sources to identify the position of the breast on a short-acquisition anterior image avoids much of the guesswork on where the attenuation is occurring, but because of time considerations and the growing availability of attenuation correction methods, these are seldom used. On review of the gated images, the presence of motion and thickening helps to differentiate between attenuation and infarction.

Diaphragm and Subdiaphragmatic Structures

The position of the left hemidiaphragm can be identified from the left lateral or left posterior oblique view as a curvilinear region of activity representing the diaphragm itself or as a photopenic defect resulting from liquid, solids, or gas in the stomach. On the SPECT images, the inferior wall exhibits a decrease in count density. On gated SPECT images, defects resulting from attenuation will show normal wall motion and thickening.[16] When dual-isotope imaging is used, patients are in fasting state for the resting thallium 201 study and have empty stomachs. After the technetium 99m stress study, patients are often allowed to eat to stimulate liver extraction and gallbladder emptying or are given liquids to move stomach or intestinal radioactivity. This often results in a full stomach, and in the supine position, the diaphragm is pushed upward, causing a greater degree of attenuation and the appearance of inferior ischemia relative to the resting study. It is best to have comparable stomach distension for the rest and stress studies. If this is not possible, one should look for photopenic defects and be aware that subtle changes in the inferior wall may be a result of a differential extent of diaphragmatic attenuation.

Table 3. Approaches to managing SPECT attenuation

1. Indirect approaches
Cine review of projection images
ECG gating
Quantitative analysis
2. Direct approaches (patient-specific attenuation map)
External radionuclide source systems
Computed tomography–based systems

Lateral Chest Wall Fat

Lateral chest wall fat is present in obese patients of both genders and may cause an artifactual defect in the lateral wall. On the rotating projection images, the left ventricle will show markedly decreased count density in the lateral and left posterior oblique views. Such artifacts can be differentiated from scarred lateral wall by visualization of normal wall motion in the gated images.

An important step in SPECT image interpretation is visualization of the rotating projection images for possible sources of attenuation, which can be identified and thus accounted for during image interpretation and corrected, if possible. There are direct and indirect approaches used in daily practice to address the problem of soft-tissue attenuation, as shown in Table 3.[17] The indirect approaches include the use of cine review, electrocardiography (ECG) gating, and quantitative analysis. The more direct approach involves the creation of patient-specific attenuation maps by use of external radionuclide sources or computed tomography.

General Approach to Manage Attenuation

ECG-gated assessment of wall motion. Inspection of wall motion on ECG-gated SPECT images can be useful in distinguishing attenuation artifact from infarction; if there is a corresponding regional perfusion and wall motion abnormality, the diagnosis of infarction can be made with certainty.[13] However, normal wall motion in the presence of a reversible or partially reversible perfusion defect neither confirms nor disproves an attenuation artifact, as the gated images are acquired a minimum of 15 minutes after termination of stress, which allows recovery of ischemia-induced wall motion. Furthermore, some patients with normal wall motion and fixed perfu-

Table 4. Characteristics of high-quality attenuation map

High count density
Minimal or no truncation of transmission projections
High-quality reference scans
Precise registration of emission and transmission data
Minimal noise

sion defects at stress and rest may have coronary artery disease with nontransmural injury.[17]

Quantitation. Quantitative analysis of myocardial perfusion compares a patient's relative distribution of tracer against a database of gender-matched patients with normal coronary anatomy. It was not designed to overcome attenuation, and in fact, quantitation has not been shown to improve interpretive accuracy by visual assessment in obese patients.[18]

Direct approaches to attenuation include the use of patient-specific transmission maps. SPECT attenuation correction systems measure the nonhomogeneous attenuation distribution by use of external collimated radionuclide sources[19] or x-ray computed tomography with hybrid systems.[20] High-quality attenuation maps are essential for accurate attenuation correction. Attenuation maps of high quality are characterized by high count density, minimal or no truncation of the transmission projections, high-quality reference scans, precise alignment of emission and transmission data, and minimal noise (Table 4).[17]

ECG gating and attenuation correction provide synergistic and complementary information and should be used together for optimal diagnostic accuracy. Links et al[21] had readers interpret static images and then added the information from gating. Both sensitivity and normalcy improved progressively going from static (85% and 54%, respectively) to uncorrected gated (78% and 62%, respectively) to static attenuation-corrected (93% and 77%, respectively) to gated attenuation-corrected image sets (96% and 85%, respectively). Sensitivity was the highest for all 3 coronary territories for the combination of gating and attenuation correction.

In a similar study Bateman et al[22] performed a consensus blinded read in 247 patients. The interpreters scored gated attenuation-corrected and gated non–attenuation-corrected images independently and without knowledge of whether the images had undergone attenuation correction. The results showed that the attenuation-corrected studies were associated with a significant improvement in both specificity (64% to 86%) and normalcy (93% to 98%), with no change in sensitivity.

Attenuation correction also performs well in obese and nonobese individuals. Several studies have suggested that attenuation correction performs well in obese patients and, unlike non–attenuation-corrected studies, does not appear to have accuracy erode with increasing body habitus.[23-25] There are data to indicate that attenuation correction also enhances specificity and normalcy in nonobese patients.

IMAGE PROCESSING AND RECONSTRUCTION

Selecting Oblique Cardiac Axes

A critical step in cardiac SPECT reconstruction is selection of the long axis of the left ventricle, which is then used for oblique angle reformatting to reorient the heart into 3 planes perpendicular to the long axis of the left ventricle to standardize LV display and analysis. Quality-control screens are available in all of the major commercially available systems for review of the axes selected for tomographic slice and polar map reconstruction.

The long axis of the left ventricle should be selected from the transaxial tomographic midventricular slice showing the widest ventricular cavity and should bisect the apex and the valve plane. From this selection, the vertical long-axis (VLA) images are reoriented. Next, the VLA slice with the longest LV cavity is chosen, and a line dividing the cavity into anterior and posterior halves is drawn. From this, the short-axis and horizontal long-axis slices are formed. Finally, on the midventricular VLA image, the user chooses the apex and base to be used in generating the polar perfusion maps. Care should be taken so that the axes selected bisect the apex and valve plane. The obliquity of the axes should be identical for stress and rest/redistribution images to guarantee comparison of the same areas of the myocardium.

If the long axis is selected incorrectly on either the transaxial or midventricular VLA slice, the geometry of the heart in reconstructed slices may be distorted and an LV wall may be foreshortened, thus showing an artifactual defect visually and on the polar map display. This mostly occurs in the basal myocardial segments at the periphery of the bull's-eye map. In addition, the apex, which may show decreased count density as a result of apical thinning, will be displaced from the center of the polar map, causing an artifactual defect.

Long-axis selection is particularly difficult in hearts with large infarcts or distortion and in small hearts. In small hearts zooming in may aid accurate identification of the apex and midpoint of the valve plane by improving visualization of the heart's landmarks. In the presence of large severe apical infarcts, after the valve plane is bisected, a possible way to try to optimally bisect the apex is by identifying the midpoint of the closest LV cavity to the apex. Another alternative is to extend the line drawn from the midpoint of the valve plane to

parallel the anterior and inferior walls; this is applicable only if these walls are parallel to each other, which may not be the case in distorted hearts. In all cases consistency between the stress and rest studies is very important; this can be accomplished if the user applies these methods with both the stress and rest images on the same screen.

Incorrect axis selection may be suspected if the LV cavity appears oblong rather than circular (except in patients with extensive regional dysfunction resulting in cavity deformity), and the resultant defects usually do not correspond to a discrete vascular territory.

Selecting Cardiac Apex, Base, and Boundaries

For quantitative analysis and for ejection fraction calculation on ECG-gated studies, a midventricular short-axis slice is used to identify the outer limits of the radial-search boundaries and LV cavity center. The midventricular VLA and horizontal long-axis slices are used for placement of the apical and basal slice selection at the mitral valve plane.

Accurate and reproducible selection of apex and base is necessary in stress and rest studies. Positioning the limits for slice selection too far beyond the base or apex will result in apparent perfusion defects. On the other hand, slice limits that are too tight will not accurately sample the full extent of the myocardium and may result in underestimation of the size and extent of a defect.

NORMALIZATION AND SCALING

Abdominal visceral activity may be increased in some patients as a result of liver retention, duodenogastric reflux (stomach uptake), small bowel uptake, or rapid small bowel transit (colon uptake). This increased activity causes problems by adding counts to the adjacent inferior wall as a result of scatter during acquisition, or it may actually overlap the myocardium, where it directly adds counts and has the potential to cause normalization or display problems that interfere with both visual and quantitative analyses. SPECT images are normalized to the region of the field of view or the myocardium with the highest count density. If liver or other abdominal visceral activity is superimposed on or adjacent to the inferior wall or scatter adds counts to this area, images will be incorrectly normalized to this area, making other regions of the heart appear count-deficient. Subsequent visual and quantitative analysis may incorrectly identify defects remote from this area. For polar map reconstruction, it is sometimes necessary to exclude as much abdominal visceral activity as possible from regions used for image reconstruction. Several techniques are available.[26]

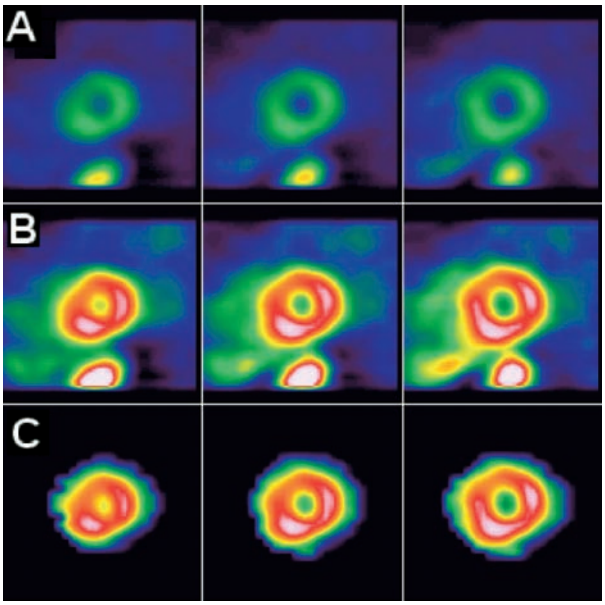

Figure 3. Examples of image normalization on representative short-axis slice. **A**, Volume normalized; hot area underneath the myocardium to have low counts. **B**, Normalization to heart. **C**, Heart extracted from background.

Methods of Image Normalization

There are 3 generally used methods for scaling or normalizing SPECT perfusion images: series, frame, and cardiac.

Series or volume. Series normalization is the most commonly performed method. When it is used, the hottest or maximum-intensity pixel or cluster of pixels in the entire reconstructed field or volume for the rest and stress images is identified and set as the maximum intensity. The assumption is made that this area will be within the heart and represents the greatest blood flow. Unfortunately, with Tl-201 and especially with the Tc-99m–radiolabeled agents, the hottest areas are not always in the myocardium, and any of these hot areas outside the myocardium will cause downscaling of the intensity of the myocardium, not as a result of lack of blood flow but because of inappropriate scaling. If the stress images are downscaled and the rest images are not, the differential diagnosis is between a normal study and severe multivessel disease. An example is shown in Figure 3*A*. The myocardium looks severely reduced.

Frame normalization. When the scaling problem is outside of the matched slices, frame normalization may be used to eliminate this problem. This method identifies the hottest pixel or pixels on the aligned/

matched stress and rest images and sets each to the maximum intensity. It then looks at the next set of matched slices and, independent of the prior set, resets the maximum for the rest and stress images. If the hottest pixel is outside the matched slices, this method will correctly scale the myocardium. When a noncardiac hot spot is in the field for one of the matched slices, the scaling problem is not eliminated but is present only for that matched set, and the other matched sets without hot noncardiac activity will be appropriately scaled.

Cardiac normalization. Cardiac normalization is the best method for correctly normalizing the myocardium. Software searches within the epicardial borders defined for quantitative analysis to look for the maximum pixels. Scatter and overlap from liver and gastrointestinal activity are still a problem, but hot areas adjacent to the heart that cause problems with series and frame normalization are eliminated. This is shown in Figure 3*B*. Not all software versions offer this option, but when available, it is the method of choice.

Alternative Methods of Image Normalization

Alternative methods to eliminate display and image normalization problems include narrowing the area of reconstruction, extracting the heart from the background activity for display, and deleting focal hot spots.

Narrowing or cropping reconstruction area. During acquisition and processing, a large field of view and even a small field of view acquire areas outside the heart that can be eliminated during reconstruction by narrowing the upper and lower vertical boundaries. A horizontal line is place above and below the heart on the projection images to include the smallest possible area adjacent to the heart but including the heart on every projection. This does not eliminate scatter that has occurred during acquisition but allows image display without scaling to a hot pixel that is outside the heart.

Software extraction. If narrowing the boundaries of the reconstruction data does not eliminate hot spots without truncation of the heart, workstation programs allow placement of a circular or manually drawn region around the myocardium and deletion of all of the background activity outside this region, thereby extracting the heart from the background. This is shown in Figure 3*C*. By eliminating all of the noncardiac background activity, a frame of reference to evaluate the severity of defects is lost and structures such as the right ventricle may not be displayed. It is not recommended that studies be routinely extracted unless there are scaling problems on the display. Unfortunately, some facilities have the technologists perform extractions of the heart on all patients so that the matched perfusion slices and rotating projection images show only the heart without visualization of sources of scatter and overlap.

Software deletion. An alternative method is to delete the areas of subdiaphragmatic activity by manually placing an ROI around the hot areas and deleting them so that some background activity is present when the projection images and matched perfusion slices are reviewed. Care must be taken to be certain that the ROI does not cut off the heart on some of the projections. This method may not be available on all software programs and takes longer to process because manual review of all slices is required.

Dial-a-Lesion

If all of the methods listed previously fail, some revert to selection and individual scaling for each slice—so-called "dial-a-lesion." With this approach, the intensity of the images, usually in color, is lowered and then increased until the same maximum color setting is reached on a single area on the stress and rest images. Some readers will also truncate the background activity. An alternative method has been proposed whereby the hottest area on the stress images is renormalized visually to approximate the activity of that segment at rest. This technique improved the detection of multivessel coronary artery disease.[27] Although these methods are attempts to overcome the lack of absolute blood flow measurements and the need to depend on relative flows, there is an element of arbitrary normalization that is not likely to be reproducible and has not been clinically validated.

RECONSTRUCTION AND FILTERING ARTIFACTS

Image reconstruction is performed to initially generate transaxial slice images of the heart from the raw projection data.[28] The reconstruction algorithm maps the distribution of the radiotracer in the projection images to create an image of the heart. Because of limited count statistics, a smoothing filter is also applied to reduce high-frequency noise and improve the overall image quality.[29,30] Certain features and artifacts may result from the reconstruction and filtering processes, and it is important for the interpreting physician to be aware of such potential problems.

The most common image reconstruction method used in nuclear cardiology is the filtered backprojection (FBP) algorithm. This algorithm is computationally very efficient and consists of only 2 steps. First, the projection data are filtered: a smoothing filter and also a mathematical "ramp" filter are applied. The ramp filter is required by the algorithm to properly account for the data sampling of the projections. After the filtering step, the data

are backprojected through the image space, tracing rays from the projection pixels through the image voxels and summing the angular contributions of all rays. Most software programs use this method because it is the least technically demanding of the workstations and allows rapid processing.

More recently, iterative image reconstruction algorithms have become available on clinical nuclear medicine workstations and offer some advantages over FBP reconstruction. As the name suggests, iterative algorithms work by repeatedly comparing estimated projections (generated from the current image estimate) to the actual raw projection data and adjusting the image estimate to account for the observed difference. In repeating this step, the image estimate converges toward a better-quality image in face of the low count statistics. A postfilter is often applied afterward to reduce image noise.

One possible image artifact affecting nuclear cardiology is often referred to as *ramp filter artifact*. Intense extracardiac activity that is adjacent to the heart may alter the observed myocardial uptake. During the filtering step of FBP, the area surrounding an intense region is much reduced, such that negative values may be backprojected.[31] Figure 4 shows an example of a hot gall bladder that is in the same transaxial slice as the myocardium. Streak artifacts and regions of abnormally low uptake are produced, significantly altering the myocardial distribution and giving the appearance of decreased blood flow when, in reality, it is normal. This is shown in Figure 5 during FBP. Thus the diagnosis of ischemia may be made when, in reality, it is normal. Iterative reconstruction can often minimize or eliminate this effect. Figure 6 compares images reconstructed via FBP and iterative reconstruction in the presence of an intense gallbladder. The inferior wall counts are decreased with FBP reconstruction, due to ramp filter artifact. The artifact is minimized, but not eliminated, with iterative reconstruction.

Ramp filter artifacts may be suspected when there is high extracardiac uptake close to the heart on the images. However, looking at the cropped reoriented images may not always identify the presence of the hot spot, as it has been cut off from above or below the heart or may be beyond the apex or base of the heart, which is not displayed. Hence, it is critical to review the raw projection images, as well as the transaxial views, to look for potential sources of ramp filter artifacts.

Other issues related to filtering and image quality involve differences between rest and stress images. For example, a stress study may have significantly more counts than a rest study, which is often the case for the dual-isotope Tl-201–Tc 99m protocol and the same-day low-dose/high-dose Tc-99m–Tc-99m protocol. The rest images appear noisier, and the physician must consider the different noise levels in distinguishing defects from noise fluctuations. Some guidelines recommend using different filter settings for the 2 studies to better optimize image appearance.[32] In this situation the rest study is smoothed more than the stress study and has reduced spatial resolution, which must be accounted for in the interpretation.

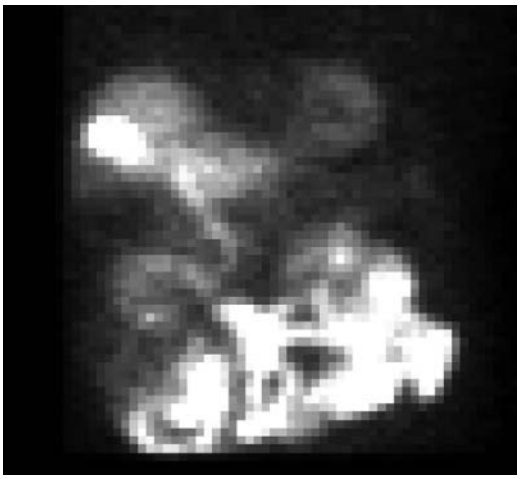

Figure 4. Anterior projection image showing an intense intrahepatic gallbladder that is capable of causing a ramp filter artifact.

GATED IMAGES

The quality of the gated images is affected by the same factors as the nongated images. Unique to gated images are the artifacts produced by variation in the cardiac cycle and the resulting variability in counts in the myocardium.

As with nongated SPECT, the first step in interpretation of gated perfusion images should be review of the rotating projection images for motion, sources of attenuation, and so on. In addition, one should look for "flashing" in the projection images, which is indicative of rejected beats (Figure 2). This occurs in the presence of arrhythmias or changes in heart rate during the acquisition, with rejection of inordinately short or long beats and subsequent variation of count density in the projection images. This in turn may lead to a falsely low ejection fraction and may appear as streak artifacts in the tomographic images.[33]

The magnitude of the gating problem may be verified by reviewing the quality-control curves, which are total counts per projection curves for each of the gated frames. If there are no gating errors, all 8 projection curves (or 16 in 16-frame gating) should superimpose nearly perfectly.[34] On some computer systems, a statis-

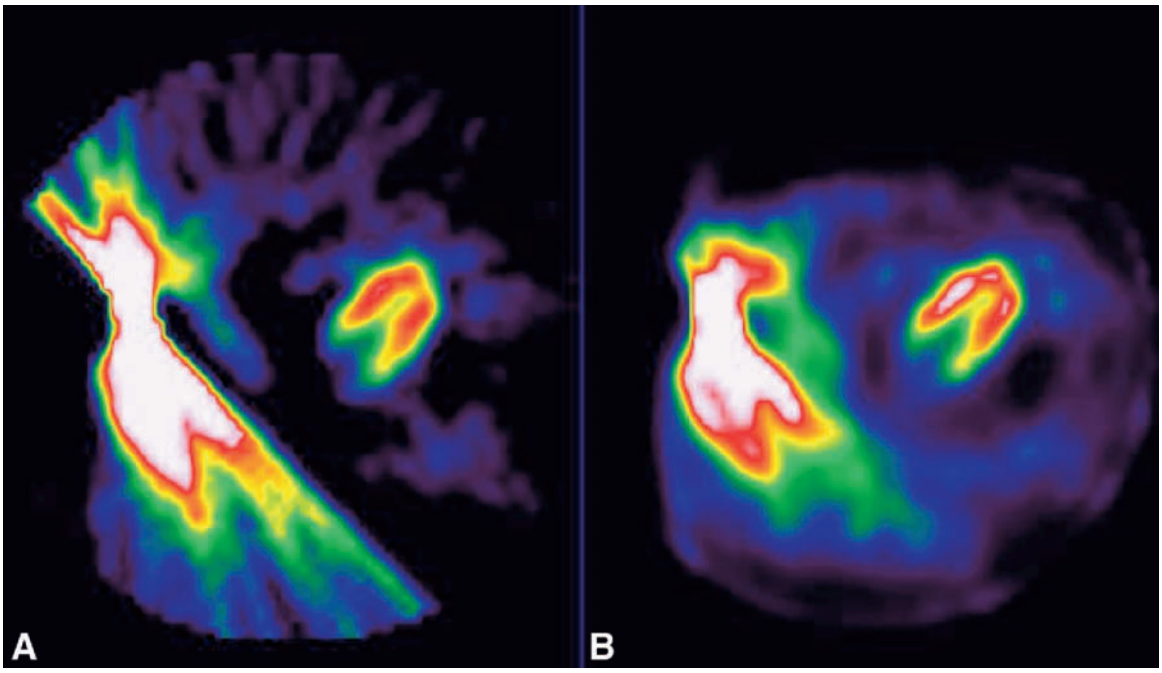

Figure 5. Transaxial slices of study from Figure 4 showing streaking from ramp filter artifact. The image on the left (**A**) was reconstructed using filtered back projection, while the image on the right (**B**) was reconstructed using interactive reconstruction.

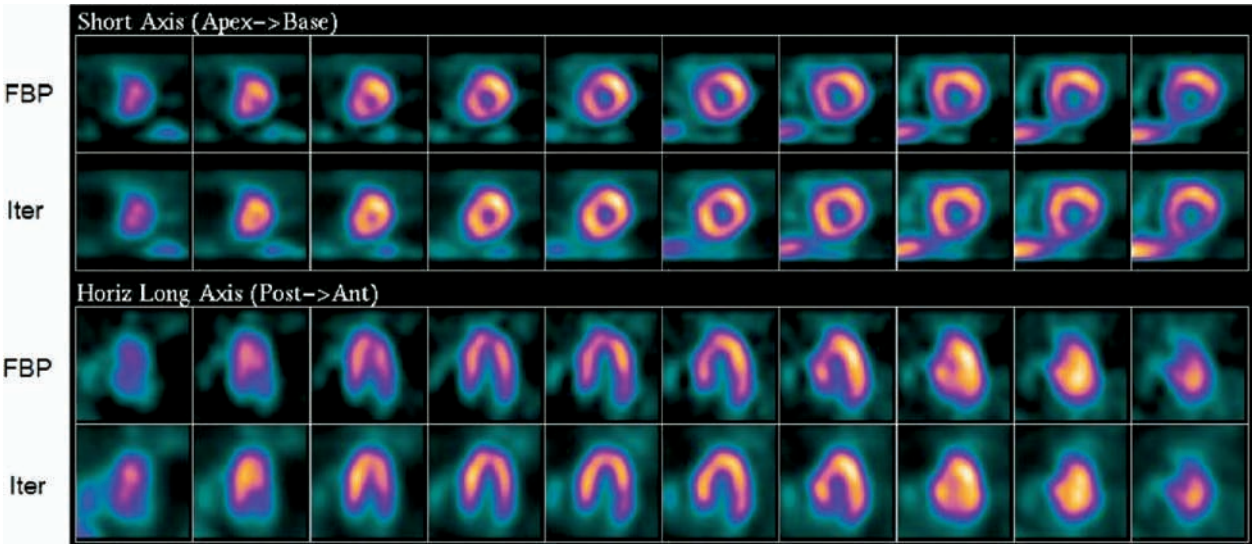

Figure 6. Example of FBP and iterative (*Iter*) methods for SPECT reconstruction in the patient from Figure 4. The inferior wall defect is less pronounced with the iterative method. *Horiz*, Horizontal; *Post*, posterior; *ant*, Anterior.

tical description of the R-R interval in the form of a histogram can be analyzed to identify potential gating artifacts.

The next step in quantitative interpretation is assessment of the accuracy and correction, if needed, of the selected apex, valve plane, and epicardial and endocardial borders.[35] In cases of severe hypoperfusion, 2 techniques have been developed: the regional image enhancement technique[36] and saturation of the color/gray scale so as to allocate the entire scale range to the lowest-activity portion of the image.[37]

Finally, it is important to ensure that the reported

volumes and ejection fraction values are in the physiologic range and are consistent with the visual impression provided by the cinematic playback of the tomographic slices.

CONCLUSION

Several quality-control measures take place before (patient and camera preparation) and during SPECT acquisition to achieve high-quality images. Not uncommonly, technologists and physicians are left with suboptimal images that have to be addressed to reach the "right answer" for patient diagnosis and hence management. In many cases patients may be reimaged, especially if the problem is detected early, but in other cases either the patient has left the nuclear laboratory or there is an inevitable problem that, even with reimaging, will not be resolved. In these situations the technologist and physician have to seek the available techniques to obtain the best images possible. These resources are discussed in this issue as an aid in quality control to obtain the best possible images.

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