Three-Dimensional Display of Gated Cardiac Blood-Pool Studies

Tom R. Miller, Jerold W. Wallis, and Kondapuram S. Sampathkumaran

The Edward Mallinckrodt Institute of Radiology, Washington University School of Medicine,
St. Louis, Missouri

There has been little interest in use of single photon tomography in gated cardiac blood-pool imaging. This fact arises most likely from two principal causes: the difficulty associated with interpretation of images presented as series of beating slices, and the formidable computational burdens involved in processing the data. We have addressed both of these issues. A new method, called volume rendering, is used to generate realistic and easily interpreted three-dimensional images of the cardiac blood pool. These images of the beating heart can be displayed in a continuously rotating cine format or viewed in any orientation selected by the observer. Total computation time for a 16-frame gated study, including filtered backprojection, spatial and temporal filtering, and volume rendering, is 82.7 min employing a 32-bit computer and an array processor. With greater use of the array processor it should be possible to reduce the time to ~40 min, thus making routine use of these three-dimensional images clinically feasible.

J Nucl Med 30:2036–2041, 1989

Single photon emission computed tomography (SPECT) is an important and widely used imaging technique. This three-dimensional procedure has not, however, become popular in gated cardiac blood-pool imaging. This fact is likely because of two principal reasons. The first factor is the cumbersome and confusing nature of the display methods. The images are usually viewed as multiple cine loops of transaxial or obliquely oriented slices (*1–7*). Analysis of this slice data is difficult and unappealing because the observer must synthesize large quantities of data in a way that makes appreciation of spatial relationships difficult. The second factor arises from the great demands placed on the computer by the very large quantity of digital data generated in a three-dimensional study consisting of many time frames. Processing of these studies frequently consumes several hours of computer time for each patient (*1*). Thus, for these reasons, gated cardiac blood-pool studies are still almost universally collected and interpreted as planar images.

We have developed new techniques for SPECT gated blood-pool imaging that attempt to overcome the limitations described above. A new three-dimensional display method called volume rendering (*8*) is used to produce images of the beating and rotating heart. These images combine the advantages of enhanced contrast and viewing from many orientations that derive from SPECT with the ready appreciation of spatial relationships inherent in planar imaging. Use of an array processor reduces the processing time to a clinically-practical length of time.

METHODS

Data Collection

Following in vivo red cell labeling with 25 mCi technetium-99m (^{99m}Tc), the tomographic data were collected on a large field-of-view scintillation camera equipped with a high-resolution, parallel-hole collimator. Images were acquired at 64 angles over a 180-degree arc from 45° right anterior oblique (RAO) to 45° left posterior oblique (LPO). Images were collected for 25 sec at each angle, making a total imaging time of ~30 min, including the time for camera movement between stops. The patient's left arm was placed over the head and care was taken to position the camera face as close as possible to the patient. Images were collected in a 64×64 pixel matrix with 16 frames per R-R interval.

To provide a comparison between the new method and conventional studies, planar imaging was also performed in anterior, LAO and left lateral views with use of a standard field-of-view camera and a low-energy, all-purpose collimator. Each view was acquired for 7 million counts over ~7 min. These planar images were digitally filtered with the Wiener and low-pass filters described previously (*9*).

Received May 4, 1989; revision accepted July 24, 1989.

For reprints contact: Tom R. Miller, MD, PhD, The Edward Mallinckrodt Institute of Radiology, 510 S. Kingshighway Blvd., St. Louis, MO 63110.

Filtered Backprojection

The acquired projection data were reconstructed by filtered backprojection with modifications recently developed by us and described in detail elsewhere (*10*). The filters were selected by visual inspection based on our extensive experience with filtering of planar gated blood-pool studies and SPECT images (*10*). First, 40 transaxial slices centered about the heart in each of the 16 time frames were reconstructed with use of a ramp filter. Next, the images were filtered three-dimensionally with use of a Wiener filter. Then, a low-pass temporal filter with cutoff frequency of 0.21 cycles/pixel was applied to all 16 time frames for each of the image voxels. Finally, the images were zoomed by a factor of 1.6 by trilinear interpolation so the heart was the same size as usually viewed in planar imaging employing a standard field-of-view camera.

Volume Rendering

Three-dimensional volume rendering was performed using a method we recently developed (*8*). Following filtered backprojection to form a cubic data set, a viewing orientation (e.g., anterior) was chosen and exponential depth weighting was applied to the values in each of the voxels of the cube to enhance the three-dimensional effect. The attenuation coefficient was empirically chosen to be 3% per pixel according to the distance from the viewing plane with the voxels closest to the viewing plane not attenuated. Greater attenuation would reduce visualization of the deeper structures, e.g., the left atrium in an anterior oblique view. The values in the cube were then reprojected along each ray to the viewing plane to form the two-dimensional image at the selected orientation. To enhance contrast, the maximum value along each ray, rather than the sum, was placed in the final image during reprojection. In gated blood-pool imaging, the overlying and underlying background activity occupies a greater number of voxels than does the chambers of the heart. Use of summation during reprojection would weight the background activity more heavily than desired (i.e., in proportion to the number of voxels), while use of the maximum voxel more closely achieves the contrast present in individual slices (8). The cubic data set was then rotated through 28 viewing positions uniformly spaced in a 360-degree arc about the patient with reprojection performed at each angle. This step was repeated for all 16 cubes representing the 16 time frames.

Display

To display this large quantity of digital data in cine format, all the images were first loaded into the physical memory of the computer. This required 3.7 Mbytes of memory to hold the 1.85 million (64×64×16×28) pixels. This large quantity of data precluded storage in the frame buffer of the display system. Then, each 64×64 pixel image frame was transferred to the display memory and viewed on the video monitor at an adjustable rate of ~16 frames per second to give a heart rate of 60 bpm. The heart was made to rotate as it beat by automatically incrementing the frames stored in computer memory as they were displayed on the monitor. Thus, as the study was displayed the heart would continue to beat and rotate either clockwise or counterclockwise or remain fixed at any angle according to the user's preference.

Computer Hardware

Uniformity correction and ramped backprojection of the transaxial slices was performed with use of a bit-slice processor (MicroDelta, Siemens Medical Systems, Des Plaines, IL). The remaining computations were performed on a MicroVAX II (Digital Equipment Corp., Maynard, MA) equipped with 9 Mbytes of memory. The most time-consuming steps of three-dimensional filtering, interpolation and cube rotation were performed on a 20 Mflop array processor equipped with 4 Mbytes of data memory (MicroMSP-IV, CDA/Analogic, Inc., Peabody, MA). Images were displayed on a frame buffer video system with 0.32 Mbytes of image memory (Lexidata Model 3700, Adage, Inc., Billerica, MA).

RESULTS

Images

Figure 1 shows three-dimensional images in anterior and LAO projections at end-diastole and end-systole in a normal subject. In Figure 2, LAO and left lateral views are shown in a patient with aneurysms of the left- and right-ventricular apices. The dyskinetic wall motion is easily appreciated in these static frames in the right ventricle while the left-ventricular abnormality is more readily observed in the cine display. Figure 3 is a comparison of the planar and three-dimensional images at end-diastole in the same patient with ventricular aneurysms. Note the better overall image quality of the volume-rendered images. Importantly, although not evident from the static images, the ability to interactively adjust the viewing angle helped resolve ambiguity about the motion of the cardiac structures. In Figure 4, left posterior oblique (LPO) and right posterior oblique (RPO) views are shown to demonstrate the visualization of the atria achieved with the three-dimensional method. Figure 5 shows the heart and great vessels at end-diastole as seen from above and below at end-diastole in a normal subject. While these viewing orientations have limited value, these images demonstrate the unique capability of the three-dimensional technique to provide views of the heart not achievable by conventional planar imaging. A tumbling, end-over-end display can be readily computed and displayed in cine format.

Computation Times and Storage Requirements

The computation times currently achieved with use of the bit-slice processor, MicroVAX and array processor are shown in the first column of the table. When the array processor is fully used, the times will be greatly reduced, as shown in the second column of the table and described in the Discussion section. The backprojected slice data, stored in word mode, consumed 5 Mbytes on the disc and the volume rendered images required 3.7 Mbytes.

DISCUSSION

Many papers have been written on SPECT acquisition of gated cardiac blood-pool studies (*1–7*). In almost

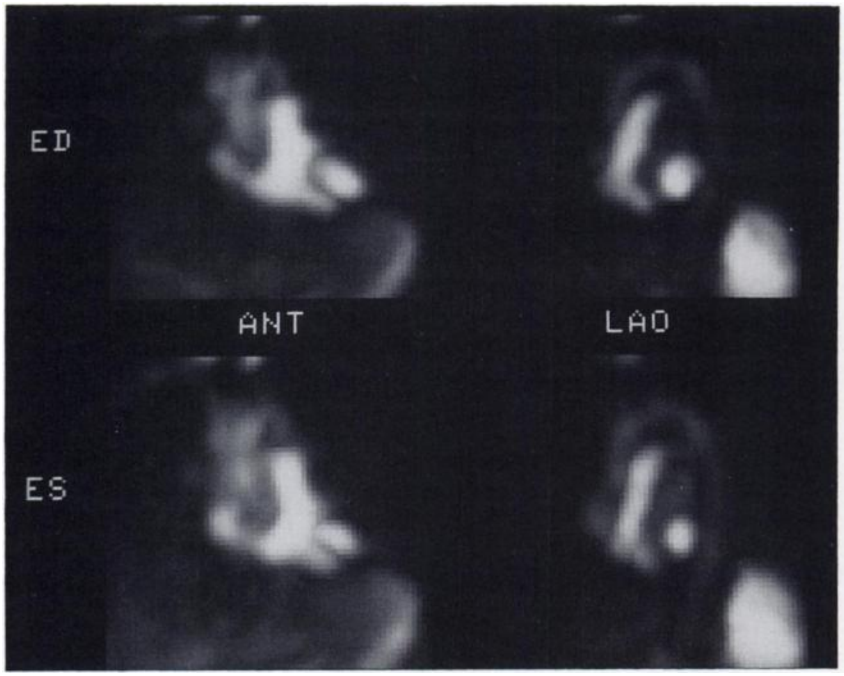

FIGURE 1
Three-dimensional images in a normal subject are shown at end-diastole (ED) in the top row and at end-systole (ES) on the bottom row. Anterior (ANT) and LAO views are displayed.

all cases a cine-mode display of gated slices was used, either in transaxial, coronal and sagittal planes or in obliquely-oriented long- and short-axis planes. Despite this work spanning a decade, gated tomographic display is still not widely used. This fact is in sharp contrast to the general and frequently enthusiastic acceptance of single-photon tomography in many other areas of nuclear medicine, including thallium-201 studies of the heart and studies of most other organ systems with a variety of radiopharmaceuticals.

In the work reported here, we have attempted to address the two main problems that have hindered the acceptance of SPECT gated blood-pool imaging, the use of a slice display and the formidable computational burdens associated with reconstruction and three-dimensional processing. The previously described slice-based displays are confusing and difficult to interpret because of uncertainty in position and orientation of individual slices, and because structures move in and out of a given slice as the heart beats. Building on our recent work in volume rendering (*8*), we have applied this new approach to three-dimensional display of gated blood-pool studies. This volume-based method provides a natural, realistic display of the heart and great

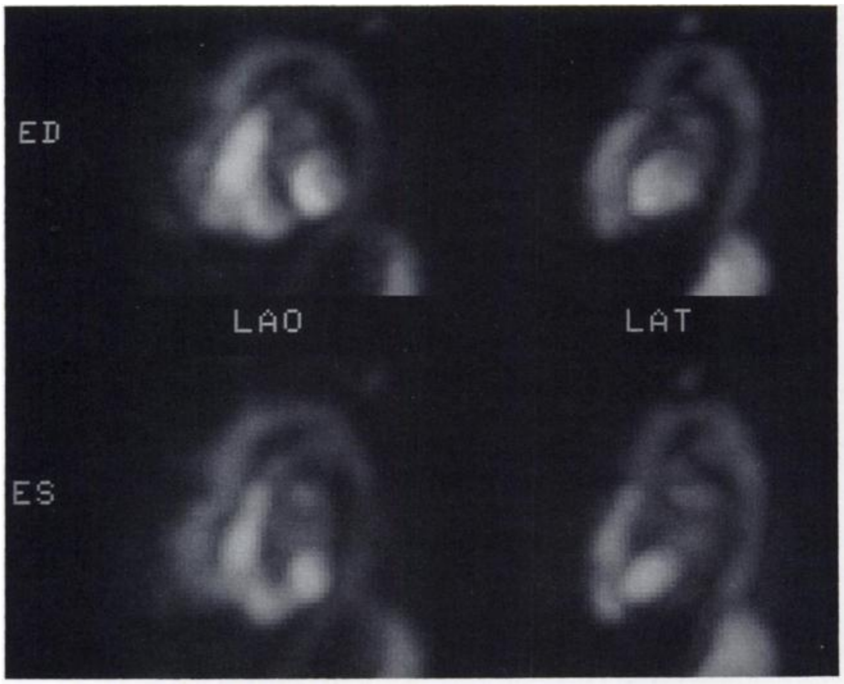

FIGURE 2
Three-dimensional images in LAO and left lateral (LAT) projections are shown at end-diastole and end-systole in a patient with dyskinetic motion of both ventricular apices.

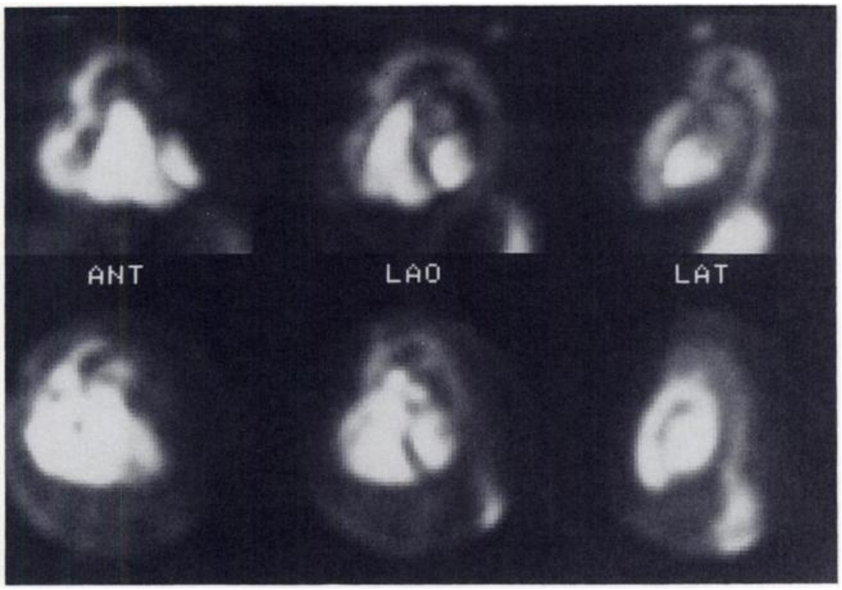

FIGURE 3
Three-dimensional images at end-diastole are shown in the top row in the same patient with abnormal apical wall motion presented in Figure 2. The bottom row shows the corresponding views obtained from the planar imaging study performed immediately before the tomographic study.

vessels with both beating rate and viewing angle interactively controlled by the user. Little effort is required to learn to interpret these new images because they appear visually very similar to conventional planar images, but with the advantages described below.

This volume approach differs from surface rendering methods developed previously by us (*11*) and others (*7*). A surface display requires detection of the surface of the blood pool, typically by a thresholding algorithm. This method can generate very misleading artifacts that can cause a ventricle to appear either dilated or small with filling defects, depending on the choice of threshold (*8*). Thus, we feel it is best not to rely on the surface-rendering technique for clinical imaging. The volume-based approach described here is essentially immune to this type of artifact. The ventricular edge is not detected; instead, information in the entire volume of the image is used. Only one parameter is set by the operator—the strength of depth attenuation. This variable is held fixed at a physically reasonable value and is never varied between studies. This paucity of user-determined parameters leads to generation of images with consistent quality with little likelihood that unexpected artifacts will arise.

The other significant problem hindering the widespread acceptance of tomographic gated imaging is the

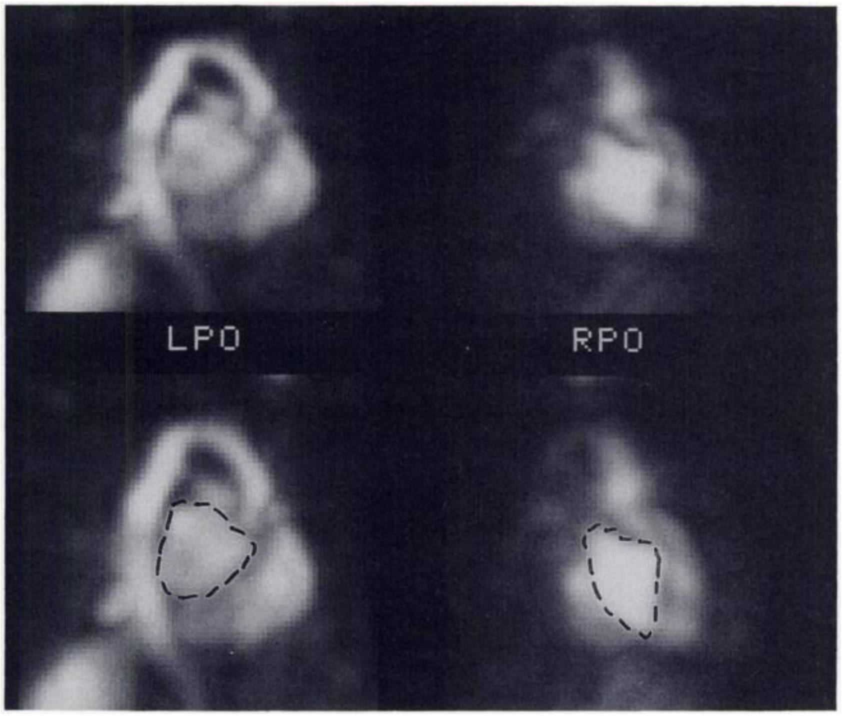

FIGURE 4
End-diastolic images in LPO and RPO orientations are shown. The same views are displayed on the bottom row with outlining of, respectively, the left atrium and right atrium.

FIGURE 5
Three-dimensional images are shown at end-diastole as viewed from above and below the heart. The most readily visualized cardiac chambers are outlined in the same images on the bottom row. Going from the observer's left to right they are the left ventricle, right ventricle and right atrium. The very bright structure in the image from below is the spleen. Also note the aortic arch as seen from above.

great demands placed on the computer. Sixteen time frames are produced, each of which requires a cube of data with dimensions of 64×64×40 pixels or greater. Thus, the raw reconstructed data comprise at least 2.5 million voxels or 5 Mbytes. Others have described processing times as long as 3–4 hr per patient (*1*), making routine clinical application difficult or impossible. We have addressed these problems through use of a modern 32-bit computer with virtual memory management capability and a moderate physical memory (9 Mbytes). This type of computer is now widely available in nuclear medicine and is being used increasingly for computationally demanding tasks. Significant use was made of an array processor, a device becoming increasingly common in clinical nuclear medicine. Currently, our method requires ~80 min of processing, a time that is likely still too long for routine use. In the near future the computation time will decrease by one-half through increased application of the array processor (Table 1). The ramped backprojection will be performed in the array processor, reducing that step from 30 min to 6 min (private communication Marcelo G. Lima, Siemens Gammasonics, Inc.). Optimization of ray tracing in the array processor will reduce the time required for volume rendering from 37 min to ~18 min (private communication, Andy Lukas, CDA/Analogic Inc.). Thus, total processing time will be reduced to ~40 min, a clinically practical length of time. Acquisition of a study can proceed while the previous study is being processed, since the array processor and acquisition computer operate independently and with little operator intervention.

There are several advantages to the three-dimensional display described here compared to conventional three-view planar imaging. Since the orientation of the heart is continuously variable following batch mode processing of the 28 preselected, standard series of views, it is always possible to view every cardiac structure from the best perspective, thus maximizing the accuracy of interpretation and eliminating problems due to mispositioning of routine planar views. With additional, brief proc-

TABLE 1
Processing Time

Operation	Time (min)	
	Partial AP[*]	Full AP[†]
Ramped backprojection	30.0	5.8
Spatial/temporal filtering	10.4	10.4
Zoom	1.6	1.6
Volume rendering	37.1	18.0
Disk I/O	3.6	3.6
Total	82.7	39.4

---

[*] Timings using the hardware described in the Methods section. AP = array processor.

[†] Estimated timings with full use of the array processor (see Discussion section).

essing, the heart can even be viewed from positions impossible to obtain in a conventional study, such as from above or below (Fig. 5). Certain structures are especially well seen from the orientations made possible by tomographic imaging. Both atria are much better visualized, because they can be viewed at many angles, thus facilitating identification of the chambers and assessment of their size and contractility (Fig. 4). The difficulty, evident in planar imaging, in interpretation of regional wall motion abnormalities of the posteroinferior wall of the left ventricle is reduced because the observer can view that wall at several angles, thus permitting interpretation from the orientation most favorable for the configuration of the individual patient's heart. It is possible to perform the volume rendering after digital removal of any desired chamber, thus permitting, for example, viewing of the right ventricle without the overlapping right atrium or left ventricle or viewing of the left atrium without the left ventricle or descending aorta. A potential additional advantage of volume rendering is the use of image data from all 64 projection angles in every three-dimensional image, thus possibly improving image quality (Fig. 3).

Many techniques have been proposed for acquisition of the tomographic data (*1–7*). We have selected a 180-degree rotation at 64 angles with collection in a 64×64 pixel matrix. Collection over 360° is also satisfactory if a camera is available that can acquire images in a noncircular orbit to minimize the distance between the patient and the camera (*1*). Since we do not have the noncircular capability, 180-degree rotation also achieves the advantage of camera proximity to the patient without the introduction of visually apparent reconstruction artifacts. A high-resolution collimator is employed to maximize resolution without an unacceptably low signal-to-noise ratio (*1,12,13*). It is important not to exceed a total imaging time of 30 min because many patients are too ill to lie quietly with one arm above the head for a longer interval. Acquisition in a 128×128 pixel matrix is sometimes advocated since the image of the heart is rather small when a large field-of-view camera is used. Since this matrix size entails an eightfold increase in memory and processing time compared to 64×64 pixel acquisition, we have chosen to collect in the smaller matrix and perform a trilinear interpolation to increase the size of the heart. This approach is justified because the sampling interval at a 64 pixel size is still smaller than the minimum interval determined by the Nyquist sampling theorem since the average spatial resolution in the acquired projection images is approximately 10 mm full width at half maximum (*14*).

The emphasis in the work reported here is on display methods and enhanced computer processing techniques. Determination of left ventricular ejection fraction is not discussed, since both voxel-based and count-based methods have been well described in the literature (*1–6*).

In summary, a new method of three-dimensional display of nuclear medicine images has been applied to gated cardiac blood-pool studies. This method provides visualization of the heart from any orientation and with improved image quality, thus facilitating interpretation of cardiac abnormalities. Computation time can be held to a clinically reasonable value through use of an array processor.

ACKNOWLEDGMENTS

This work was supported in part by a grant from Siemens Medical Systems, Inc., Des Plaines, IL. The authors thank Mary T. Clarke and Lorraine DiPlacido for assistance in preparation of the manuscript.

REFERENCES

1. Fischman AJ, Moore RH, Gill JB, Strauss HW. Gated blood pool tomography: a technology whose time has come. *Semin Nucl Med* 1989; 19:13–21.
2. Moore ML, Murphy PH, Burdine JA. ECG-gated emission computed tomography of the cardiac blood pool. *Radiology* 1980; 134:233–235.
3. Tamaki N, Mukai T, Ishii Y, et al. Multiaxial tomography of heart chambers by gated blood-pool emission computed tomography using a rotating gamma camera. *Radiology* 1983; 147:547–554.
4. Corbett JR, Jansen DE, Lewis SL, et al. Tomographic gated blood pool radionuclid ventriculography: analysis of wall motion and left ventricular volumes in patients with coronary artery disease. *J Am Coll Cardiol* 1985; 6:349–358.
5. Stadius ML, Williams DL, Harp G, et al. Left ventricular volume determination using single-photon emission computed tomography. *Am J Cardiol* 1985; 55:1185–1191.
6. Caputo GR, Graham MM, Brust KD, Kennedy JW, Nelp WB. Measurement of left ventricular volume using single-photon emission computed tomography. *Am J Cardiol* 1985; 56:781–786.
7. Gibson CJ. Real time 3D display of gated blood pool tomograms. *Phys Med Biol* 1988; 33:569–581.
8. Wallis JW, Miller TR, Lerner CA, Kleerup EC. Three-dimensional display in nuclear medicine. *IEEE Trans Med Imag:* in press.
9. Miller TR, Goldman KJ, Epstein DM, et al. Improved interpretation of gated cardiac images by use of digital filters. *Radiology* 1984; 152:795–800.
10. Miller TR, Wallis JW, Wilson AD. Interactive reconstruction in single-photon tomography. *Eur J Nucl Med* 1989; 15:189–193.
11. Miller TR, Starren JB, Grothe RA, Jr. Three-dimensional display of positron emission tomography of the heart. *J Nucl Med* 1988; 29:530–537.
12. Mueller SP, Polak JF, Kijewski MF, Holman BL. Collimator selection for SPECT brain imaging: the advantage of high resolution. *J Nucl Med* 1986; 27:1729–1738.
13. Muehllehner G. Effect of resolution improvement on required count density in ECT imaging: a computer simulation. *Phys Med Biol* 1985; 30:163–173.
14. Castleman KR. *Digital image processing.* Englewood Cliffs: Prentice-Hall, 1979: 226–249.