

ASNC IMAGING GUIDELINES FOR NUCLEAR CARDIOLOGY PROCEDURES

Myocardial perfusion and function: Single photon emission computed tomography

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Purpose. To evaluate regional myocardial perfusion and function.

ACQUISITION PROTOCOLS

Protocols for the various nuclear cardiology single photon emission computed tomography (SPECT) acquisition studies are presented in the following pages (Tables 1-6). For each of the protocols, the acquisition parameters are listed along with their corresponding value for exercise and rest. Implementation of these protocol acquisition parameters has been shown to provide acceptable images of good quality for routine clinical interpretation and quantitation. However, protocol parameters other than those listed may be preferred at some institutions, and ongoing research into corrections for attenuation, scatter, and camera response depth dependence may result in better parameters in the future. Therefore these protocols should be viewed as a consensus of opinion on the parameters that will provide acceptable images. A description for each of the acquisition parameters is listed below.

1. **Dose.** The doses for each of the protocols represent standard doses commonly used clinically. The standard doses described are given for an average 70-kg patient. Doses may be adjusted upward for heavier patients by 0.04 mCi/kg for thallium 201 and by 0.31 mCi/kg for technetium 99m. Other options are in-

creased imaging times, the use of multidetector systems, or 2-day imaging. Tl-201 imaging times can be adjusted based on the counts acquired for a preliminary 4-minute planar study in order to ensure acquiring at least 500,000 background-subtracted myocardial counts.

2. **Position.** Factors influencing patient position include camera/gantry design, minimization of artifacts, and patient comfort. The supine position is routinely used for SPECT imaging with most currently available systems and protocols. Prone imaging has been reported to produce less patient motion and less inferior wall attenuation than supine imaging.^{1,2} The combination of supine and prone images may be helpful in identifying attenuation artifacts due to breast and/or excessive lateral chest-wall fat, due to the shift in position of the attenuating structures that occurs in the prone position. In some laboratories the advantages of prone imaging in clarifying artifactual defects has led to a routine use of the combination of supine followed by prone acquisitions.³ It appears that prone imaging does not eliminate attenuation artifact but rather simply changes the location. By comparing supine and prone images, artifactual defects will change their location whereas true perfusion defects will remain fixed.^{4,5} Therefore it is suggested that prone imaging be done in combination with supine imaging and not simply replace it. When being used in this fashion, the acquisition time for the secondary (prone) image set is reduced by 20% to 40%. Using a dual-detector camera with 25 to 30 mCi of a Tc-99m perfusion agent, supine acquisitions are performed for 25 seconds per stop and prone acquisitions for 15

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Table 1. Patient protocol: Same-day rest-stress Tc-99m acquisition

	Rest study	Stress study		For information, see paragraph
Dose	8-12 mCi	24-36 mCi	Standard	1
Position	Supine	Supine	Standard	2
	Prone	Prone	Optional	2
	Upright/semi-upright	Upright/semi-upright	Optional	
Delay time (intervals)				
Injection → imaging	30-60 min	15-60 min	Standard	3
Rest → stress		30 min to 4 h	Standard	3
Acquisition protocol				
Energy window	15%-20% symmetric	Same	Standard	4
Collimator	LEHR	Same	Preferred	5
Orbit	180° (45° RAO to 45° LPO)	Same	Preferred	6
Orbit type	Circular	Same	Standard	7
	Non-circular	Same	Standard	7
Pixel size	6.4 ± 0.4 mm	Same	Standard	8
Acquisition type	Step and shoot	Same	Standard	9
	Continuous	Same	Optional	9
No. of projections	60-64	Same	Standard	10
Matrix	64 × 64	Same	Standard	11
Time/projection	25 s	20 s	Standard	12
ECG gated	Optional	Standard	Preferred	14
Frames/cycle	8	8	Standard	14
	8	16	Optional	
	16	16	Optional	14
R-to-R window	100%	100%	Preferred	14

RAO, Right anterior oblique; LPO, left posterior oblique.

seconds per stop, with 30 to 32 stops per detector being obtained per acquisition along a 180° orbit (right anterior oblique 45° to left posterior oblique 45°). With Tl-201, imaging should be begun approximately 10 to 15 minutes after stress testing, and if soft-tissue attenuation or patient motion compromises a study, the benefit of repeating the acquisition is questionable. In contrast, Tc-99m sestamibi or Tc-99m tetrofosmin permits stress testing and tracer injection to take place at a location remote from the imaging laboratory and image acquisition can simply be repeated when patient motion, soft-tissue attenuation, or other artifact is considered to be responsible for the production of a perfusion defect. Some camera/gantry designs require the patient to be positioned in a more upright position. Changes in patient positioning from those described above will likely cause changes in the distribution of adjacent soft-tissue attenuation and need to be considered in image interpretation. New normal databases will most likely need to be generated for different patient positions.

3. **Delay time.** These times are listed as ranges; specific values are optional. The objectives are to allow the patient to recover fully from exercise, thus allowing heart rate to return to baseline (reducing gating artifact), avoiding “upward creep” from changes in respiratory patterns while dyspnea resolves, and to minimize interference from hepatic uptake.⁶ Provided that imaging times fall within the specified ranges, clinically useful SPECT images should result.
4. **Energy windows.** Energy window position is determined by the radioisotope employed, 140 keV for technetium-based perfusion agents and 70 keV for thallium. It is reasonable to simultaneously acquire the higher energy peaks of thallium (135 and 167 keV) on cameras that are capable of doing this. The window sizes are determined largely by convention and reflect the tradeoff between image counts and resolution. The values shown are the most commonly used and have been found to be acceptable for most cameras. On systems offering improved energy resolution, the window size may be reduced, result-

Table 2. Patient protocol: Same-day stress-rest Tc-99m acquisition

	Stress study	Rest study		For information, see paragraph
Dose	8-12 mCi	24-36 mCi	Standard	1
Position	Supine	Supine	Standard	2
	Prone	Prone	Optional	2
	Upright/semi-upright	Upright/semi-upright	Optional	
Delay time (intervals)				
Injection → imaging	15 min to 1 h	30-60 min	Standard	3
Stress → rest		30 min to 4 h	Standard	3
Acquisition protocol				
Energy window	15%-20% symmetric	Same	Standard	4
Collimator	LEHR	Same	Preferred	5
Orbit	180° (45° RAO to 45° LPO)	Same	Preferred	6
Orbit type	Circular	Same	Standard	7
	Non-circular	Same	Standard	7
Pixel size	6.4 ± 0.4 mm	Same	Standard	8
Acquisition type	Step and shoot	Same	Standard	9
	Continuous	Same	Optional	9
No. of projections	60-64	Same	Standard	10
Matrix	64 × 64	Same	Standard	11
Time/projection	25 s	20 s	Standard	12
ECG gated	Optional	Standard	Preferred	14
Frames/cycle	8	8	Standard	14
	16	16	Optional	14
R-to-R window	100%	100%	Preferred	14

RAO, Right anterior oblique; LPO, left posterior oblique.

ing in decreased scatter and improved image resolution, so long as imaging times are extended to acquire the same clinically useful number of counts. The same energy windows used in performing patient studies should be used for routine daily quality control (QC).

5. **Collimator.** Parallel-hole collimators are most commonly employed for cardiac SPECT acquisitions. They fall into two categories: low-energy all-purpose (LEAP), used mostly for Tl-201 studies, and low-energy high-resolution (LEHR), used for Tc-99m studies. Compared with LEAP collimators, LEHR collimators have longer bores, thinner septa, and smaller holes, which provide better resolution at the expense of reduced sensitivity. Therefore, to use LEHR collimators, imaging agents providing high count rates are required (ie, Tc-99m agents). Generally, LEAP collimators are used for 3-mCi Tl-201 studies, including gated SPECT acquisitions. For dual-isotope studies, LEHR collimators are suggested.
6. **Orbit.** Due to the anterior position of the heart in the left hemithorax, much higher count rates are ob-

tained per given period of imaging time for a 180° orbit (45° right anterior oblique to 45° left posterior oblique) compared to a 360° orbit.⁷ The recommendation of which orbit will depend on the camera configuration; it does not seem to be worthwhile to increase imaging time to complete a 360° orbit since much better count statistics will be obtained if that time is used to increase acquisition on a 180° orbit.⁸ A 360° orbit is appropriate for 3-headed cameras with a 360° configuration where a 360° orbit is acquired in the same time as a 180° orbit. The utility of the posterior 180° of a 360° orbit is much greater for higher-energy radioisotopes (such as technetium) compared to low-energy radioisotopes (such as thallium).

7. **Orbit type.** The main orbit options in SPECT myocardial perfusion imaging are circular versus noncircular (elliptical or body-contoured) orbits. Noncircular orbits follow the contour of the patient, bringing the camera closer to the patient, thereby improving spatial resolution. Circular orbits maintain a fixed radius of rotation and on average result in the detector being further from the patient. In

Table 3. Patient protocol: Two-day stress Tc-99m acquisition

	Stress study	Rest study		For information, see paragraph
Dose	30 mCi	30 mCi	Standard	1
Position	Supine	Supine	Standard	2
	Prone	Prone	Optional	2
Delay time (intervals)				
Injection → imaging	15-60 min	30-60 min	Standard	3
Acquisition protocol				
Energy window	15%-20% symmetric	Same	Standard	4
Collimator	LEHR	Same	Preferred	5
Orbit	180° (45° RAO to 45° LPO)	Same	Preferred	6
Orbit type	Circular	Same	Standard	7
	Non-circular	Same	Standard	7
Pixel size	6.4 ± 0.4 mm	Same	Standard	8
Acquisition type	Step and shoot	Same	Standard	9
	Continuous	Same	Optional	9
No. of projections	60-64	Same	Standard	10
Matrix	64 × 64	Same	Standard	11
Time/projection	20 s	20 s	Standard	12
ECG gated	Standard	Standard	Preferred	14
Frames/cycle	8	8	Standard	14
	16	16	Optional	14
R-to-R window	100%	100%	Preferred	14

RAO, Right anterior oblique; LPO, left posterior oblique.

general, there is reduced (but more uniform) spatial resolution with circular orbits since the detector-to-source distance is greater with this technique. Circular acquisitions continue to be the most frequently used option, but some manufacturers do provide noncircular orbit capability. Imaging artifacts have been observed when noncircular orbits are used, due to increased variation of source-to-detector distance, resulting in variation of spatial resolution.⁹

8. **Pixel size.** The SPECT protocols listed here specify a 6.4 ± 0.4-mm pixel size for a 64 × 64 image matrix. This size offers satisfactory image resolution for interpretation and quantitation of both Tl-201 and Tc-99m tomograms.
9. **Acquisition type.** The most widespread mode of tomographic acquisition is the “step-and-shoot” method. In this approach, the camera acquires a projection and then stops recording data when moving to the next angle; this results in a small amount of dead time since the camera is not acquiring data while it is moving. An alternative is “continuous” mode, where the camera moves continuously and acquires each projection over an angular increment. This eliminates dead time and thus increases image counts at the expense of a small amount of blurring

due to the motion of the camera head while acquiring. It seems likely that the increase in count statistics more than offsets the small amount of blurring due to camera motion.

10. **Number of projections.** The optimal number of projections for emission studies depends on matching the number of projections to the resolution of the system. A thallium SPECT acquisition with a LEAP collimator is a relatively low-resolution study, for which 32 projections over 180° are sufficient. A higher-resolution study using Tc-99m agents should be collected with a high-resolution collimator; this requires at least 60 to 64 projections over 180° to prevent loss of resolution. Larger numbers of projections are not necessary at this time but could become beneficial if technical innovations result in improved overall system resolution.
11. **Matrix.** The standard matrix size for emission SPECT is 64 × 64 pixels.
12. **Time/projection.** The emission acquisition times listed have been found to produce images of acceptable and comparable quality for rest and stress studies.
13. **Total time.** For single-detector systems, the total time for an emission acquisition ultimately is based

Table 4. Patient protocol: Separate dual-isotope acquisition

	Rest study	Stress study		For information, see paragraph
Dose	2.5-3.5 mCi Tl-201	30 mCi Tc-99m	Standard	1
Position	Supine	Supine	Standard	2
	Prone	Prone	Optional	
	Upright/semi-upright	Upright/semi-upright	Optional	
Delay time (intervals)				
Injection → imaging	10-15 min	15-60 min	Standard	3
Rest → stress		No delay	Standard	3
Acquisition protocol				
Energy window	25%-30% symmetric, 70 keV 20% symmetric, 167 keV	15%-20% symmetric, 140 keV	Standard	4
Collimator	LEHR	Same	Preferred	5
Orbit	180° (45° RAO to 45° LPO)	Same	Preferred	6
Orbit type	Circular	Same	Standard	7
	Non-circular	Same	Standard	7
Pixel size	6.4 ± 0.4 mm	Same	Standard	8
Acquisition type	Step and shoot	Same	Standard	9
	Continuous	Same	Optional	9
No. of projections	32-64	60-64	Standard	10
Matrix	64 × 64	Same	Standard	11
Time/projection	40 s (32 fr), 25 s (64 fr)	20 s	Standard	12
ECG gated	Optional	Standard	Preferred	14
Frames/cycle	8	8	Standard	14
	16	16	Optional	
R-to-R window	100%	100%	Preferred	14

RAO, Right anterior oblique; LPO, left posterior oblique.

on how long a patient can tolerate the procedure without moving, balanced by the need to acquire sufficient counts. The maximum practical time is on the order of 30 minutes. For 90° dual-detector systems, this time can be halved, and many laboratories obtain gated perfusion SPECT studies in only 12 to 15 minutes using biplane cameras. Consideration may be made for increasing imaging time in patients likely to have lower count statistics (eg, obese patients) if it is felt that they can tolerate it.

- Gated SPECT.** Incorporation of wall motion and wall thickening information from gated SPECT has been shown to increase specificity and confidence by helping to differentiate breast and diaphragmatic attenuation artifacts from true perfusion defects. Likewise, assessment of regional wall motion and/or thickening can be a valuable tool for detecting viability within a stress-induced perfusion defect. Left ventricular (LV) ejection fractions (EFs) and volumes, as well as regional wall motion and thickening, now are computed routinely from gated SPECT data using commercially available soft-

ware.¹⁰ The majority of stress myocardial perfusion radionuclide studies currently are acquired as gated SPECT data. However, there is mounting evidence that the information content of the post-stress acquisition may be different from that of the resting data in patients who have post-ischemic stunning of myocardium.¹¹ Discrepancies may also be present if the count density is suboptimal due to the lower tracer dose in the resting scan (same-day rest/stress protocol) and/or hypoperfusion of a segment at stress. Providing that there is adequate count density, particularly with regard to the lower-dose acquisitions, both stress and rest SPECT perfusion studies may be acquired as gated data sets. Optimizing protocols for which both stress and rest gated data are acquired remains an area of investigation.

- Multidetector systems.** It is recommended for multidetector systems that total imaging time be adjusted to obtain greater than the minimum counts listed in the “Instrumentation Quality Assurance and Performance” section of these guidelines (in the subsection entitled “Clinical QA for Each Patient

Table 5. Patient protocol: Stress/redistribution TI-201 acquisition

	Stress study	Redistribution rest study		For information, see paragraph
Dose	2.5-3.5 mCi TI-201	Not applicable	Standard	1
Position	Supine	Supine	Standard	2
	Prone	Prone	Optional	
	Upright/semi-upright	Upright/semi-upright	Optional	
Delay time (intervals)				
Injection → imaging	10-15 min*	Not applicable	Standard	3
Stress → rest		3-4 h	Standard	3
Acquisition protocol				
Energy window	30% symmetric, 70 keV 20% symmetric, 167 keV	Same	Standard	4
Collimator	LEAP	Same	Preferred	5
Orbit	180° (45° RAO to 45° LPO)	Same	Preferred	6
Orbit type	Circular	Same	Standard	7
	Non-circular	Same	Standard	7
Pixel size	6.4 ± 0.4 mm	Same	Standard	8
Acquisition type	Step and shoot	Same	Standard	9
	Continuous	Same	Optional	9
No. of projections	32-64	Same	Standard	10
Matrix	64 × 64	Same	Standard	11
Time/projection	40 s (32 fr), 25 s (64 fr)	40 s (32 fr), 25 s (64 fr)	Standard	12

RAO, Right anterior oblique; LPO, left posterior oblique.

*An anterior planar image may be acquired during this interval to evaluate TI-201 lung uptake.

Procedure”) but less than a maximum total imaging time of 30 minutes.

- The following acquisition parameters are recommended for the imaging protocols described in the “Stress Protocols and Tracers” section of these guidelines.

PROCESSING PROTOCOLS

- Filtering.** Image filtering is a very complex topic that encompasses techniques for image enhancement, reconstruction, and feature extraction.^{12,13} The main area of concern for an interpreter of SPECT studies is image enhancement by reducing noise prior to image reconstruction. All forms of imaging are plagued by statistical variation in the acquired image counts commonly referred to as noise. The quality of an image can be described as the signal-to-noise ratio, which describes the relative strength of the signal component (what is actually being imaged) compared to noise. The signal-to-noise ratio is much higher at lower spatial frequencies (broad features that are constant over many pixels) and decreases at higher spatial frequencies (features that change over few pixels such as edges). In general, the greater the count

statistics, the better the signal-to-noise ratio. A low-pass filter is generally used to reduce noise because it allows low spatial frequencies to pass through and attenuates the high frequencies where image noise predominates. Low-pass filters such as the Hanning and Butterworth can be characterized by a cutoff frequency where they begin to affect the image. The cutoff frequency can be adjusted, depending on the signal-to-noise ratio, to preserve as much of the signal and suppress¹⁴ as much noise as possible. If the cutoff is too high, there is significant noise in the image; if the cutoff is too low, significant information in the signal is suppressed. Nuclear cardiology images, because of their relatively low count statistics, tend to have greater amounts of image noise, and filtered backprojection, because of its dependence on ramp filtering, tends to amplify this noise. The optimal filter for a given image depends on the signal-to-noise ratio for that image; under-filtering an image leaves significant noise in the image, and over-filtering unnecessarily blurs image detail; both over-filtering and under-filtering can reduce image accuracy. Software reconstruction packages are set with default filter selection and cutoff values that are optimized for the average patient. Adjustment of the filter cutoff can be

Table 6. Patient protocol: Stress/reinjection/redistribution Tl-201 acquisition

	Stress study	Reinjection	(Redistribution) rest study		For information, see paragraph
Dose	2.5-3.5 mCi	1.0-1.5mCi	Not applicable	Standard	1
Position	Supine		Supine	Standard	2
	Prone		Prone	Optional	2
	Upright/semi-upright		Upright/semi-upright	Optional	
Delay time (intervals)					
Injection → imaging	10-15 min		Not applicable	Standard	3
Stress → redistribution			3-4 h	Standard	3
Reinjection → imaging (MI)			20-30 min	Standard	3
24-h imaging				Optional	3
Acquisition protocol					
Energy window	30% symmetric, 70 keV		Same	Standard	4
	20% symmetric, 167 keV				
Collimator	LEAP		Same	Preferred	5
Orbit	180° (45° RAO to 45° LPO)		Same	Preferred	6
Orbit type	Circular		Same	Standard	7
	Non-circular		Same	Standard	7
Pixel size	6.4 ± 0.4 mm		Same	Standard	8
Acquisition type	Step and shoot		Same	Standard	9
	Continuous		Same	Optional	9
No. of projections	32-64		Same	Standard	10
Matrix	64 × 64		Same	Standard	11
Time/projection	40 s (32 fr), 25 s (64 fr)		40 s (32 fr), 25 s (64 fr)	Standard	12

RAO, Right anterior oblique; LPO, left posterior oblique.

done in patients with poor count statistics (eg, obese patients) to optimally filter their images. However, this is discouraged unless the physician is thoroughly familiar with filter adjustment and the potential effects. Changing the filter cutoff may have unexpected effects on the output of commercially available analysis programs, especially those that employ edge detection such as defect quantitation and LV volumes and EF. Deconvolving filters, such as the Metz and Wiener filters, can correct for blurring that occurs from scatter as photons travel through the body. Although images may look sharper with these filters, these filters have not yet been shown to improve image accuracy.¹²

2. **Reconstruction.** The traditional method of image reconstruction has been filtered backprojection, a technique based on a mathematical proof, which assumes no attenuation, no scatter, and an infinite number of projections. It is relatively straightforward and comparatively fast.¹⁵ The vast majority of clinical

experience is based upon it, and it has withstood the test of time despite its inability to model attenuation and scatter. There is a different class of reconstruction algorithms that are based on iterative techniques. These algorithms start with a rudimentary guess of the distribution, generate projections from the guess, and compare these projections to the acquired projections. The guess is refined based on the differences between the generated and actual projections, and the process is repeated (hence the term “iterative”) usually for a fixed number of iterations but can also be repeated until the error between the generated and actual projections is acceptably small. A main advantage of these algorithms is that the process of generating projections from the guess can be made as sophisticated as desired and can incorporate such variables as attenuation, scatter, and depth-dependent blur. The main disadvantage is the computational intensity of the algorithm; it takes many times longer to complete than filtered backprojection. However, due to contin-

ual increases in computer processor speed, these algorithms can now be completed in an acceptable time for routine clinical use. Nonetheless, iterative techniques have not yet been proven to be unequivocally superior to filtered backprojection.

- 3. Reorientation.** A critical phase of myocardial processing is reorientation of tomographic data into the natural approximate symmetry axes of an individual patient's heart. This is performed either by an observer or automatically and results in sectioning the data into vertical long-axis, horizontal long-axis, and short-axis planes. Long-axis orientation lines should be parallel to long-axis walls of the myocardium and should be consistent between rest and stress studies. Inappropriate plane selections can result in misaligned myocardial walls between rest and stress data sets, potentially resulting in incorrect interpretation. It is crucial that all axis choices be available as QC screens, and that these are reviewed by the technologist and the physician who reads each study to verify that axes were selected properly.
- 4. Display-cine review.** The most important post-acquisition QC procedure is to view the raw tomographic data in cine mode. This presentation offers a sensitive method for detecting patient and/or heart motion, "upward creep," breast shadow due to attenuation, diaphragmatic attenuation, and superimposed abdominal visceral activity, all of which can create artifacts in the reconstructed images. Review of the raw tomograms in cine mode is performed twice: once by the technologist immediately after the acquisition and again by the physician during image interpretation. For gated studies, usually it is only the sum of all gated tomograms that is reviewed in this manner; this will alert the observer to most types of gating errors due to arrhythmias manifested by an intermittent flashing of the images. However, for the detection of gating errors due to some types of transient arrhythmias, a full display of all count-versus-projection curve data is helpful. Cine reviews occasionally show abnormalities in the abdomen or thorax such as renal cysts or abnormal uptake that may be suspicious for neoplasm. The accuracy and clinical utility of these findings have not yet been established.
- 5. Display-study review.** It is strongly recommended that physicians use the active computer screen for reviewing images and use film and paper hard copies only for record-keeping purposes. Images produced by formatters onto transparency film or photographic paper can have variable contrast, also termed gamma, and result in inconsistent image interpretation. Computer screen outputs are relatively more stable and always have readily available monochromatic con-

trast bars or color code bars to the side of the images, enabling more consistent viewing conditions. In addition, computer screens offer rapid sequential and/or cinematic displays of image data. For all of these reasons, screen interpretation is strongly recommended over relying on interpretations from hard copies.¹⁶

PERFUSION QUANTITATION

The display medium and translation table employed can have a significant impact on image interpretation, going as far as to make a normal perfusion scan appear abnormal or vice versa. Quantitative analysis is a direct way of measuring relative uptake of a perfusion tracer that is independent of the display medium and translation table and can thus greatly reduce variations in interpretation due to subjective analysis and inconsistent image display. Quantitative analysis also allows for the comparison of a study with a gender-specific normal database. For this reason, quantitative analysis is recommended as part of image interpretation. Traditional, circumferential profile-based quantitative analysis consists of the following steps:

- 1. Image quantitation.** This measures the relative activity, most often in a short-axis slice, by generating a circumferential profile also known as a radial plot. This is done by first identifying the center of the lumen and the inner and outer boundaries of the ventricle. The activity in each part of the slice is determined by measuring the activity in each pixel lying on a radius between the inner and outer boundaries, analogous to moving along a spoke of a wagon wheel from the hub to the rim. The radius is then rotated slightly (analogous to going to the next spoke of the wagon wheel), and the activity is again measured. This is repeated until the entire circumference has been traversed. Determination of activity along each radius can be as simple as identifying the maximal pixel or as complicated as fitting the profile to a Gaussian curve.
- 2. Normalization and scaling.** Myocardial perfusion imaging can only measure relative uptake. In order to compare different studies or compare with normal databases, the images must be normalized to a certain value. Each slice can be normalized to its own maximum, but it is much more common to normalize to the maximal pixel in the ventricle. All values are multiplied by 100/value of the maximum pixel, which sets the maximum pixel to 100 and all others to a fraction of that. Finally, the ventricle is "scaled" to a constant number of curves; smaller ventricles with fewer short-axis slices are interpolated up, and larger

ventricles with more short-axis slices are decimated down to achieve a constant number of curves. Thus relative activity can be compared for any location in two ventricles regardless of their absolute tracer uptake or chamber size.

- 3. Polar plot generation (optional).** Each radial plot generated in step 1 generates a series of numbers that can be displayed as a graph. The entire LV volume would be represented by a series of graphs, which is difficult to assimilate. Alternatively, these plots can be used to make a “bull’s-eye” or polar plot.¹⁷ Instead of generating a graph, the radial profiles are used to make a series of rings of activity, where the intensity of the ring corresponds to the relative activity of the corresponding polar plot and the diameter of the rings grows moving toward the base of the heart. These can then be fused into a single image where each successive ring is formed around the one preceding it, analogous to the rings of a tree. This creates a 2-dimensional image that reflects the relative activity in the 3-dimensional left ventricle with the apex at the center of the polar plot and the base as the outer ring.^{17,18} The width of the rings can be adjusted to reflect the relative size of the corresponding short-axis images so that a given area of the polar plot corresponds to a constant fraction of the volume of the left ventricle in a process known as “volume weighting.”
- 4. Database construction and analysis.** It is frequently difficult to differentiate true perfusion defects from soft-tissue attenuation; women tend to have anterior defects from breast attenuation, and men tend to have inferior wall defects from diaphragmatic attenuation.¹⁹ A range for “normal” soft-tissue attenuation can be defined by creating a normal database; gender-specific normal databases are usually employed due to the different attenuation patterns for men and women. These can be generated by performing radial plot analysis on “normals”—that is, patients proven not to have coronary disease or, more often, patients with an acceptably low probability of having coronary disease (usually <5% or <1%). The mean and standard deviation of activity for each point of the ventricle are calculated for the male and female normals; the result is the normal database for each gender. The normalized and scaled activity for each point of the ventricle of a patient is compared to the mean of the corresponding gender-based normal database; if the activity is more than a predetermined number of standard deviations below the mean of the normals (2.5 standard deviations is most frequently used), it is considered abnormal. It should be realized that this definition of normal is statistical, not absolute. There will still be overlap between normal and abnormal uptake.

- 5. Parameters.** Different parametric images can be generated to show the results of quantitative analysis, such as “blackout,” “severity,” and “reversibility” maps. A blackout map generates a polar plot for the patient marking those points that fall a predetermined number of standard deviations below the gender-based normal limits and thus demonstrates the size or extent of the perfusion defect. Another type of parametric image can be generated which shows the number of standard deviations that activity falls below the mean of normals and thus demonstrates severity. A third can be generated which quantitates the activity on the stress and rest images and demonstrates which areas show improved perfusion at rest, which is known as a reversibility map.

GATED SPECT

Acquisition. The introduction of technetium-based perfusion tracers has resulted in images with sufficient count density to allow for cardiac gating adding parameters of wall motion, wall thickening, and EF to myocardial perfusion imaging.²⁰⁻²³ Gating requires a stable and consistent heart rhythm as well as sufficient temporal resolution to correctly characterize the cardiac cycle. A stable heart rate and rhythm can be achieved by rejecting heartbeats that fall out of range at the expense of an increase in image time. This “beat length acceptance window” can vary from 20% to 100% of the expected R-to-R duration, the recommended value being 20% if an “extra frame” is provided that allows the accumulation of rejected counts. Most laboratories gate the heart for 8 frames per cycle, although an increasing number of laboratories have reported good results with 16 frames per cycle and have used the increased temporal sampling to derive more accurate estimates of LVEF as well as parameters of diastolic function. For either 8- or 16-frame gating, the recommendations are to avoid beat rejection. The lower count statistics achieved with Tl-201 imaging make gating more challenging with this isotope, but many laboratories have reported satisfactory results using 8-frame gating in selected patients.²⁴ Processing is done using commercially available software.

INTERPRETATION AND REPORTING

General Comments

The interpretation of myocardial perfusion SPECT images should be performed in a systematic fashion to include (1) repeat evaluation of the raw tomographic images to determine the presence of technical sources of abnormalities and extracardiac activity; (2) interpretation of images with respect to the location, size, severity, and

reversibility of defects as well as chamber sizes and, for TI-201, presence or absence of pulmonary uptake; (3) incorporation of the results of quantitative analysis; (4) consideration of functional data obtained from the study; and (5) consideration of clinical factors that may have influenced the presence of any findings. All of those factors contribute to the production of a final clinical report. Guidelines for interpreting and reporting myocardial perfusion SPECT are listed in [Tables 8 and 9](#).

Display

1. **Recommended medium for display.** It is strongly suggested that the reading physician use the computer monitor screen rather than hard copy to interpret the study since a monitor screen is capable of displaying more variations in gray scale or color (making it easier to discern smaller variations in uptake) and is more consistent than film. Moreover, it is not possible to properly view moving images (eg, raw tomographic data or gated images) on hard copy. A linear gray-scale translation table is generally preferred to color tables since it demonstrates consistent grades of uptake compared to pseudocontouring seen with color scales, but this is also dependent on how familiar the reader is with a given translation table.^{16,25} The reader should be aware that the appearance of an image can change significantly when changing from one translation table to another. A linear scale is preferred to nonlinear (eg, sigmoidal) scales since it most faithfully characterizes uptake over the range of activity. A logarithmic scale may be used for evaluating regions of lower-count density such as soft-tissue uptake and the right ventricle but should never be used for interpreting LV uptake.^{16,25}
2. **Conventional slice display of SPECT images.** Three sets of images should be displayed: (a) a view generated by slicing perpendicular to the long axis of the left ventricle (short axis); (b) a view of long-axis tomograms generated by slicing in the vertical plane (vertical long axis); and (c) a view of long-axis tomograms generated by slicing in the horizontal plane (horizontal long axis). The short-axis tomograms should be displayed with the apical slices to the far left with progression of slices toward the base in a left-to-right fashion. The vertical long axis should be displayed with septal slices on the left and progression through the midventricular slices to the lateral slices in a left-to-right fashion. Similarly, the horizontal long-axis tomographic display should proceed left to right from the inferior to the superior (anterior) surface. It is also recommended that, for purposes of interpretation and comparison of se-

quential images (eg, stress and rest, rest and redistribution), these images be displayed aligned and adjacent to each other serially. There are two widely used approaches to image normalization. Each series (vertical, horizontal, short axis) may be normalized to the brightest pixel in the entire image set, which is known as "series normalization." This is considered to provide the most intuitively easy way to evaluate the extent and severity of perfusion defects. The drawbacks of this approach are its sensitivity to focal hot spots, the frequently poor visualization of normal structures at the base and apex of the left ventricle, and the lack of an ideal display of each individual slice.

The other approach is "frame normalization" in which each image is normalized to the brightest pixel within the frame. That method provides optimal image quality of each slice. The drawback of this approach is that the brightness of each slice is unrelated to the peak myocardial activity in the entire series such that gradations in activity between slices of a series may be lost. That drawback is mitigated by the display of three orthogonal planes.

3. **Three-dimensional display.** Most commercial software programs allow creation of 3-dimensional displays. These help less experienced readers identify coronary distributions associated with perfusion defects. These should be used only as an adjunct to, not a replacement for, the conventional image formatting described above.

Evaluation of Images for Technical Sources of Error

4. **Patient motion.** The interpreting physician should also review the raw tomographic images for possible sources of artifact. Images should again be inspected for the presence of patient motion. A cine display of the planar projection data is highly recommended because motion in both the craniocaudal and horizontal axes is readily detectable. Additionally, a static "sinogram" and sometimes "linogram" may be used to detect motion. Software routines are available for quantitation and correction of motion. The experienced reader should be familiar with the normal appearance of raw tomograms and be able to identify motion artifact. In patients who have had a technetium-based perfusion agent, consideration should be made for repeating the image acquisition where feasible when significant motion is detected. Alternatives such as planar imaging or prone positioning may be considered as well. The effect of patient motion on the final reconstructions is complex.^{6,26-28} Generally, up-and-down motion (espe-

cially when the heart returns to the same baseline) has less of an effect on the accuracy of the study than sideways motion. Also, up-and-down motion is much easier to correct either manually or with semiautomated software. Rotation currently cannot be corrected either manually or with available motion correction software. Since motion correction software may sometimes introduce motion artifact, corrected raw tomographic images should be evaluated in the same way for adequacy of the correction.

5. **Attenuation and attenuation correction.** The cine display of the planar projection images is also recommended for the identification of sources of attenuation, the most common being diaphragmatic in men and the breast in women.²⁹ Breast attenuation artifact is most problematic when it is different between the rest and stress images. When breast attenuation artifact is more prominent on the stress images than on the rest, it can be very challenging to exclude ischemia. Breast attenuation can sometimes be improved by repeating the acquisition with the breast repositioned. Diaphragmatic attenuation and breast attenuation may be reduced by imaging the patient prone. Hardware and software for attenuation and scatter correction are commercially available and may obviate or at least mitigate these common attenuation artifacts. The evaluation of attenuation-corrected (AC) images is performed with the same approach as that used for non-AC images. As with the interpretation of non-AC studies, it is essential that the interpreting physician be familiar with the segment-by-segment normal variation of uptake of radioactivity at stress and rest associated with the specific attenuation correction system that is being used.³⁰⁻³² AC images are displayed in the same manner as uncorrected images. Because the currently available correction algorithms are imperfect, it is recommended that the uncorrected data be interpreted along with the AC data.
6. **Reconstruction artifacts.** Superimposed bowel loops or liver activity may create artifactually intense uptake in adjacent myocardium that could mask a real perfusion defect or be misinterpreted as reduced uptake in adjacent or contralateral segments. Non-superimposed but adjacent extracardiac activity may also affect the reconstructed myocardial images. Intense activity in bowel loops or adjacent liver may cause a negative reconstruction artifact, resulting in an apparent reduction in activity in the adjacent myocardial segments. There is currently no reliable correction for such artifacts, although they may be less prominent with iterative as opposed to filtered backprojection techniques. They can often

be eliminated by repeating the acquisition after the activity level in the adjacent structure has decreased.

7. **Myocardial statistics.** Many factors are involved in the final count density of perfusion images including body habitus, exercise level, radiopharmaceutical dose, acquisition time, energy window, and collimation. The interpreting physician should make note of the count density in the planar projection images because the quality of the reconstructed data is a direct reflection of the raw data. Perfusion defects can be artifactually created simply because of poor statistics. As a general rule, peak pixel activity in the LV myocardium in an anterior planar projection should exceed 100 counts for a Tl-201 study and 200 counts in a Tc-99m study.

Initial Image Analysis and Interpretation

The initial interpretation of the perfusion study should be performed without any clinical information other than the patient's gender, height and weight, and peak exercise heart rate. Such an approach minimizes the bias in study interpretation. All relevant clinical data should be reviewed after a preliminary impression is formed.

8. **Ventricular dilation.** Before segmental analysis of myocardial perfusion, the reader should note whether there is LV enlargement at rest or during stress. Dilation on both the stress and resting studies usually indicates LV dysfunction, although it may be seen in volume overload states with normal ventricular function. Transient ischemic dilation (TID) has been described as a marker for high-risk coronary disease.³³ It is most likely due to diffuse subendocardial ischemia^{34,35} and can be seen in other conditions, such as microvascular disease, that cause diffuse subendocardial ischemia even in the absence of epicardial disease. TID is typically described quantitatively but may be quantified.³⁶ Normal limits by quantitation will depend on both the software and perfusion agents being used.
9. **Lung uptake.** The presence of increased lung uptake after thallium perfusion imaging has been described as an indicator of poor prognosis and should therefore be evaluated in all patients when using this perfusion agent.^{34,35,37} No clear consensus has emerged as to the significance of lung uptake with technetium-based perfusion agents.
10. **Right ventricular uptake.** Right ventricular (RV) uptake may be qualitatively assessed on the raw projection data and on the reconstructed data. There are no established quantitative criteria for RV uptake, but in general, the intensity of the right ventricle is approximately 50% of peak LV intensity. RV uptake increases in the presence of RV hypertrophy,

most typically because of pulmonary hypertension.³⁸ The intensity of the right ventricle may also appear relatively increased when LV uptake is globally reduced.³⁹⁻⁴¹ Regional abnormalities of RV uptake may be a sign of ischemia or infarct in the distribution of the right coronary artery. The size of the right ventricle should be noted.

11. **Noncardiac findings.** Both thallium- and technetium-based agents can be concentrated in tumors, and uptake outside the myocardium may reflect unexpected pathology. However, the accuracy and, in particular, the specificity of myocardial perfusion imaging for diagnosing noncardiac conditions have not been established. Splanchnic Tl-201 activity following adequate exercise stress (>85% maximum predicted heart rate) is generally reduced compared to resting images. This difference is not present following pharmacologic Tl-201 stress testing with dipyridamole, adenosine, or dobutamine.
12. **Perfusion defect location.** Myocardial perfusion defects should be identified by use of visual analysis of the reconstructed slices. The perfusion defects should be characterized by their location as they relate to specific myocardial walls—that is, apical, anterior, inferior, and lateral. The term posterior should probably be avoided because it has been variably assigned either to the lateral wall (circumflex distribution) or to the basal inferior wall (right coronary distribution) and is thus ambiguous. Standardization of segment nomenclature is highly recommended. (See the segmentation models described below.)
13. **Perfusion defect severity and extent: Qualitative.** Defect severity is typically expressed qualitatively as mild, moderate, or severe. Mild defects may be identified by a decrease in counts compared to adjacent activity without the appearance of wall thinning, moderate defects demonstrate wall thinning, and severe defects are those that approach background activity.^{42,43} Defect extent may be qualitatively described as small, medium, or large. In semiquantitative terms, small represents 5% to 10%, medium represents 15% to 20%, and large represents 20% of the left ventricle or greater.⁴³ Alternatively, defect extent may also be estimated as a fraction such as the “basal one half” or “apical one third” of a particular wall or as extending from base to apex. Defects whose severity and extent do not change between image sets (eg, stress and rest) are typically categorized as “fixed” or nonreversible. When changes do occur, a qualitative description of the degree of reversibility is required.
14. **Perfusion defect severity and extent: Semiquantitative.** In addition to the qualitative evaluation of

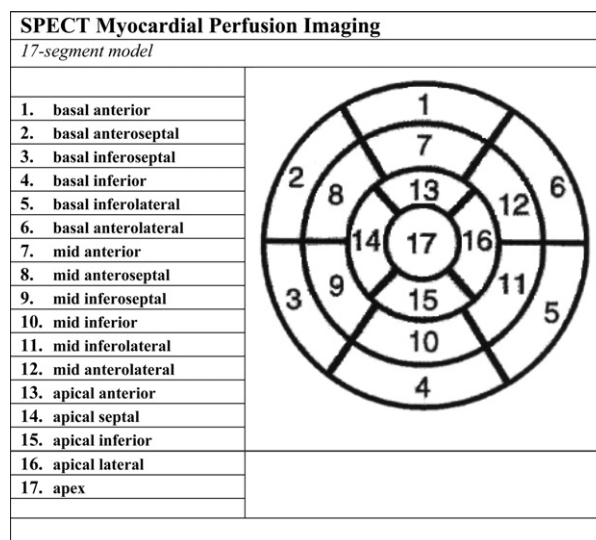


Figure 1. SPECT myocardial perfusion imaging: 17-segment model.

perfusion defects, it is preferred that the physician may also apply a semiquantitative method on the basis of a validated segmental scoring system. This approach standardizes the visual interpretation of scans, reduces the likelihood of overlooking significant defects, and provides an important semiquantitative index that is applicable to diagnostic and prognostic assessments. It is generally considered preferable to use a system with at least 16 segments.

The quality assurance (QA) committee of the American Society of Nuclear Cardiology has considered several models for segmentation of the perfusion images and has previously recommended either a 17- or 20-segment model for semiquantitative visual analysis. The models use three short-axis slices (apical, mid, and basal) to represent most of the ventricle and one vertical long-axis slice to better represent the LV apex. In both the 17- and 20-segment models, the basal and mid short-axis slices are divided into 6 segments. In the 17-segment model, the apical short-axis slice is divided into 4 segments, whereas in the 20-segment model, the apical short-axis slice is divided into 6 segments. In the 17-segment model, a single apical segment is taken from the vertical long-axis slice, whereas in the 20-segment model, the apex is represented by 2 segments. Each segment has a specific name. In order to facilitate consistency of nomenclature with other imaging modalities, the 17-segment model has become the preferred nomenclature.

Seventeen-segment nomenclature (Figure 1). Segments 1, 7, and 13 represent the basal (1), mid (7), and apical (13) anterior segments. Segments 4, 10, and 15 represent the basal (4), mid (10), and apical (15)

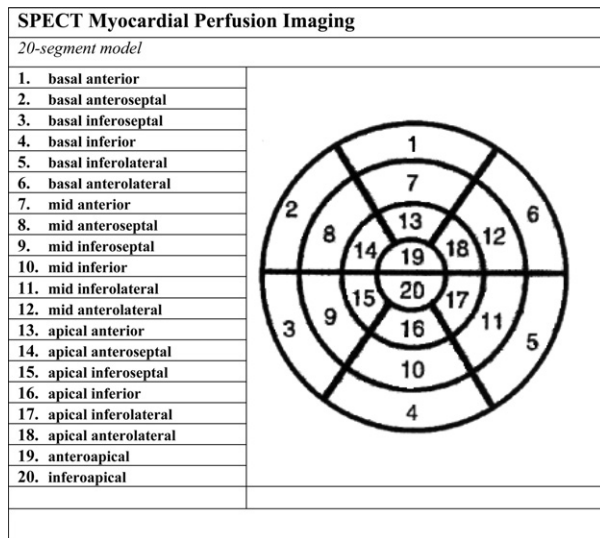


Figure 2. SPECT myocardial perfusion imaging: 20-segment model.

inferior segments. The septum contains 5 segments, the basal anteroseptal (2), the basal inferoseptal (3), the mid anteroseptal (8), the mid inferoseptal (9), and the apical septal (14). Similarly, the lateral wall is divided into the basal anterolateral (6), the basal inferolateral (5), the mid anterolateral (12), the mid inferolateral (11), and the apical lateral (16). The long-axis apical segment is called the apex.

Twenty-segment nomenclature (Figure 2). Segments 1, 7, and 13 represent the basal (1), mid (7), and apical (13) anterior segments. Segments 4, 10, and 16 represent the basal (4), mid (10), and apical (16) inferior segments. The septum contains 6 segments, the basal (2), mid (8), and apical (14) anteroseptal and the basal (3), mid (9), and apical (15) inferoseptal. Similarly, the lateral wall contains 6 segments, the basal (6), mid (12), and apical (18) anterolateral and the basal (5), mid (11), and apical (17) inferolateral segments. The apex from the vertical long-axis slice is divided into anteroapical (19) and inferoapical (20) segments.

The myocardial segments may be roughly assigned to coronary arterial territories as indicated in Figure 3 as long as the reader realizes that there can be considerable variation among patients especially in the inferior and inferolateral segments of the left ventricle due to the variable extent of the circumflex and right coronary artery territories.

Semiquantitative Scoring System: The Five-Point Model

The use of a scoring system provides a reproducible semiquantitative assessment of defect severity and ex-

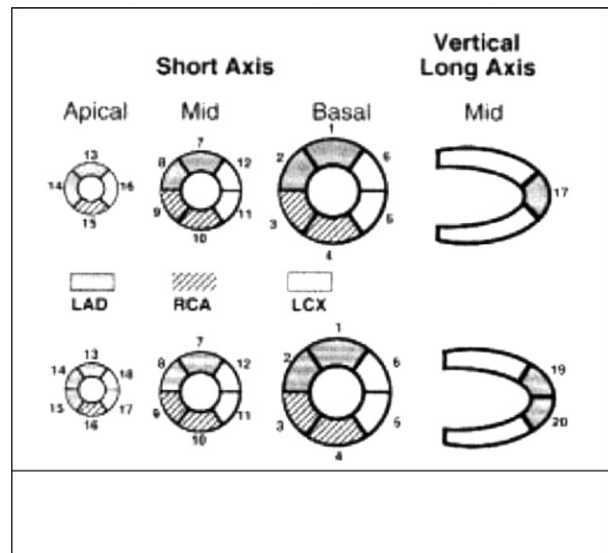


Figure 3. SPECT myocardial perfusion imaging: coronary artery territories. LAD, Left anterior descending artery; RCA, right coronary artery; LCX, left circumflex artery.

Table 7. Semiquantitative scoring system: 5-point model

Category	Score
Normal perfusion	0
Mild reduction in counts—not definitely abnormal	1
Moderate reduction in counts—definitely abnormal	2
Severe reduction in counts	3
Absent uptake	4

tent. A consistent approach to defect severity and extent is clinically important because both of those variables contain independent prognostic power. Furthermore, semiquantitative scoring can be used to more reproducibly and objectively designate segments as normal or abnormal. Points are assigned to each segment in direct proportion to the perceived count density of the segment (Table 7).

In addition to individual scores, it has been recommended that summed scores be calculated. The summed stress score equals the sum of the stress scores of all the segments, and the summed rest score equals the sum of the resting scores or redistribution scores of all the segments. The summed difference score equals the difference between the summed stress and the summed resting (redistribution) scores and is a measure of reversibility. In particular, the summed stress score has been shown to have significant prognostic power.⁴³ Before

scoring, it is necessary for the interpreting physician to be familiar with the normal regional variation in count distribution of myocardial perfusion SPECT.

15. Perfusion defect severity and extent: Quantitative. Quantitative analysis is useful to supplement visual interpretation.⁴²⁻⁴⁴ Most techniques of quantitative analysis are based on radial plots of short-axis slices. Different techniques analyze the apex separately. These plots are then normalized to allow creation of or comparison to normal databases. Defects can be defined as where activity falls a given amount below the mean of a normal database to evaluate size and severity of defects. Quantitation of the stress images is compared to the rest images to assess the degree of ischemia versus infarction. It is customary to generate separate normal databases based on gender as well as the perfusion agent used. This quantitative analysis is usually displayed as a "bulls-eye" or polar plot.⁴⁵ The quantitative programs are effective in providing an objective interpretation that is inherently more reproducible than visual analysis, eliminates the variability of the appearance of a defect when viewed in different media (with different gammas) and different translation tables, and is particularly helpful in describing changes between two studies in the same patient. Quantitative analysis also serves as a guide for the less experienced observer who may be uncertain about normal variations in uptake. Quantitative programs are by no means sophisticated enough to unequivocally differentiate perfusion defects from artifact but help in understanding the range of uptake that can be encountered in patients without disease. Because of artifacts during imaging and also the nature of coronary blood flow, there will always be an overlap between normals and patients with mild perfusion defects; this overlap can be reduced but not completely eliminated by careful attention to image acquisition and reconstruction. Therefore quantitative analysis should only be used as an adjunct to and not a substitute for visual analysis.

Defect extent may be quantitatively expressed as a percentage of the entire left ventricle or as a percentage of individual vascular territories, the latter being less reliable because of the normal variations in coronary anatomy. Defect severity may be quantitatively expressed as the number of standard deviations by which the segment varies from the normal range for that particular segment or segments. Defect reversibility may also be expressed as a percentage of the entire left ventricle or of a vascular territory.

16. Reversibility. Reversibility of perfusion defects may be categorized qualitatively as partial or complete, the latter being present when the activity in the defect returns to a level comparable to surrounding normal myocardium. The semiquantitative scoring system may be used to define reversibility as a ≥ 2 -grade improvement or improvement to a score of 1. Reversibility on a quantitative polar plot or on 3-dimensional displays will depend on the particular software routine in use and the normal reference databases used in the program. Areas of reversibility are typically described by pixels that improve to less than 2.5 SDs from the normal reference redistribution or resting database. How many pixels have to improve for reversibility to be deemed present is arbitrary.

So-called reverse redistribution may be seen in stress delayed thallium imaging sequences and has been described in rest delayed technetium sestamibi sequences. Reverse redistribution refers to segments with decreased or normal intensity on the initial set of images that show even less relative intensity on the delayed images. The interpretation of the finding remains controversial, but in certain clinical situations, it seems to represent segments with a mixture of viable and nonviable myocardium that are frequently supplied by patent infarct-related arteries.⁴⁶

GATED MYOCARDIAL PERFUSION SPECT

Because of the comparatively low additional cost and substantial benefit of the information obtained, gated studies of ventricular function should be a routine part of myocardial perfusion SPECT.²⁰ A systematic approach to display and interpretation of the ventricular function derived from gated SPECT is important.

17. Gated SPECT display. Multiple ventricular slices should be evaluated. At a minimum, a quad-screen display of apical and mid-basal short-axis, a mid-ventricular horizontal long-axis, and a mid-ventricular vertical long-axis slice should be viewed. Other slices may be viewed for completeness or to resolve a discrepancy between the clinical impression and what is seen on the four standard cine views. Ideally, the software should allow the user to scroll through any of the slices in any axis in cine mode. Each view should be normalized to the series of end-diastolic to end-systolic slices to maintain the count density changes that reflect wall thickening. When available, software routines that automatically define epicardial and endocardial borders and that subsequently calculate ventricular volumes and EF should be applied.

Table 8. Myocardial perfusion SPECT: Guidelines for interpretation

		For information, see paragraph
A. Display		
1. Medium		
a. Computer screen	Preferred	1
b. Film hard copy	Discouraged	1
2. Format		
a. Conventional slice display	Preferred	2
i. Frame normalization	Optional	2
ii. Series normalization	Preferred	2
b. Three-dimensional display	Optional	3
B. Technical sources of error		
1. Motion	Standard	4
2. Attenuation	Standard	5
a. Attenuation correction	Optional	5
3. Reconstruction artifacts	Standard	6
4. Myocardial statistics	Standard	7
C. Initial image interpretation		
1. Ventricular dilation		
a. Qualitative	Standard	8
b. Quantitative	Optional	8
2. Lung uptake		
a. Qualitative	Standard	9
b. Quantitative	Preferred	9
3. Non-cardiac	Standard	11
4. Perfusion defect assessment		
a. Location	Standard	12
b. Extent/severity		
i. Qualitative	Standard	13
ii. Semiquantitative	Optional	14
iii. Quantitative	Optional	15
5. Reversibility	Standard	16
D. Gated SPECT		
1. Display	Standard	17
2. QC	Standard	18
3. Regional wall motion	Standard	19
4. Regional wall thickening	Standard	19
5. LVEF		
a. Qualitative	Standard	20
b. Quantitative	Preferred	20
6. LV volume		
a. Qualitative	Standard	20
b. Quantitative	Recommended	20
E. Integration of perfusion and function results	Standard	21
F. Myocardial viability		
1. Qualitative	Standard	22
2. Semiquantitative	Optional	23
3. Quantitative	Preferred	24
G. Modification of interpretation	Preferred	25

Table 9. Myocardial perfusion SPECT: Guideline for reporting

		For information, see paragraph
A. Demographic data		
1. Name	Standard	26
2. Gender	Standard	26
3. Age	Standard	26
4. Date(s) of acquisition(s)	Standard	26
5. Medical record identification	Standard	26
6. Height/weight (body surface area)	Standard	26
7. Relevant medications	Optional	26
8. Indication for study	Standard	28
B. Acquisition parameters		
1. Type(s) of studies	Standard	27
2. Radionuclide(s) and doses	Standard	27
C. Results: Exercise/intervention data		
1. Resting ECG findings	Standard	29
2. Exercise/intervention parameters		
a. Heart rate, blood pressure, % maximal predicted heart rate, metabolic equivalents	Standard	30
b. Symptoms	Standard	30
c. Reason for terminating	Standard	30
d. ECG changes with exercise	Standard	30
D. Results: perfusion scan data		
1. Potential sources of error		
a. Motion	Standard	4
b. Attenuation	Standard	5
c. Adjacent/overlapping uptake	Standard	6
2. Chamber sizes	Standard	8
3. Lung uptake (thallium)		
a. Qualitative	Standard	9
b. Quantitative	Preferred	9
4. Initial defect location	Standard	12
5. Initial defect severity and extent		
a. Qualitative	Standard	13
b. Semiquantitative	Preferred	14
c. Quantitative	Optional	15
6. Reversibility		
a. Qualitative	Standard	16
b. Semiquantitative	Preferred	16
c. Quantitative	Optional	16
7. RV uptake	Standard	10
8. Abnormal noncardiac uptake	Standard	11
E. Results: gated SPECT		
1. Regional wall motion	Standard	19
2. Regional wall thickening	Standard	19
3. EF		
a. Qualitative	Recommended	20
b. Quantitative	Recommended	20
4. LV volume	Optional	20
F. Overall study quality		
	Optional	31

Table 9. (Continued)

	For information, see paragraph	
G. Conclusion		
1. Normal/abnormal		
a. Three categories	Recommended	16
b. Five categories	Optional	16
2. Probability of CAD	Optional	32
3. Estimated risk of adverse events	Optional	32

Regional wall motion should be interpreted with a gray-scale display. When computer edge analysis software is available, the physician may choose to analyze wall motion by use of the assigned endocardial and epicardial contours, but reference should also be made to the wall motion without computer-derived edges. Regional wall thickening may be analyzed in gray scale or in a suitable color scheme, although color displays may make it easier to see changes in count intensity.

18. **Gated SPECT QC.** All the QA procedures for routine SPECT are applicable to gated SPECT with the addition of the evaluation of the adequacy of the electrocardiographic (ECG) gate.²¹ The most common manifestation of poor gating is the appearance of a flashing pattern on the rotating planar projection images that results from count loss in the later frames. Ideally, a heart rate histogram should also be viewed to verify beat length uniformity. Inspecting the time-volume curve is particularly useful since gating errors may distort the curve. As yet, there is no clear consensus on the beat length window for gated SPECT acquisitions. As in blood pool imaging, the narrower the window, the more physiologic the data, but this runs the risk of compromising the quality of the SPECT perfusion images unless the acquisition software allows for an “extra frame” to accumulate rejected counts during the gated acquisition. Another important aspect of QC is a visual or quantitative determination that the number of counts acquired in each frame of the gated study was adequate for assessment of function. Software that collects all counts into a separate bin for the summed image can minimize the effect that gating errors have on the summed image.
19. **Gated SPECT: Regional wall motion and thickening.** Regional wall motion should be analyzed by use of standard nomenclature: normal, hypokinesis, akinesis, and dyskinesis. Hypokinesis may be further qualified as mild, moderate, or severe. A semiquantitative scoring system is recommended, where 0 is

normal, 1 is mild hypokinesis, 2 is moderate hypokinesis, 3 is severe hypokinesis, 4 is akinesis, and 5 is dyskinesis.

This is comparable to the 5-point scoring system used in both contrast and radionuclide ventriculography. As in any assessment of regional ventricular function, one must be cognizant of expected normal and abnormal variations such as the reduced wall excursion at the base compared with the apex, the greater excursion of the basal lateral wall compared with the basal septum, and paradoxical septal motion, which may result from left bundle branch block, post pericardiotomy, or pacing from the right ventricle.

Normal myocardial wall thickness is below the resolution of image reconstruction from currently available SPECT systems. However, regional wall thickening can be estimated by use of the count increase from end diastole to end systole. Visually, it is not as easy to assign degrees of abnormality of thickening as it is to wall motion. However, the evaluation of thickening with gated perfusion SPECT lends itself to quantitation because it is characterized by count changes.

Wall motion and wall thickening are generally concordant. The principal exception to this occurs in patients who have undergone cardiac surgery where septal wall motion is frequently abnormal (paradoxical) but there is normal wall thickening. Rather than separately scoring wall motion and wall thickening, it is commonly accepted to incorporate the two findings into a single score while noting the presence of discordance in wall motion and wall thickening when it occurs. In addition to noting LV wall motion, wall thickening, and EF, the size of the left and right ventricles should be observed, and the function of the right ventricle should be noted.

Quantitative normal databases are now available for assessment of regional wall thickening.

20. **LVEF and volume.** LVEF and LV and RV chamber sizes should routinely be evaluated qualitatively.⁴⁷

EF may be categorized as normal or mildly, moderately, or severely reduced.²² Volume may be categorized as normal or mildly, moderately, or severely increased. Alternatively, LVEF and end-diastolic and end-systolic volumes may be calculated with geometric models applied to the reconstructed data set. Several software routines that correlate well with contrast and other radionuclide measurements are commercially available.²²

21. **Integration of perfusion and function results.** The results of the perfusion and gated SPECT data sets should be integrated into a final interpretation. The wall motion is particularly helpful in distinguishing real nonreversible perfusion defects from attenuation or motion artifacts. Fixed perfusion defects that do not show a corresponding abnormality of motion or thickening are more likely to be due to artifacts, especially if the clinical data do not support prior infarction.²⁹

Myocardial Viability

22. **Viability: Qualitative assessment.** The assessment of myocardial viability is a complex issue made even more difficult by the lack of consensus in the literature of the precise meaning of the term viability—whether it refers merely to the absence of scar or requires improvement in wall motion after revascularization. It is, however, clear that the quantitative uptake of radionuclides such as Tl-201 and the available technetium agents does correlate with myocardial viability as defined by post-revascularization improvement in both tracer uptake and regional function. Myocardial segments with normal or mildly reduced tracer uptake at rest or on delayed imaging almost invariably prove to be viable. The majority of myocardial segments in which there is unequivocal improvement of uptake on either redistribution or resting images also prove to be viable. The more difficult challenge for the single photon assessment of viability is in segments with severely reduced tracer uptake.
23. **Myocardial viability: Semiquantitative assessment.** The semiquantitative scoring system described above may be used to assess viability as follows. Segments with rest, reinjection, or redistribution scores of 0 (normal perfusion) and 1 (slight reduction in counts) are considered viable. Segments with rest, redistribution, or reinjection scores of 2 (moderately decreased perfusion) are consistent with a combination of viable and nonviable myocardium, and segments with scores of 3 and 4 are generally nonviable. Segments with final scores of 4 are considered nonviable.

24. **Myocardial viability: Quantitative assessment.**

An alternate and perhaps more rigorous approach to the assessment of the viability of any segment is the quantitative determination of ischemic-to-normal ratios. Regions of interest may be placed over the segment in question and over the most normal segment of the myocardium in that particular series of images. The analysis should be applied to the resting images for technetium images or to the resting, redistribution, or reinjection images for thallium. When this approach is used, one must take into account the normal count variations such as the relatively reduced counts in the normal inferior wall. Segments with ratios of less than 0.30 are considered nonviable. Areas with ratios greater than 0.50 are considered viable, whereas areas with ratios of 0.30 to 0.50 are equivocal for viability. As indicated above for the semiquantitative approach, such regions require additional data such as wall motion of the region, exercise perfusion in the region, the change in perfusion or wall motion after nitroglycerin, the response of regional function to low-dose dobutamine, or myocardial metabolic imaging with fluorine 18 fluorodeoxyglucose.²²

It is also important to recognize that viability of a given segment does not necessarily equate to improvement in clinical outcome after revascularization unless enough segments that are viable are available. The critical number of segments necessary to justify revascularization strategies has not been adequately studied.

Modification of Interpretation by Relevant Clinical Information

25. Due to imperfections in the technology as well as the gradual impairment of coronary blood flow as stenoses become hemodynamically significant, there will always be overlap between normal and mildly abnormal perfusion scans. In these patients it is often particularly helpful to incorporate other clinical information (eg, symptoms, risk factors, ST-segment changes, exercise tolerance) as well as prognostic information in order to help the referring physician make the most appropriate management decisions for patients. Homogeneous perfusion images of patients who have other markers of severe ischemia, such as marked ST-segment changes, should be carefully evaluated for adjunctive markers of ischemia such as TID or increased lung uptake (with thallium) in order to identify those patients with balanced ischemia. The majority of artifacts encountered will produce mild defects; therefore moderate or severe defects, in the absence of dramatic artifact,

should be considered as reflecting pathology. Finally, it needs to be understood that not all pathology detected by perfusion imaging reflects epicardial coronary artery disease (CAD).

Reporting of SPECT Myocardial Perfusion Scan Results

26. **Subject information.** The age, gender, height, weight, and body surface area should be included in the report because they may directly affect the image results and interpretation. For medical records purposes, any identification number should be included. Pertinent medications that may influence the results may be included.
27. **Type of study.** The imaging protocol should be specified, including the radiopharmaceutical and dose, imaging technique (gated vs ungated, supine or prone), imaging sequence (stress/4-hour redistribution, 1-day or 2-day rest/stress or stress/rest, and so on), and a specific statement about whether images were or were not corrected for attenuation. The date(s) of study acquisitions should also be included.
28. **Indication for study.** Placing the indication for the study in the report helps focus the interpreting physician on the clinical question raised by the ordering physician and may be subsequently important for reimbursement issues.
29. **Resting ECG findings.** Inclusion of ECG findings that may have a direct bearing on the study interpretation should be included such as the presence of left bundle branch block or LV hypertrophy.
30. **Summary of stress data.** The type of stress (bicycle or treadmill) and the protocol should be identified (Bruce, modified Bruce, Naughton, manual). For pharmacologic stress, the agent, route of administration, and dose should be indicated. The reason for stopping the test should be noted. All symptoms experienced by the patient during stress (eg, chest pain, dyspnea, claudication, dizziness) should be mentioned.

If a separate stress test report is generated, then the stress variables that could impact on the perfusion study quality or findings should be included in the perfusion scan report. At a minimum, the report should include the total exercise duration, maximal heart rate and percent of predicted maximum heart rate, resting and maximal blood pressure achieved and workload achieved (estimated metabolic equivalents), and magnitude (in millimeters) and location of any ST-segment deviation.

If only one report is used for both the exercise or pharmacologic study and the perfusion results, then more detail about the stress test should be included

such as time of onset, duration and exact ECG leads with ST-segment changes, the type of chest pain (typical, atypical, non-anginal) and its severity (mild, moderate, severe), and the presence of arrhythmia.

31. **Overall study quality.** Including a statement about the quality of the study is helpful, as it alerts the physicians using the report to any shortcomings that might reduce the accuracy of the data and their interpretation.
32. **Conclusions.** The final interpretation of the scan should obviously reflect the reader's impression as to whether the scan is normal or abnormal. This may be refined to address uncertainty by adding 3 or 5 categories reflecting certainty. That is, the scan may be on a 2-category scale as normal or abnormal; a 3-category scale as normal, equivocal, or abnormal; or a 5-category scale as normal, probably normal, equivocal, probably abnormal, or abnormal.
33. **Diagnosis and prognosis of CAD.** The probability of CAD may be determined with available algorithms that use the pre-scan likelihood of CAD as determined by age, gender, character of chest pain, the number of coronary risk factors, and the results of the stress electrocardiogram. The perfusion data are then added to the model to produce a probability of CAD. A qualitative probability may be reported on the basis of the definite presence or absence of a perfusion defect, the severity and extent of any perfusion defects, and the presence of other markers of CAD such as transient LV dilation, post-stress stunning, or increased lung uptake. When CAD is known to be present, the likelihood of stress-induced ischemia is reported instead of the likelihood of significant CAD.

Though not widely available, some large laboratories have enough internal follow-up data to be able to statistically predict outcomes (death and nonfatal myocardial infarction) on the basis of perfusion image scores. If such data are available, incorporation of the likelihood of an adverse event in the report is desirable. Otherwise, a qualitative statement about risk may be appropriate because the likelihood of an adverse event increases with the presence of any of the following: perfusion defects in multiple vascular territories, transient LV dilation, increased lung uptake, and decreased LV systolic function.

34. **Clinical interpretation of AC SPECT studies.** The interpretation of AC SPECT myocardial perfusion images follows a similar approach to that used for uncorrected myocardial perfusion images, but there are differences, and these should be taken into account in order to obtain good results. The normal

distributions of perfusion tracer uptake are significantly different with AC compared to uncorrected studies, and because of this, it is important that the interpreting physician have available and learn databases of normal tracer distribution(s). Although from system to system these normal distributions are generally relatively similar, there can be differences that are dependent on the geometry of the imaging system, acquisition protocol, and processing algorithms.³¹ There can also be differences in normal distribution(s) related to patient gender and ventricular volume. The interpreting physician must be aware of these differences if they exist for their imaging system(s) and take them into account on a patient-by-patient basis when assessing clinical studies.

AC SPECT studies generally have more uniform regional activity in the anterior, septal, inferior, and lateral walls, but mild reductions in apical and distal anterior activity are typical of the normal AC image distribution. This apical and distal anterior activity reduction is similar to that seen with positron emission tomography myocardial perfusion imaging. This finding becomes more prominent when resolution recovery and scatter correction are included in the AC processing workflow and is often more prominent in patients with larger hearts. In low-likelihood normal patients, this reduction in distal activity is generally more prominent in men than in women, as men generally have larger hearts. If men and women with similar heart sizes are compared, the difference disappears. The unsuspecting observer may mistake this expected normal activity reduction for a distal or mid and distal left anterior descending coronary perfusion defect. In general, the success of AC SPECT appears related to the diligence of the clinical laboratory in following recommended procedures for image acquisition, reconstruction, QA, display, and quantification. Although it may seem reasonable that AC SPECT should simply provide better images, like those without correction, but with the bothersome artifacts that often result in false-positive tests removed, the normal distributions are significantly different and must be accounted for to achieve optimal clinical benefit. The distribution of normal activity is different with AC SPECT. If these differences are not understood by interpreting physicians, AC SPECT will be unreliable. Likewise, quantification and display programs without appropriate normal AC databases should not be used for quantification, as spurious results will occur.

QA requirements are more demanding with AC than non-AC images and should be carefully as-

essed for each patient study. Artifacts due to movement, either respiration or patient movement, misregistration, and extracardiac radiotracer uptake can be amplified by the iterative algorithms that are employed in AC reconstructions and processing. The quality and registration of the attenuation maps (or mu maps) with the emission image data are additional key factors that must be ensured, and if they cannot be ensured, the associated AC images should be read with greater caution. QA tools to aid these assessments of registration and mu map quality are still not uniformly available, but this should improve in the near future.

For the clinical interpretation of AC SPECT myocardial perfusion images, it is recommended that AC and non-AC images be displayed side by side with displays of the normal activity distribution(s) and their variance distribution available as required for comparison. This requires the availability of normal databases specific for the imaging device, imaging protocol, and processing approach employed clinically. Extracardiac activity especially when combined with respiratory and/or patient movement can introduce artifacts and/or normalization errors that may require renormalization or abandonment of the AC images altogether. Artifactual reductions in activity most often affecting the apparent anterior and/or lateral wall perfusion tracer uptake can occur when there is misregistration of SPECT and mu map images such that the myocardial activity from the SPECT images is matched with the relatively low attenuation coefficients for adjacent lung tissue in the mu maps. Some attenuation correction-capable SPECT systems acquire the SPECT and the transmission image data sequentially rather than simultaneously. If there is a change in position of arm(s) or breasts between emission and transmission imaging, even though there may be perfect registration of the heart in the emission and transmission images, there can be artifactual defects introduced into the SPECT perfusion images by the misregistration of tissues outside the thorax.

The SPECT/CT systems that have become available recently require sequential emission and transmission imaging with a change in bed position between acquisitions. Although the quality of the mu maps with these systems will consistently far exceed the quality of sealed-source transmission system mu maps, the greatly improved resolution of the mu maps they provide make it even more important that registration of emission and transmission reconstructions be exact to a tolerance of less than 1 pixel.

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References

1. Segall GM, Davis MJ. Prone versus supine thallium myocardial SPECT: a method to decrease artifactual inferior wall defects. *J Nucl Med* 1989;30:548-55.
2. Kiat H, Van Train KF, Friedman JD, Germano G, Silagan G, Wang FP, et al. Quantitative stress-redistribution thallium-201 SPECT using prone imaging: methodologic development and validation. *J Nucl Med* 1992;33:1509-15.
3. Esquerre JP, Coca FJ, Martinez SJ, Guiraud RF. Prone decubitus: a solution to inferior wall attenuation in thallium-201 myocardial tomography. *J Nucl Med* 1989;30:398-401.
4. Nishina H, Slomka PJ, Abidov A, et al. Combined supine and prone quantitative myocardial perfusion SPECT: method development and clinical validation in patients with no known coronary artery disease. *J Nucl Med* 2006;47:51-8.
5. Slomka PJ, Nishina H, Abidov A, et al. Combined quantitative supine-prone myocardial perfusion SPECT improves detection of coronary artery disease and normalcy rates in women. *J Nucl Cardiol* 2007;14:44-52.
6. Friedman J, Van Train K, Maddahi J, Rozanski A, Prigent F, Bietendorf J, et al. "Upward creep" of the heart: a frequent source of false-positive reversible defects during thallium-201 stress-redistribution SPECT. *J Nucl Med* 1989;30:1718-22.
7. Eisner RL, Nowak DJ, Pettigrew R, Fajman W. Fundamentals of 180 degree acquisition and reconstruction in SPECT imaging. *J Nucl Med* 1986;27:1717-28.
8. Liu YH, Lam PT, Sinusas AJ, Wackers FJ. Differential effect of 180 degree acquisition and reconstruction in SPECT imaging. *J Nucl Med* 2002;43:1115-24.
9. Maniowski PJ, Morgan HT, Wackers FTH. Orbit-related variation in spatial resolution as a source of artifactual defects in thallium-201 SPECT. *J Nucl Med* 1991;32:871-5.
10. Germano G, Kiat H, Kavanagh PB, Moriel M, Mazzanti M, Su HT, et al. Automatic quantification of ejection fraction from gated myocardial perfusion SPECT. *J Nucl Med* 1995;36:2138-47.
11. Johnson LL, Verdesca SA, Aude WY, Xavier RC, Nott LT, Campanella MW, et al. Postischemic stunning can affect left ventricular ejection fraction and regional wall motion on post-stress gated sestamibi tomograms. *J Am Coll Cardiol* 1997;30:1641-8.
12. Hansen C. Digital image processing for clinicians, part II: filtering. *J Nucl Cardiol* 2002;9:429-37.
13. Hansen CL, Kramer M, Rastogi A. Lower accuracy of Tl-201 SPECT in women is not improved by size-based normal databases or Wiener filtering. *J Nucl Cardiol* 1999;6:177-82.
14. King MA, Glick SJ, Penney BC, Schwinger RB, Doherty PW. Interactive visual optimization of SPECT prereconstruction filtering. *J Nucl Med* 1987;28:1192-8.
15. Hansen C. Digital image processing for clinicians, part III: SPECT reconstruction. *J Nucl Cardiol* 2002;9:542-9.
16. Hansen CL. The role of the translation table in cardiac image display. *J Nucl Cardiol* 2006;13:571-5.
17. Eisner R, Churchwell A, Noever T, Nowak D, Cloninger K, Dunn D, et al. Quantitative analysis of the tomographic thallium-201 myocardial bullseye display: critical role of correcting for patient motion. *J Nucl Med* 1988;29:91-7.
18. Klein JL, Garcia EV, DePuey EG, Campbell J, Taylor AT, Pettigrew RI, et al. Reversibility bull's-eye: a new polar bull's-eye map to quantify reversibility of stress-induced SPECT thallium-201 myocardial perfusion defects. *J Nucl Med* 1990;31:1240-6.
19. Wackers FJ. Artifacts in planar and SPECT myocardial perfusion imaging. *Am J Card Imaging* 1992;6:42-58.
20. Bateman TM, Berman DS, Heller GV, Brown KA, Cerqueira MD, Verani MS, et al. American Society of Nuclear Cardiology position statement on electrocardiographic gating of myocardial perfusion SPECT scintigrams. *J Nucl Cardiol* 1999;6:470-1.
21. Cullom SJ, Case JA, Bateman TM. Electrocardiographically gated myocardial perfusion SPECT: technical principles and quality control considerations. *J Nucl Cardiol* 1998;5:418-25.
22. DePuey EG, Nichols K, Dobrinsky C. Left ventricular ejection fraction assessed from gated technetium-99m-sestamibi SPECT. *J Nucl Med* 1993;34:1871-6.
23. Smanio PE, Watson DD, Segalla DL, Vinson EL, Smith WH, Beller GA. Value of gating of technetium-99m sestamibi single-photon emission computed tomographic imaging. *J Am Coll Cardiol* 1997;30:1687-92.
24. He ZX, Cwajg E, Preslar JS, Mahmarian JJ, Verani MS. Ejection fraction determined by gated myocardial perfusion SPECT with Tl-201 and Tc-99m sestamibi: comparison with first-pass radionuclide angiography. *J Nucl Cardiol* 1999;4:412-7.
25. Hansen C. Digital image processing for clinicians, part I: basics of image formation. *J Nucl Cardiol* 2002;9:343-9.
26. Cooper JA, Neumann PH, McCandless BK. Effect of patient motion on tomographic myocardial perfusion imaging. *J Nucl Med* 1992;33:1566-71.
27. Friedman J, Berman DS, Van Train K, Garcia EV, Bietendorf J, Prigent F, et al. Patient motion in thallium-201 myocardial SPECT imaging. An easily identified frequent source of artifactual defect. *Clin Nucl Med* 1988;13:321-4.
28. Goerres GW, Burger C, Kamel E, Seifert B, Kaim AH, Buck A, et al. Respiration-induced attenuation artifact at PET/CT: technical considerations. *Radiology* 2003;226:906-10.
29. Choi JY, Lee KH, Kim SJ, Kim SE, Kim BT, Lee SH, et al. Gating provides improved accuracy for differentiating artifacts from true lesions in equivocal fixed defects on technetium 99m tetrofosmin perfusion SPECT. *J Nucl Cardiol* 1998;5:395-401.
30. Ficaro EP, Fessler JA, Shreve PD, Kritzman JN, Rose PA, Corbett JR. Simultaneous transmission/emission myocardial perfusion tomography. Diagnostic accuracy of attenuation-corrected 99mTc-sestamibi single-photon emission computed tomography. *Circulation* 1996;93:463-73.
31. Fricke H, Fricke E, Weise R, Kammeier A, Lindner O, Burchert W. A method to remove artifacts in attenuation-corrected myocardial perfusion SPECT. Introduced by misalignment between emission scan and CT-derived attenuation maps. *J Nucl Med* 2004;45:1619-25.
32. Grossman GB, Garcia EV, Bateman TM, Heller GV, Johnson LL, Folks RD, et al. Quantitative Tc-99m sestamibi attenuation-corrected SPECT: development and multicenter trial validation of myocardial perfusion stress gender-independent normal database in obese population. *J Nucl Cardiol* 2004;11:263-772.
33. Weiss AT, Berman DS, Lew AS, Nielsen J, Potkin B, Swan HJ, et al. Transient ischemic dilation of the left ventricle on stress thallium-201 scintigraphy: a marker of severe and extensive coronary artery disease. *J Am Coll Cardiol* 1987;9:752-9.
34. Hansen CL, Cen P, Sanchez B, Robinson R. Comparison of pulmonary uptake with transient cavity dilation after dipyridamole Tl-201 perfusion imaging. *J Nucl Cardiol* 2002;9:47-51.
35. Hansen CL, Sangrigoli R, Nkadi E, Kramer M. Comparison of pulmonary uptake with transient cavity dilation after exercise

- thallium-201 perfusion imaging. *J Am Coll Cardiol* 1999;33:1323-7.
36. Chouraqui P, Rodrigues EA, Berman DS, Maddahi J. Significance of dipyridamole-induced transient dilation of the left ventricle during thallium-201 scintigraphy in suspected coronary artery disease. *Am J Cardiol* 1990;66:689-94.
37. Gill JB, Ruddy TD, Newell JB, Finkelstein DM, Strauss HW, Boucher CA. Prognostic importance of thallium uptake by the lungs during exercise in coronary artery disease. *N Engl J Med* 1987;317:1486-9.
38. Wackers FJT. On the bright side. *J Nucl Cardiol* 2005;12:378-80.
39. Berger HJ, Matthay RA, Loke J, Marshall RC, Gottschalk A, Zaret BL. Assessment of cardiac performance with quantitative radionuclide angiocardiology: right ventricular ejection fraction with reference to findings in chronic obstructive pulmonary disease. *Am J Cardiol* 1978;41:897-905.
40. Brent BN, Mahler D, Matthay RA, Berger HJ, Zaret BL. Noninvasive diagnosis of pulmonary arterial hypertension in chronic obstructive pulmonary disease: right ventricular ejection fraction at rest. *Am J Cardiol* 1984;53:1349-53.
41. Williams KA, Schneider CM. Increased stress right ventricular activity on dual isotope perfusion SPECT: a sign of multivessel and/or left main coronary artery disease. *J Am Coll Cardiol* 1999;34:420-7.
42. Reisman S, Maddahi J, Van Train K, Garcia E, Berman D. Quantitation of extent, depth, and severity of planar thallium defects in patients undergoing exercise thallium-201 scintigraphy. *J Nucl Med* 1986;27:1273-81.
43. Caldwell JH, Williams DL, Harp GD, Stratton JR, Ritchie JL. Quantitation of size of relative myocardial perfusion defect by single-photon emission computed tomography. *Circulation* 1984;70:1048-56.
44. Kaul S, Chesler DA, Okada RD, Boucher CA. Computer versus visual analysis of exercise thallium-201 images: a critical appraisal in 325 patients with chest pain. *Am Heart J* 1987;114:1129-37.
45. Burow RD, Pond M, Schafer AW, Becker L. "Circumferential profiles:" a new method for computer analysis of thallium-201 myocardial perfusion images. *J Nucl Med* 1979;20:771-7.
46. Weiss AT, Maddahi J, Lew AS, et al. Reverse redistribution of thallium-201: a sign of nontransmural myocardial infarction with patency of the infarct-related coronary artery. *J Am Coll Cardiol* 1986;7:61-7.
47. DePace NL, Iskandrian AS, Hakki AH, Kane SA, Segal BL. Value of left ventricular ejection fraction during exercise in predicting the extent of coronary artery disease. *J Am Coll Cardiol* 1983;1:1002-10.