AAPM REPORT NO. 22

ROTATING SCINTILLATION CAMERA SPECT ACCEPTANCE TESTING AND QUALITY CONTROL

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ROTATING SCINTILLATION CAMERA SPECT ACCEPTANCE TESTING AND QUALITY CONTROL

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I. Introduction

The purpose of this document is to present a uniform set of procedures that can be used for acceptance testing and quality control of a scintillation camera-based SPECT system.

Emission computed tomography has a number of advantages over conventional nuclear medicine imaging:

1. Contrast improvement
2. Total volume imaging
3. Quantitation
    a. Detection of lesion and its location
    b. Determination of length and volume
    c. Absolute regional radionuclide concentrations

In order to realize these advantages. strict quality control procedures must be performed on a routine basis. Important considerations for tomography. unlike planar imaging. include levelness of gantry. collimator hole angulation, strict attention to field uniformity, attenuation correction, filtering. and camera response at different angular orientations of the camera head. In addition, both linear and angular sampling are of concern: use of the finest matrix size and angular sampling are recommended. Using a 64 x 64 acquisition matrix will make certain measurements unrealiable. e.g.. resolution and linearity. If the system is capable, a minimum matrix size of 128 x 128 (3 mm linear sampling, 400 mm FOV) should be employed. Angular sampling can be performed with either a continuous rotation or "step-and shoot" acquisition using a circular or noncircular orbit.

Tomographic techniques are very sensitive to inadequate calibration procedures. Additional time must be set aside for the quality control of SPECT studies in order to ensure artifact-free images. As a caveat. if the measurement protocols described herein are to be used for acceptance testing, then the burden is upon the prospective buyer to negotiate the performance specifications with the manufacturer prior to the submission of a purchase order.

II. Pre-Test Conditions

When performing the acceptance and quality control tests, sources of radioactivity should be handled in accordance with proper techniques. All containers of unsealed sources should be kept on absorbent pads and handled by gloved personnel wearing appropriate dosimeters. In all cases the measurements should be performed with the room background as low as achievable and other sources (such as patients who have received radiopharmaceuticals) excluded from the area. During the period of time the crystal is not protected by the collimator, for example, when performing intrinsic studies. extreme care must be taken not to damage the crystal by mechanical or thermal insult.

If transparency film is used, the processor should be checked to assure that it is operating within specifications. The same type of film should be used for acceptance testing as will be used for quality control and routine clinical studies.

III. Log Book

At the time of acceptance testing a new system, a permanent record book should be initiated for that system. The user should obtain all available performance data from the manufacturer and include this in the log book. The results of the performance testing should be recorded, including the labeled images and all information necessary to duplicate the results at some later date. Parameters recorded should include the date and time, radionuclide. source activity, configuration of source, console and system parameters. collimator, data acquisition time, number of counts, matrix size. number of projection angles, continuous rotation or "step-and-shoot" acquisition, radius of rotation, reconstruction filter, slice thickness, and scatter material. If the system provides the actual total number of counts that contributed to a specific sectional image then that value should be recorded. Furthermore, any pre- and/or post-processing procedures (e.g.. two dimensional prefiltering of projection data, three dimensional volume smoothing of reconstructed images) should be recorded. Some console parameters may change if adjustments are made on the camera.

Subsequent quality control. component failure and maintenance records should be recorded in the same book.

IV. Test Equipment Required

1. Tc-99m or Co-57 point sources.

   The point sources should contain sufficient activity to produce count rates of 10,000 cps with the collimator on the camera. A convenient method of preparing a Tc-99m point source is to draw 0.05 ml into a 1 ml syringe. Be sure to remove the needle and cap the syringe to prevent leakage.

2. Tc-99m line source

   The line source should contain sufficient activity to produce a count rate of 10,000 cps with the collimator on the camera. It should have an internal diameter of less than 1.5 mm and be of sufficient length to cover the useful axial field of view. Plastic or glass capillary tubes can be used as line sources, however, care must be taken to avoid spills. Refillable line sources are commercially available (Appendix C).

3. Tc-99m flood or Co-57 sheet source with +/- 1% uniformity.

   The liquid-filled flood source should contain 5 - 7 mCi of Tc-99m. Caution should be taken to ensure uniform filling. Refillable flood phantoms, especially those of larger diameter designed for large field of view systems, may sag in the center during rotation and thus become nonuniform (hot center). The count rate from either the Tc-99m flood or Co-57 sheet source must be below 30 kcps with the collimator on the camera.

4. Water-filled cylindrical phantom with various sized cold sphere inserts.

The phantom should have a diameter of 20 - 22 cm and a height of at least 15 cm. The sphere diameters should vary from approximately one FWHM to >3 x FWHM (e.g., if system FWHM is 12 mm, then spheres should range in diameter from <12 mm to > 36 mm) and be centered at the same level in the phantom. The phantom should contain 10-15 mCi of Tc-99m. Appropriate vendors of commercially available phantoms are listed in Appendix C.

5. Jig or rigid holder for line source positioning

6. Rigid support for cylindrical phantom positioning

7. Small platform jack

8. Bubble level and level-protractor

9. Smith orthogonal phantom

V. Protocol

A. Single-Head Systems

1.0 Physical Inspection for Shipping Damages and Production Flaws.

1.1 Procedures described in AAPM Report No. 9, section 1.1-1.7 and 1.9 should be followed.

1.2 Gantry
Inspect the tomographic gantry alignment, vertically and horizontally. and all cables, switches, or other controls.

1.3 Scan Table
Inspect the bed alignment, vertically and horizontally. and other controls.

1.4 Angle Indications
Check registration of angle indicators by rotating camera 360 degrees, one indicator at a time, using a level-protractor. Check accuracy of angular velocity for continuous gantry rotation.

1.5 Patient Safety Devices
Inspect patient safety devices (e.g.. touch pads, emergency stop) to ensure proper operation.

2.0 System Alignment

Tomographic sections are reconstructed from projections acquired at multiple angles about the object being imaged. The rotating detector has an axis of rotation (Figure 1). This axis is a line fixed in space parallel to the scan table and perpendicular to the plane of the gantry. It should intersect the gantry plane very close to its center.

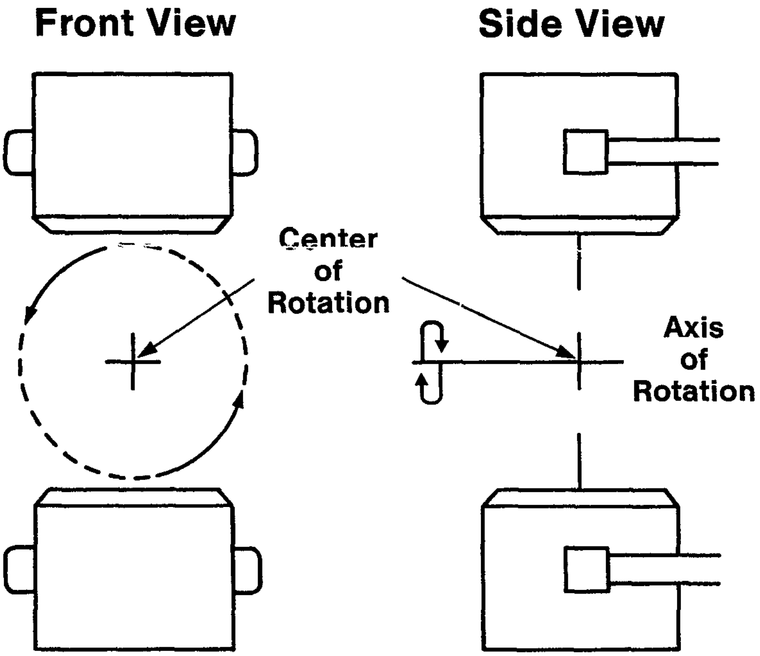

FIGURE L Schematic drawing of a SPECT system illustrating the center and axis of rotation.

In order to reconstruct the tomographic sections it is necessary to know where the projection of the axis of rotation (AOR) is located on the planar image pixel matrix. This location is referred to as the center of rotation (COR) as shown in Figure 1. The alignment of this mechanical axis of rotation of the detector with respect to the image pixel matrix, i.e., the center of the collection matrix of the computer, and its stability during rotation are important physical calibrations for transverse-section tomography.

Since errors as small as +/- 1.5 mm (or 0.5 pixels using a 128 x 128 matrix, 400 mm field of view) will degrade the quality of the reconstructed images, it is necessary to determine the COR to within +/- 1 mm. In addition to accurately knowing where the COR is located, it is preferable that it coincide with the center of the image matrix. This yields the best field of view and reduces the effect of changing gains and matrix size. It is therefore recommended that the offset calibration of the COR used by the reconstruction program from the center of the image matrix be <6 mm (or <2 pixels for a 128 x 128 matrix). Note: this does not imply that COR errors as great as 6 mm can be tolerated.

The COR may vary due to mechanical problems with detector rotation, changes in amplifier gain and offset, errors in the analog to digital converter, and lack of parallelism between the collimator/detector plane and the axis of rotation.

2.1 Determination of Center of Rotation (COR)

2.1.1 Prepare a point source of Tc-99m.

2.1.2 Center a 20% window symmetrically about the Tc-99m photopeak and place a low-energy all purpose collimator (or the one which will be routinely used) on the camera.

used) on the camera.

2.1.3 Position the point source 5 cm from the axis of rotation and extend it over the edge of the imaging table. Use a bubble level to ensure that the collimator is level, i.e. parallel to the axis of rotation.

2.1.4 Acquire a 360 degree tomographic study using a 128 x 128 matrix and 32 projections (or with the angular and linear sampling as supplied by the manufacturer). 20,000 counts per projection, and a circular orbit with a radius of rotation of 15 cm. Note: The largest available matrix size should be used: more projections are not necessary.

2.1.5 Create a sinogram image (using the manufacturer- supplied algorithm or the FORTRAN algorithm as given in Appendix A) using the central row (i.e.. row 64 for a 128 x 128 matrix) from each of the 32 projection images. Make sure that the activity is present on all views. The sinogram should look like a sine wave (Figure 2).

2.1.6 Quantitative Analysis

2.1.6.1 Find the x centroid for each row in the sinogram image.

2.1.6.2 Fit these values to a sine function:
A sin (q + Ø + B. where A is the amplitude, q is the angle of rotation, q is the phase angle of the fitted sine function, and B is the best fit center of rotation. A FORTRAN algorithm for the sine fit is given in Appendix B.

2.1.6.3 Compare B to the expected center of the image matrix. i.e., 64.5 for a 128 x 128 matrix This difference is the mean offset, R. from the COR.
$R = (N+1)/2 - B$
where N is the matrix size.

2.1.6.4 The fitted sine curve should be subtracted from the curve obtained from step 2.1.6.1 to step 2.1.6.1 obtain the offset error as a function of angle. $R(\theta)$.

2.1.6.5 Alternate Method: The offset error, $P(\theta)$. as obtained from steps 2.1.6.1 - 2.1.6.4 can also be calculated by
$P(\theta) = [N+l - X(\theta) - X\ \theta + 180)]/2$
where N is the matrix dimension in the x direction,
$X(\theta)$ is the centroid for the projection at degrees, and
$X(\theta + 180)$ is the centroid for the projection at θ plus 180 degrees.
R(8) should be calculated for each pair of angles separated by 180 degrees to generate offset values as a function of angle for each slice.

2.1.6.6 Record the results as a maximum offset (R_{max}), an average offset (R_{av}),

and offset as a function of angle, $R(\theta)$. The maximum offset from the center of rotation, $R(\theta)$. should be less than 2 pixels (6 mm). Note: The COR (obtained from step 2.1.6.2) should be known to within 1.5 mm.

2.1 .6.7 In addition to the COR. the y axis must be parallel to the axis of rotation. The constancy of the y-axis alignment during rotation should be calculated as described in section 2.1.6 after a 90 degree rotation of the raw data. The y-axis offset should be independent of angle, i.e., a linear plot should be obtained (Figure 2. 1. Deviations of greater than 0.5 pixels from the average y axis offset indicate a problem with head tilt. collimator hole angulation. or gantry alignment.

2.2 Determination of COR as Function of Axial Position Along Axis of Rotation

2.2.1 Prepare a line source of Tc-99m.

2.2.2 Center a 20% window symmetrically about the Tc-99m photopeak and place a low energy all purpose collimator on the camera.

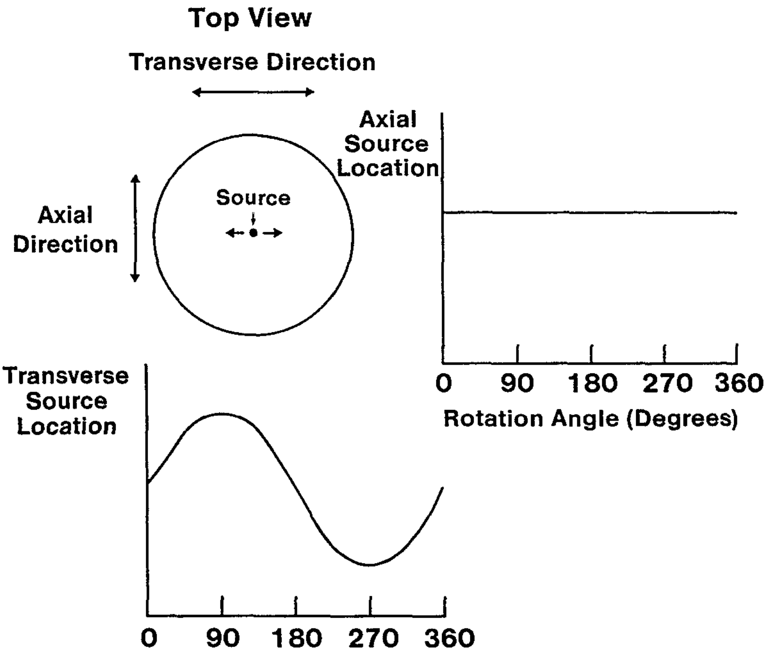

FIGURE 2. In the tranverse (x) direction, the source moves sinusoidally across the field of view as the scintillation camera rotates. A plot of the source location as a function of gantry angle results in a sinusoid.

In the axial (y) direction, the source location should remain fixed and a plot of the source location as a function of angle should be a straight line.

2.2.3 Position the line source 5 cm from the axis of rotation and extend it over the edge of the imaging table. The line source should be parallel to the AOR. Use a bubble level to ensure that the collimator is also parallel to the AOR.

2.2.4 Repeat tomographic acquisition in section 2.1.4.

2.2.5 Repeat 2.1.5 - 2.1.6.6 for every sixteenth transverse 1 pixel (3 mm) thick slice (5 cm increments) in the useful axial field of view. Note: Gantry sag and angular registration problems are global and will be identical in each sinogram. Nonlinearities which show up only in certain slices are the result of intrinsic or collimator spatial nonlinearities.

2.2.6 Record the results as a maximum offset, an average offset. and offset as a function of angle for each slice. Acceptable performance is less than a 0.5 pixel (1.5 mm) deviation throughout.

2.3 Collimator Hole Angulation

For SPECT imaging, the angulation of the holes in a slant hole collimator must be known in order to ensure its proper set up during a tomographic acquisition, i.e., its holes must be perpendicular to the AOR. The displacement of the image of a point source is examined as the source is moved vertically i.e., away from the collimator face (Figure 3). In order to ensure the accurate alignment of the source, it will be necessary to have a jig which will support the source at two vertical distances from the collimator face.

2.3.1 Prepare a Tc-99m or Co-57 point source.

2.3.2 Center a 20% window symmetrically about the Tc-99m or Co-57 photopeak and place a slant hole collimator on the camera.

2.3.3 Contruct a holder which will allow the accurate positioning of the point source at two vertical settings separated by 10 cm. Alternatively, a small platform jack can be used for this purpose.

2.3.4 Position the source holder containing the point source under the center of the collimator so that it is approximately 5 cm from the face of the collimator. The levelness of both the source holder and the collimator face should be checked with a bubble level. It is very important that the holder is accurately aligned with the collimator.

2.3.5 Acquire a 50K count conventional planar image using the largest available matrix size.

2.3.6 Lower the holder exactly 10 cm (100 mm) and acquire a second planar image as in 2.3.5.

2.3.7 Determine the x and y centroids of the two point images:
lower position - (xl,yl)
upper position - (xu,yu)

2.3.8 Calculate the distance (d) between the images

according to $d = ((xl-xu)^2 + (yl-yu)^2)^{1/2}$
Use the pixel calibration factor from section 5.6 to calculate d in mm.

2.3.9 Calculate the hole angulation (HA) according to HA = arctan (d/100). Record value of HA.

2.3.10 Repeat 2.3.5 - 2.3.9 at other locations on the collimator.

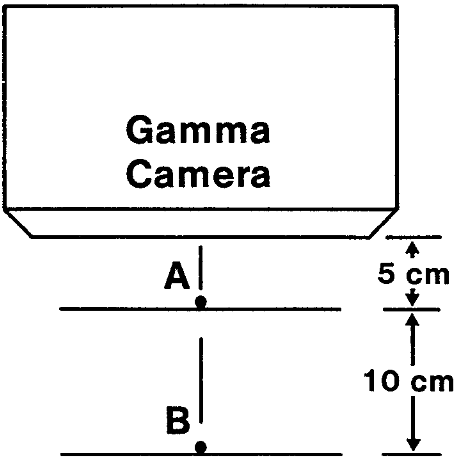

FIGURE 3. Configuration for the collimator hole angulation test. A measurement is made at source location A. The source is then displaced vertically by 10 cm to location B where a second measurement is made.

3.0 Uniformity

3.1 Tomographic Slice Uniformity

The uniformity of the camera should first be tested without regard to tomography or gantry rotation to establish the static performance of the system. The procedures described in AAPM Report No. 9. section 3 should be used to test integral and differential uniformity for comparison to manufacturer's specifications. The effects of count rate and PHA misadjustment on uniformity should also be tested.

The tomographic reconstruction process places stringent demands on detector uniformity. Camera uniformity must be corrected to within 0.5 - 1.0% in order to keep image distortion minimal. The correction is accomplished with a matrix of multiplicative correction factors applied to the projected raw views. Virtually all manufacturers provide software to do this. The correction factors are based on a high count reference flood.

3.1.1 Prepare a liquid-filled flood source with Tc-99m or use a Co-57 sheet source with +/- 1% uniformity.

3.1.2 Center a 20% window symmetrically about either the Tc-99m or Co-57 photopeak and place a low energy all purpose collimator on the camera.

3.1.3 Acquire a flood field with a 1% precision per pixel. This requires 30 million counts for a 64 x 64 matrix. Thirty million counts are also adequate for a 128 x 128 matrix if the flood field image is smoothed.

3.1.4 Check tomographic slice uniformity by tomographic imaging of a uniform cylindrical phantom containing a uniform distribution of activity.

3.1.4.1 Prepare a water-filled cylindrical phantom containing Tc-99m. The long axis of the phantom must be parallel to the axis of rotation.

3.1.4.2 Repeat step 3.1.2.

3.1.4.3 Acquire a 360 degree tomographic study using a 128 x 128 matrix, the finest angular sampling possible, and a circular orbit with a radius of rotation of 15 cm. Acquisition time should be sufficient to accumulate at least 500K counts per planar view. Note: It may be necessary to extend the phantom over the edge of the table in order to achieve a 15 cm radius of rotation. This can be accomplished by placing the phantom on a rigid support which is securely fastened to the table.

3.1.4.4 After data acquisition, uniformity correct each projection image with the field from 3.1.3.

3.1.4.5 Reconstruct images using 4 pixel (12 mm) thick slices (each containing at least 2 million counts). a ramp filter (or the filter which will be routinely used). and attenuation correction. Use the attenuation coefficient determined in section 8.8.

3.1.4.6 Review each transverse section image for concentric ring or "bulls-eye" artifacts, if they occur.

3.1.4.7 Quantitatively assess uniformity in each transverse section by obtaining integral and differential uniformity and the statistical uniformity index together with high and low pixel images as described in AAPM Report No. 9, section 3.2. Record these values.

3.1.5 Repeat tests in section 3.1.4 for a tomographic acquisition using a noncircular orbit, if this option is available.

3.1.6 Repeat sections 3.1.2 - 3.1.4 for all collimators to be routinely used.

Note: The zoom and energy window settings must be the same for the reference flood as for the clinical acquisition. The reference flood must also be acquired with the same collimator as the clinical acquisition. If the collimator is changed. a new reference flood is required.

3.2 Rotational Uniformity or Electronic Stability during Rotation

Global and local changes in camera sensitivity during gantry rotation should be maintained below 1%. Nearly all recently manufactured ECT systems have incorporated magnetic shielding to avoid interactions between the PM tubes and weak magnetic fields, but earlier systems were not adequately shielded against magnetic fields and variations on the order of 10% were observed. In addition to magnetic field effects, there may also be gravitational-mechanical effects with potential to change camera sensitivity during gantry rotation.

3.2.1 Global Measure of Constancy during Rotation

3.2.1.1 Rigidly mount a Co-57 sheet source on top of a low-energy all purpose collimator. It should be emphasized that great care must be used in securing the source to the gamma camera.

3.2.1.2 Center a 20% window symmetrically about the Co-57 photopeak.

3.2.1.3 Acquire a 360 degree tomographic study using the smallest angular sampling available with a 64 x 64 matrix. Acquisition time should be sufficient to accumulate 300 counts per pixel per projection image.

3.2.1.4 Identify a single pixel. Let x_i. be the counts in that pixel in the i th projection image.
Assuming Poisson statistics.

$$\mathrm{VAR}(x_i) = x_i$$

3.2.1.5 The total variance of all the values for x_i is calculated by:

$$\mathrm{VAR}_T = \sum_{i=1}^{N} (x_i - \bar{x})^2 / (N-1)$$

where N is the number of projection images, and $\bar{x}$ is the average of the N values for x_i.

3.2.1.6 The within groups variance is the variance due to the assumed Poisson statistics of each pixel count and is given by

$$\mathrm{VAR}_W = \sum_{i=1}^{N} x_i / N$$

3.2.1.7 Subtract the within groups variance from the total variance. The remainder is the variance for this pixel due to changes in sensitivity with gantry angle (variance of the means):

$$\mathrm{VAR}_M = \mathrm{VAR}_T - \mathrm{VAR}_W$$

3.2.1.8 The variance of the means is normalized by the square of the average pixel count for this pixel. This normalized variance is rho squared:

$$\rho_i^2 = \mathrm{VAR}_M / \bar{x}^2$$

3.2.1.9 Finally, to characterize the global constancy of the camera, repeat steps 5 - 8, for each pixel i, in the field of view. Take the average of rho squared over all the pixels in the field of view, $\overline{\rho^2}$. The square root of the resulting average, $\hat{\rho}$, is the root-mean-square estimate of rho, the camera constancy during rotation. (Note: $\hat{\rho} = \mathrm{SQR}(\overline{\rho^2})$ if $\overline{\rho^2} \geq 0$, otherwise set $\hat{\rho} = 0$). $\hat{\rho}$ should be less than 0.01.

3.2.2. Local Measure of Constancy during Rotation

3.2.2.1 If a local constancy problem must be ruled out repeat steps in section 3.2.1 but adjust acquisition time to achieve at least 600 counts per pixel per frame.

3.2.2.2 Flag pixel locations where rho is greater than 0.02 and save these locations.

3.2.2.3 Repeat acquisition and computation.

3.2.2.4 If same pixel or group of pixels are flagged again for a high value for rho, there is likely to be a local constancy problem.

4.0 Sensitivity

Increased or decreased sensitivity at certain locations within each projection can lead to reconstruction artifacts. These artifacts are independent of the character of the projection data and become more noticeable towards the axis of rotation Sensitivity measurements should include planar sensitivity, per axial centimeter volume sensitivity, and total volume sensitivity. The scatter fraction (scatter-to-nonscatter event ratio) should also be estimated since it directly affects volume sensitivity, i.e., volume sensitivity will be larger for systems with a large scatter contribution although image contrast will be degraded. Sensitivity measurements are dependent upon collimator type, window width, deadtime. gamma ray energy. slice thickness. field of view, filter type, attenuation-correction method, and other factors.

4.1 Planar sensitivity

The planar sensitivity should be measured for all collimators according to the procedure described in AAPM Report No. 9. section 3.4.

4.2 Per Axial Centimeter Volume Sensitivity

4.2.1 Prepare a water-filled cylindrical phantom containing Tc-99m. The actual diameter of the cylinder should be recorded. The activity concentration must be accurately determined. The long axis of the phantom must be parallel to the axis of rotation.

4.2.2 Center a 20% window symmetrically about the Tc-99m photopeak and place a low-energy all purpose collimator on the camera.

4.2.3 Acquire a 1 million count conventional planar image using a 128 x 128 matrix. Note acquisition time, T_{acq}.

4.2.4 Draw a rectangular region of interest (ROI) 20 centered on the image. The length of the ROI should be large enough to cover the cylinder diameter and the width should be 20 pixels in the axial direction. Record the number of counts in the ROI, C_{ROI}.

4.2.5 Calculate the axial width of the ROI, AW_{ROI}:

$$AW_{ROI}(cm) = 20\ pix \times PC(mm/pix) \times cm/10mm.$$

where PC = pixel calibration. The determination of the pixel calibration is described in section 5.

4.2.6 Calculate the per axial volume sensitivity, AVS, by dividing the ROI counts by the product of the activity concentration (AC). acquisition time (T_{acq}) and axial ROI width (AW_{ROI}):

$$AVS(cps/uCi/cm^2) = \frac{C_{ROI}(counts)}{AC(uci/cm^3) \times T_{acq}(sec) \times AW_{ROI}(cm)}$$

4.2.7 Record per axial centimeter volume sensitivity.

4.3 Total Volume Sensitivity

The total volume sensitivity is the product of the per axial centimeter volume sensitivity and the axial width of the gamma camera field of view.

4.3.1 Calculate the total volume sensitivity, TVS, by multiplying the per axial volume sensitivity from 4.2.6 by the width of the useful field of view in the axial direction, AW_{UFOV}:

$$TVS(cps/uCi/cm^3) = AVS(cps/uCi/cm^2) \times AW_{UFOV}(cm)$$

4.3.2 Record total volume sensitivity.

4.4 Estimation of System Sensitivity to Scatter

4.4.1 Place a large diameter (6 cm) nonradioactive, water-filled sphere near the center of the cylindrical phantom prepared in step 4.2.1.

4.4.2 Repeat step 4.2.2.

4.4.3 Acquire a 360 degree tomographic study using a 128 x 128 matrix, the finest angular sampling possible, and a circular orbit with a radius of rotation of 15 cm. Acquisition time should be sufficient to accumulate at least 250K counts per planar view.

4.4.4 Uniformity correct the planar images and reconstruct the projection data using 4 pixel (12 mm) thick slices, a ramp reconstruction filter, and attenuation correction. Use the attenuation coefficient determined in section 8.8.

4.4.5 Center a 5 x 5 pixel rectangular region of interest in the cold sphere in a central slice and record counts per pixel (cpp).

4.4.6 Place a rectangular region of interest of the same dimensions in a background region (5 pixels from the edge of the cold sphere) in the same slice and record cpp.

4.4.7 Estimate system's sensitivity to scatter (SF_{est}) according to:

SF_{est}=cpp in sphere/(cpp in bkgd-cpp in sphere).

4.4.8 Record value of SF_{est}. It should be noted

that what has been measured is not exactly equal to the true scatter fraction. The determination of the true SF is extremely difficult experimentally; however, the measurement procedure described above is simple and will provide a useful and reproducible indication of the system's ability to reject scattered photons.

5.0 Pixel Calibration

Pixel, actually voxel. dimensions are necessary for ray length calculation in attenuation correction algorithms, for accurate image scaling, for oblique axis transformation, and for quantitative measurements. Voxel dimensions are subject to drift and variation due to changes in camera tuning, ADC gain, and offset.

5.1 Prepare two point sources of Tc-99m or Co-57.

5.2 Center a 20% window symmetrically about the Tc-99m photopeak and place a low-energy all purpose collimator on the camera.

5.3 Position the point sources along the x axis and exactly 20 cm apart. The sources should be at least 5 cm from the collimator face to eliminate collimator septa-induced distortion.

5.4 Acquire a 100K count conventional planar image using the largest available matrix size. Ensure that no zoom is used.

5.5 Generate a count profile that passes through the center of both point sources.

5.6 Determine the distance in pixels between the centroids of the two sources. The mm/pixel calibration factor is given by: mm/pixel = 200 mm/(number of pixels)

5.7 Record calibration factor in x direction.

5.8 Repeat 5.2 - 5.6 with the point sources along the y axis.

5.9 Record calibration factor in y direction.

5.10 Note: Calibration factors in x and y directions should be within 5% of each other.

5.11 Repeat 5.2 - 5.9 for all zoom settings to be routinely used for tomographic acquisition (ensure that both point sources are within the field of view).

6.0 Spatial Resolution

The intrinsic and extrinsic spatial resolution of the gamma camera should be initially tested according to the procedure described in AAPM Report No. 9, section 6. In addition to evaluating the extrinsic resolution at 10 cm, measurements should also be made at 15 cm and optionally at 20 and 25 cm. The 15 cm determination is performed to allow comparison between the planar and tomographic resolution at the same distance. The finest linear sampling possible should be used. A 64 x 64 matrix (6 mm sampling) is not adequate and will likely yield misleading results, particularly for close distances and high resolution collimators.

The tomographic plane resolution is dependent upon the gammma ray energy, the presence or absence of scattering material, the radius of rotation, window width. collimation, as well as the reconstruction filter. The type of orbit, i.e., circular or noncircular will also affect tomographic plane resolution. The system resolution should be tested in all of the above configurations which will be routinely used.

6.1 Transverse Plane Resolution Without Scatter (In Air)

6.1.1 Prepare a line source of Tc-99m.

6.1.2 Center a 20% window symmetrically about the Tc-99m photopeak and place a low-energy all purpose collimator on the camera.

6.1.3 Position the long axis of the line source on the axis of rotation. A jig or rigid holder is recommended for this purpose.

6.1.4 Acquire a 360 degree tomographic study using the largest matrix size and finest angular sampling possible and a circular orbit with a radius of rotation of 15 cm. Acquisition time should be sufficient to accumulate at least 250K counts per planar view.

6.1.5 Reconstruct the projection data using 1 pixel (3 mm) thick slices and a ramp reconstruction filter.

6.1.6 Find the transverse section in which the image of the line source first appears (it should appear as a point source). Generate two count profiles. The first is obtained from counts along a horizontal profile (x direction) which passes through the maximum pixel count. The second is obtained from counts along a vertical profile (y direction) that passes through the maximum pixel count.

6.1.7 Using the count profiles, calculate the full-width at half-maximum (FWHM) and full-width at tenth-maximum (FWTM) for the horizontal and vertical profiles. Use linear interpolation to calculate each FWHM and FWTM to 0.1 pixel. A more precise approach would be to perform a least squares Gaussian fit of the spread function data as described in AAPM Report No. 9. section 6.

6.1.8 Use the pixel calibration factors obtained in section 5.7 and 5.9 to express the FWHM and FWTM in mm. Record both values for the horizontal and vertical profiles. The corresponding values of FWHM and FWTM for the X and Y profiles should be within 1 mm of each other. In addition. the FWHM and FWTM should be within 1 mm of the measured planar resolution (measured at 15 cm). assuming adequate linear sampling was used.

6.1.9 Repeat 6.1.6 - 6.1.8 for every sixteenth transverse slice (5 cm increments for 128 x 128 matrix).

6.1.10 Repeat steps 6.1.5 - 6.1.9 for each of the commonly used reconstruction filters. A description that identifies the filters should be included in the report. Note: The reconstructed FWHM and FWTM may now be larger than the planar values due to the filter cutoff frequency.

6.1.11 Repeat 6.l.4 - 6.1.9 with the line source displaced 10 cm laterally from the axis of rotation There should be little difference in the results obtained from the two separate line source placements. Note: The off-axis source will likely be asymmetric in shape, i.e., the tangential FWHM will be < the radial FWHM.

6.1.12 Repeat 6.1.5-6.1.11 for a tomographic acquisition using a noncircular orbit. if this option is available.

6.1.13 Repeat the above for all radionuclides and collimators to be routinely used.

6.2 Transverse Plane Resolution With Scatter

This test is identical to that described in section 7.1 except that the line source is positioned in a water-filled phantom.

6.2.1 Place the line source prepared in section 6.1.1 in a water-filled cylindrical phantom with a diameter of 20-22 cm and a height of at least 15 cm in the same orientation as described in section 6.1.3.

6.2.2 Repeat 6.1.4 - 6.1.11.

6.2.3 Repeat the above for all radionuclides and collimators to be routinely used.

6.3 Axial Slice Thickness

The thickness of a tomographic slice (Z axis dimension) can be determined by measuring the spread function from a point source or a line source aligned parallel to the x-axis (perpendicular to AOR) through a set of tomographic sections.

Slice thickness will depend on the factors listed above for the SPECT system resolution including collimation, photon energy, window width, radius of rotation, and the presence or absence of scatter. However. changes in the slice thickness resolution can be estimated from the changes in spatial resolution under the different configurations. Therefore, a measurement with Tc-99m under scatter conditions with a radius of rotation of 15 cm should suffice to characterize the slice thickness.

6.3.1 Prepare a point source of Tc-99m or Co-57. The line source prepared in section 6.1.1 may also be used: it must be aligned parallel to the x-axis of the camera.

6.3.2 Place the point source on the axis of rotation.

6.3.3 Repeat steps 6.1.2 and 6.1.4.(20,000 counts per planar view are sufficient).

6.3.4 Uniformity correct the planar images and reconstruct the transverse section images using a ramp reconstruction filter.

6.3.5 Find the transverse section in which the point source is most clearly seen. Generate a one pixel region of interest on the pixel with the maximum count. Using this ROI, obtain a curve of counts versus transverse section. Note: If the tomographic study is configured as a dynamic study, standard time-activity curve software can be used to generate this curve.

6.3.6 Determine FWHM and FWTM as in 6.1.7.

6.3.7 Use the pixel calibration factor obtained in section 5.6 to express the FWHM and FWTM in mm. Record both values. The axial resolution should be within 1 mm of the values found in section 6.1.8, provided that at least a 128 x 128 matrix (3 mm linear sampling) was used.

7.0 Image Contrast

Resolution as measured by FWHM or FWTM is not sufficient as a descriptor of performance for tomography since scatter, attenuation, and collimator penetration greatly affect the measured contrast for cold spherical objects in a warm or hot background. In addition, reconstruction filters also affect contrast. In this section, a number of cold spheres will be used to evaluate image contrast. It is difficult to obtain consistent results for small sphere sizes. i.e., of diameter < 2 x FWHM due to finite spatial resolution, partial volume effects, and problems in defining ROIs. A large number of counts (at least one million counts per transaxial slice) will be collected to reduce the effects of noise. This approach will allow the machine-limited contrast to be determined.

7.1 Prepare a water-filled cylindrical phantom containing the various sized cold spheres (refer to section IV.4) with Tc-99m. The long axis of the phantom must be parallel to the axis of rotation.

7.2 Center a 20% window symmetrically about the Tc-99m photopeak and place a low-energy all purpose collimator on the camera.

7.3 Acquire a 360 degree tomographic study using a 128 x 128 matrix, the finest angular sampling possible. and a circular orbit with a 15 cm radius of rotation. Acquisition time should be sufficient to accumulate at least 500K counts per planar view.

7.4 Uniformity correct the planar images and reconstruct the projection data using 4 pixel (12 mm) thick slices, a ramp filter with no window or rolloff, and attenuation correction using the attenuation coefficient determined in section 8.8. Attenuation correction is very important here.

7.5 Using 2 x 2 pixel rectangular regions of interest centered in image of sphere and in background, calculate image contrast (C_{image}) or all sphere diameters according to:

$$C_{image} = (cpp_{background} - cpp_{sphere})/cpp_{background}$$

where $cpp_{background}$ are the background counts per pixel,

and cpp_{sphere} are the sphere counts per pixel.

Note: The contrast values obtained for the smaller spheres (diameter 2x FWHM) will have larger uncertainties associated with them, mainly due to their low contrast and difficulty in positioning the ROIs.

7.6 Record results from section 7.5 along with the images.

7.7 Repeat 7.3 - 7.6 for all other collimators. radionuclides, and reconstruction filters which will be routinely used.

8.0 Attenuation Correction and Patient Contour Positioning

Attenuation correction is required to compensate for count loss due to absorption and scatter of gamma rays within the body. Reconstructed images of large homogeneous organs such as the liver which are not corrected for attenuation will exhibit a "hot rim" artifact. Several of the commercial systems perform an attenuation correction based on the assumption of an elliptical shape for the body contour. Other systems use dual energy windows to measure the patient contour from data acquired in an energy window set on the Compton scatter portion of the energy spectrum. In this section. the ellipse accuracy and attenuation correction will be evaluated.

The measurement of the effective attenuation coefficient (μ_{eff}) for Tc-99m is determined from a single projection image of the uniformity phantom. It requires the following parameters which have been previously measured:

1. The activity concentration in the phantom. AC ($\mu Ci/cm^3$) -section 4.

2. The system sensitivity, SS (counts/min/μCi) - section 4.

3. The pixel calibration factor, PC (mm/pixel) - section 5, and

4. The phantom thickness. D (cm). Note: For a cylindrical phantom, D is the internal diameter and for an elliptical phantom. D is the internal width of the minor axis.

8.1 Prepare a water-filled cylindrical phantom containing Tc-99m. Alternatively. a cylindrical phantom of elliptical cross section with major and minor axes of approximately 30.5 and 22 cm, respectively, and a height of at least 15 cm can be used. The long axis of the phantom must be parallel to the axis of rotation.

8.2 Center a 20% window on the Tc-99m photopeak and place a low energy all purpose collimator on the camera.

8.3 Acquire a conventional planar image of the phantom using a 128 x 128 matrix. The phantom should be aligned along the AOR with a 15 cm radius of rotation. The acquisition time, T_{acq}, should be long enough so that a

maximum pixel count of 500 is attained. T_{acq} (min)

must be accurately known.

8.4 Generate a count profile across the phantom image. The slice width (SW) should be approximately 6 cm wide (20 pixels for 128 x 128 matrix).

8.5 Find the maximum counts in the count profile, CM_{obs}.

8.6 Calculate the expected count maximum, CM_{exp}, assuming no

attenuation. First, find the volume (V) of activity in cm^3 corresponding to the maximum counts in the count profile:

$$V(cm^3)=D(cm) \times SW(pix)^2 \times PC^2(mm/pix)^2 \times cm^2/100\ mm^2$$

The expected count maximum from the activity in V is then determined from

$$CM_{exp}=AC(\mu Ci/cm^3) \times V(cm^3) \times SS(cpm/\mu Ci) \times T_{acq}(min)$$

8.7 Calculate the ratio $R = CM_{obs}/CM_{exp}$

8.8 It can be shown that

$$R = (l-\exp(-\mu_{eff}D))/\mu_{eff}D \text{ or}$$

$$\mu_{eff} = (l-\exp(-\mu_{eff}D))/RD.$$

Although this cannot be solved analytically, μ_{eff} can be accurately estimated with an iterative calculation. In the first iteration, let

μ_l = (l-exp(-0.12 x D))/RD, which is approximately equal to 0.9/RD for D = 20 cm. In the second iteration. calculate μ_{eff} = (1-exp(-μ_1 x D))/RD.

8.9 Acquire a 360 degree tomographic study using the cylindrical phantom with a 128 x 128 matrix, the finest angular sampling available and a circular orbit of 15 cm radius of rotation. The acquisition time should be sufficient to allow at least 250K counts per planar view.

8.10 Reconstruct projection data obtained from section 8.9 using attenuation coefficient (μ_{eff}) calculated in section 8.8. Save the elliptical contour generated for the attenuation correction if the software allows.

8.11 Superimpose the contour over the reconstructed transverse slice and check the correspondence.

8.12 Repeat 8.11 for each transverse section image in the study.

8.13 Generate a count profile through the center of the source distribution. Verify that count uniformity is within +/-10% across the count profile.

8.14 Repeat 8.13 for each transverse section image in the study.

8.15 Repeat 8.1 - 8.8 for all other radionuclides which will be routinely used.

9.0 Total System Performance Evaluation

A water-filled cylindrical phantom containing a variety of cold sphere inserts as described in section 8.1 can be used to monitor any system degradation that occurs after the initial acceptance testing of the SPECT system.

9.1 Repeat steps 7.1 - 7.4.

9.2 Assess uniformity as described in sections 3.1.4.6 - 3.1.4.7 for uniform regions of the phantom.

9.3 Note smallest-sized cold sphere detected and measure its image contrast as described in section 7.5.

9.4 Record the results from sections 9.2 and 9.3. The routine quality control results should agree with those obtained at acceptance. Any degradation of performance should be further evaluated with the more specific tests described in this document.

9.5 Repeat 9.2-9.4 for a tomographic acquisition using a noncircular orbit, if this option is available.

10.0 Acceptance Testing and Quality Control Time Schedule

All tests described in sections 1 - 9 should be performed at installation for initial acceptance of the SPECT unit. The recommended test schedule for the various procedures is given below.

Test	Weekly	Monthly	Annually
1.0 Physical Inspection			X
2.0 System Alignment			
2.1 COR	X		
2.2 COR as Function of Axial Position Along AOR			X
2.3 Collimator Hole Angulation			X
3.0 Uniformity			
3.1 Flood Field	X		
3.2 Rotational			X
4.0 Sensitivity			X
5.0 Pixel Calibration		X	
6.0 Spatial Resolution			X
7.0 Image Contrast			X
8.0 Attenuation Correction			X
9.0 Total Performance Evaluation		X	

B. Additional Considerations for Dual-Head Systems

1. Same overall criteria that are used for single detector systems are valid: however, it is essential that response of all cameras be matched to each other. All calibration factors and centroid locations should be within 0.5% of each other. Quantitative comparisons should be performed for each head separately and then after the responses of both heads have been added together.

For example, reconstruct array of point or line sources and/or cylindrical phantom with cold sphere inserts for each camera head separately. Perform all the routine quality control tests for each head. Then add two reconstructed images from each camera to ensure that the added image has not been degraded. Note: If spheres are used. the image contrast should stay the same but the signal-to-noise ratio should improve.

2. There should be coincidence of both collimator/detector axes of rotation. Separate centers of rotation should be acquired for each head. In addition, each head must have its own unique reference flood. The collimators should be uniquely identified so that the reference floods for uniformity correction will be applied to the correct collimator.

3. Ideally. the centroid of the projection (image) of a point source located anywhere in the source distribution volume of interest should be within 1 mm of its true geometrically projected value (based on the relative location of the point source in space, and the locations of the gamma cameras) for all angular orientations of the gamma cameras.

4. In general the +/-x and +/-y absolute integral linearity should be within 1 mm, and matched, if possible. A similar comment is valid for absolute differential linearity.

5. Energy windows and collimators should also be matched.

VI. References

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APPENDIX A

FORTRAN Algorithm for Sinogram Generation

Since different systems have different ways of handling file operations, only general statements are included for these commands.

```
      IMAGE (128,128)       ; Projection Image Data
      ISINOG (128,128)      ; Sinogram Image
      JROW                  : Projection level of Sinogram
      JTHCK                 ; Thickness of cut

      Open Projection Image File
      DO 10 K = 1,128
      Read projection image L into the array IMAGE
      DO 20 I = 1,128
      ISINOG (I,K) = 0
      DO 20 J= JROW-JTHCK,JROW+JTHCK
      ISINOG (1,K) = ISINOG(I,K)+IMAGE(I,J)
 20   CONTINUE
 10   CONTINUE
```

APPENDIX B

FORTRAN algorithm for the fit to function $A \sin(\theta + \phi) + B$ as given in section 2.1.6.2.

```
        DIMENSION Y(128)
C       Y is the array with the centroid locations of the sinogram
        M is a variable indicating the number of angular samples
        PI = 4*ATAN (1.)
        DTHETA = (PI/M)*2.
        SUM= 0.
        S1 = 0.
        C1 = 0.
        DO 10 I = 1,M
        THETA = FLOAT(I-1)*DTHETA
        SUM = SUM+Y(I)
        S1 = S1 + Y(I)*SIN(THETA)
        C1 = C1 + Y(I)*COS(THETA)
 10     CONTINUE
        A = SQRT(S1*S1 + C1*C1)
        PHI = ATAN(S1/C1)
        B = SUM/l28.
```

APPENDIX C
Vendors of Commercially Available SPECT Phantoms and Accessories

1. Data Spectrum Corporation
   2307 Honeysuckle Road
   Chapel Hill, NC 27514
   (919) 942-6192

2. Nuclear Associates
   100 Voice Road
   Carle Place, NY 11514
   (516) 741-6360