NEMA STANDARDS PUBLICATION NU 2

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Performance Measurements of Positron Emission Tomographs

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NEMA Standards Publication NU 2-1994

PERFORMANCE MEASUREMENTS OF POSITRON EMISSION TOMOGRAPHS

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Foreword

This Standards Publication is intended to provide a uniform and consistent method for measuring and reporting various performance parameters of a positron emission tomograph. These measurements are expected to help inform interested parties of the relative levels of performance among various types of positron emission tomographs and to monitor the performance of any particular positron emission tomograph as needed.

User input has been considered in the development of this publication. Proposed or recommended revisions should be submitted to:

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Scope

A serious and concerted effort has been made to include positron emission tomographs of every design under the scope of this Standard. Included are time-of-flight and non-time-of-flight coincidence systems, discrete and continuous detector designs, single and multiple slice devices, and multi-planar and volume reconstruction models. It is assumed that every system to be tested under this Standard is able to create sinograms and transverse plane images, define and manipulate two-dimensional regions of interest with circular and rectangular boundaries, and extract such parameters as coincidence event counts detected within specified intervals of time. Tomographs are assumed to have a transverse field of view at least 260 mm in diameter. Positron emission tomographs without these capabilities may not be able to be tested against all the standards. It is assumed that ^{18}F is available in amounts sufficient to perform the count rate losses and randoms measurements. These specifications represent a subset of measurements that define the performance of positron emission tomographs. This subset is deemed to be common across the tomographs existing at the time of writing.

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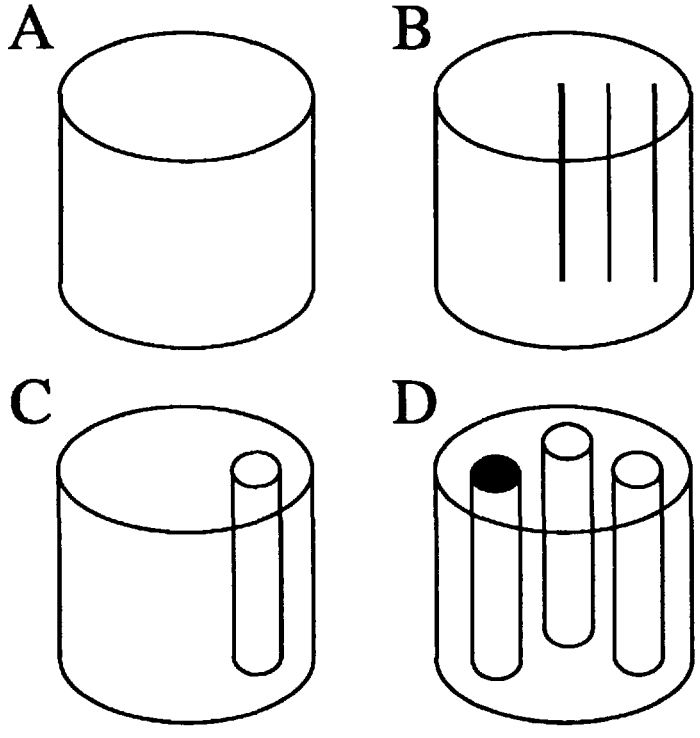
Section 1
DEFINITIONS, SYMBOLS AND REFERENCED PUBLICATIONS

1.1 DEFINITIONS

Axial field-of-view (FOV_{axial}) is the maximum length parallel to the long axis of a positron emission tomograph along which true coincidence events can be detected.

Test phantom is a right circular cylinder composed of virgin polymethyl methacrylate, PMMA, with an outside diameter of 203 ± 3 mm, a wall thickness of 3 ± 1 mm, and an overall interior length of 190 ± 1 mm. It is capped at both ends using PMMA, with provisions for water filling and the interior placement of the inserts listed below (see Figure 1-1).

Test phantom cylinder inserts are three right circular cylindrical phantoms each having an overall length of 190 mm +10/-5 mm. One shall be solid with an outside diameter of 50 ± 3 mm and composed of polytetrafluoroethylene of specific gravity between 2.13 and 2.19. Two inserts shall have fillable cavities at least 185 mm in length, outside diameters of 50 ± 3 mm and wall thicknesses of 3 ± 1 mm. The three 50 mm diameter inserts are installed together, their central axes being positioned at 120° ± 10° intervals from each other in the same transverse plane, each placed 60 ± 3 mm off-center and parallel to the central axis of the test phantom.



A - With no inserts for the system sensitivity, count losses, uniformity and countrate correction measurements.
B - With line source inserts for the scatter measurement.
C - With hollow cylinder filled with water for the scatter correction measurement.
D - With hollow cylinder filled with air, hollow cylinder filled with water and solid cylinder for the attenuation correction measurement.

Figure 1-1
TEST PHANTOM

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Two types of compact sources shall be available for procedures which do not use the test phantom:

Fillable point source is a liquid source assembly no larger than two millimeters in all dimensions.

Fillable line source is a liquid source assembly, constructed of stainless steel, at least as long as the FOV_{axial} and no greater than two millimeters in other dimensions.

Test phantom line source insert is a phantom insert having a fillable cavity of at least 185 mm in length and of no larger than two millimeters in its other dimensions. It may be positioned within the test phantom parallel to the long axis of the tomograph at radii of 0, 45, and 90 millimeters with an accuracy of ± 3 mm.

Transverse field-of-view (FOV_{trans}) is the maximum diameter circular region perpendicular to the long axis of a positron emission tomograph within which objects can be imaged.

1.2 STANDARD SYMBOLS

Symbolic expressions for certain quantities are used throughout this Standard. Symbols which use any one of the standard subscripts to specify a basic quantity are identified by the subscript string $_{xxx}$. All quantities expressed as a function of an independent variable shall be symbolically represented as Q(x), where x is a lower case letter representing the variable as defined in the related text.

Axial Response Function—is measured by moving point sources in short incremental steps along the axial direction of the tomograph.

Coefficient of Variation (CV_{xxx}) — used as part of the uniformity measurement:

a. CV_i coefficient of variation for all regions of interest (ROI's) in a slice *i*
b. CV_{vol} coefficient of variation for all ROI's in a defined volume of a system
c. CV_{sys} coefficient of variation for all slices of the system

Counts (C_{xxx})—the number of coincidence events:

a. C_{ROI} events in a two-dimensional ROI
b. C_{TOT} total number of events
c. C_t number of true events counted
d. C_s number of scattered events counted
e. C_r number of random events counted

Non-uniformity (NU_{xxx})—a pair of percentage numbers, (+x%, -y%), which are the relative variations from the mean:

a. NU_i non-uniformity in a designated 2-D region of slice *i*
b. NU_{vol} non-uniformity in a volume of the system
c. NU_{sys} non-uniformity within all slices of a system taken together

Normalized Axial Response Function—An axial response function in which the count rate at each point is divided by the relative point slice sensitivity. The area under a normalized axial response function is unity.

Peak to valley ratio (PV)—a measure of the variation in sensitivity as a function of axial position.

Percent dead time ($PDT_{xxx,j}$)—lost counts as a percentage of input count rate.

a. $PDT_{i,j}$ percent dead time for ith slice during jth acquisition
b. $PDT_{sys,j}$ percent dead time for the entire system during j^{th} acquisition

Radioactivity (A_{xxx})—a nuclear decay rate in units of megaBecquerels, i.e., in units of 1 million disintegrations per second, and optionally expressed in units of milliCuries, i.e., in units of 37 million disintegrations per second:

a. A_0 initial radioactivity at T_0
b. A_j radioactivity at start of jth acquisition
c. $A_{ave,j}$ average radioactivity for jth acquisition
d. A_{cal} radioactivity at time T_{cal}
e. $A_{t,peak}$ radioactivity at the maximum true event rate
f. $A_{t,50\%}$ radioactivity at 50% dead-time
g. $A_{t=r}$ radioactivity at which random event rate equals true event rate

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The initial radioactivity at the beginning T_0 of an acquisition shall be estimated using the activity A_{cal} as measured by a dose calibrator or by a well counter at time T_{cal} according to:

$$A_0 = A_{cal} \exp\left(\frac{T_{cal} - T_0}{T_{1/2}} 1n\ 2\right)$$

The average radioactivity during an acquisition interval shall be calculated from the activity, A_0, at the beginning T_0 of the acquisition, the half-life of the radionuclide, $T_{1/2}$, and the duration of the acquisition, T_{acq}, according to:

$$A_{ave} = \frac{A_0}{1n\ 2}\left(\frac{T_{1/2}}{T_{acq}}\right)\left\{1 - Exp\left(\frac{-T_{acq}}{T_{1/2}} 1n\ 2\right)\right\}$$

The initial radioactivity, A_j, shall be determined by a dose calibrator or well counter activity measurement A_{cal}, decay corrected to the starting time, T_j of the j^{th} acquisition, using the following equation:

$$A_j = A_{cal} \exp\left(\frac{T_{cal} - T_j}{T_{1/2}} 1n\ 2\right)$$

Radioactivity concentration (a_{xxx})—a nuclear decay rate per unit volume in units of megaBecquerels per milliliter, i.e., in units of 1 million decays per second per milliliter, and optionally expressed in units of milliCuries per milliliter, i.e., in units of 37 million decays per second per milliliter:

a. a_0 initial radioactivity concentration at T_0
b. a_{ave} average radioactivity concentration
c. $a_{t,peak}$ radioactivity concentration at peak true event rate
d. $a_{t,50\%}$ radioactivity concentration for 50% dead-time
e. $a_{t=r}$ radioactivity concentration at which random event rate equals true event rate

The radioactivity concentration of a quantity of radioactivity distributed uniformly throughout a volume V shall be found dividing the activity, A_{xxx} by the volume V according to:

$$a_{xxx} = \left(\frac{A_{xxx}}{V}\right)$$

The average radioactivity concentration is thus:

$$a_{ave} = \left(\frac{A_{ave}}{V}\right)$$

Radioisotopic half-live ($T_{1/2}$)—the interval of time during which half of the nuclei of a radionuclide are likely to decay:

Element	Radionuclide	$T_{1/2}$
Fluorine	^{18}F	6588 seconds (109.8 min 1.830 hours)

Rate (R_{xxx})—a coincidence event rate measured in events per second, defined as the coincidence counts divided by the time interval T_{acq}:

a. R_{ROI} rate in a two-dimensional ROI
b. R_{TOT} total event rate
c. R_{Extr} potential event rate (no losses)
d. R_t true event rate
e. R_s scatter event rate
f. R_r random event rate
h. $R_{t,peak}$ true event rate at which R_t saturates
i. $R_{t,50\%}$ true event rate at which 50% dead-time occurs
j. $R_{t=r}$ true event rate at which random event equals true event rate

Rate per radioactivity concentration (r_{xxx})—a coincidence event rate per radioactive concentration unit measured in events per second per mega-Becquerels-per-milliliter, and optionally expressed in units of events per second per milliCurie-per-milliliter, defined as the coincidence rate obtained in the time interval T_{acq}, divided by the average radioactivity concentration a_{ave}:

a. r_{ROI} event rate in a two-dimensional ROI per radioactivity concentration a_{ave}
b. r_{TOT} total event rate per average radioactivity concentration, a_{ave}
c. r_t true event rate per average radioactivity concentration, a_{ave}
d. r_s scatter event rate per radioactivity concentration a_{ave}
e. r_r random event rate per radioactivity concentration a_{ave}

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Relative Point Slice Sensitivity—a measure of the rate at which coincidence events are detected in the presence of radioactive point sources in the limit of low activity levels below which count rate losses are negligible. The relative point slice or axial sensitivity is the sum of all the counts in each axial response function.

Remnant scatter fraction (ΔSF_{corr})—a measure of the error in a reconstructed image after scatter correction has been applied.

a. $\Delta SF_{corr,i}$ remnant scatter fraction for slice *i*
b. $\Delta SF_{corr,sys}$ remnant scatter fraction for entire tomograph system calculated as the average of all slices.

Scatter fraction (SF)—a dimensionless ratio of scattered coincidence events to the sum of scattered and true coincidence events in a transaxial ROI of the tomograph field-of-view.

Sensitivity (S)—a measure of the rate at which true coincidence events are detected in the presence of radioactive sources in the limit of activity levels below which count rate losses are negligible.

a. S_i sensitivity of slice *i*
b. S_{tot} total system sensitivity

Sinogram—A two dimensional projection space representation of a transaxial image in which one dimension represents radial distance from the center of the tomograph and the second dimension represents the projection angle.

Spatial resolution ($FWHM_{xxx}$)—the full width at half maximum of the spatial response of a tomograph to a two-dimensional or three dimensional spatial impulse function:

a. $FWHM_{rad}$ in transverse plane in a radial direction
b. $FWHM_{tan}$ in transverse plane normal to a radius.
c. $FWHM_{ax}$ in axial plane direction

Standard deviation (SD_{xxx})—used as part of the uniformity measurement:

a. SD_i standard deviation of values for all ROI's in a slice *i*
b. SD_{vol} standard deviation of values for all ROI's in a defined region of a system
c. SD_{sys} standard deviation of values for all slices of the system

Time (T_{xxx})—a relative time measured in seconds:

a. $T_{1/2}$ time interval of one half-life
b. $T_{acq,j}$ time interval of acquisition *j*
c. T_0 starting time of an acquisition
d. T_{cal} time of well counter measurement

Volume (V)—a physical volume measured in milliliters.

1.3 REFERENCED PUBLICATIONS

Karp et. al., "Performance Standards in Positron Emission Tomography" *J. Nucl Med* 32: 2343-2350, 1991.

F. W. Walker, J.R. Parrington, and F. Feiner, Chart of the Nuclides, 14th edition, Knolls Atomic Power Laboratory, Revised 1989.

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Section 2
GENERAL

2.1 PURPOSE

The purpose of this Standard is to specify procedures for evaluating performance of positron emission tomographs. The resulting standardized measurements can be cited by manufacturers to specify the guaranteed performance levels of their tomographs. As these measures become available throughout the industry, potential customers may compare the performance of tomographs from various manufacturers.

The measurements described can be performed using devices or methods readily available to most users. Thus, the standard measurement procedures can be used by customers for acceptance-testing of tomographs before and after installation of the equipment. Several of the measurements may also be useful for quality control.

A further discussion of the intent and purpose of the procedures can be found in "Performance Standards in Positron Emission Tomography" by Karp et. al.

2.2 PURVIEW

The standards committee has tried to specify methods that can be performed on all currently available positron emission tomographs. These include multi-ring, continuous detector and time-of-flight instruments. Wherever possible, future developments which could be readily anticipated were taken into account.

The tomographs whose performance are to be evaluated are, however, assumed to have a transverse field of view suitable for human subjects, and for the purposes of these procedures, must have an accessible diameter of at least 260 millimeters. The test phantom is 19.0 cm in length and is suitable for performing measurements in all slices of tomographs with an axial field of view of less than 17.0 cm. For tomographs having an axial field of view greater than 17.0 cm, the phantom is to be centered axially and only information for the center 17.0 cm can be reported.

2.3 UNITS OF MEASURE

Systeme International d'Unites (SI) units shall be used in all reports of positron emission tomograph performance measurements. Customary units such as milliCuries may be optionally reported as auxiliary values in parenthetical statements with the standard specifications for individual performance reports.

2.4 CONSISTENCY

All measurements must be performed without altering any of the instrument's parameters which are mutually exclusive, unless otherwise directed for a particular measurement. These include, but are not limited to the following parameters: energy discrimination windows, coincidence timing window(s), pulse integration time, motions to increase spatial sampling such as wobbling or axial translation, reconstruction filter, pixel size, slice thickness, axial acceptance angle, and axial averaging or smoothing.

The reconstruction filter, matrix and pixel size shall be that recommended by the manufacturer and shall remain fixed for all NEMA measurements of tomograph performance unless otherwise directed for a particular measurement.

Most systems organize the raw measurements into parallel projection matrices corresponding to transverse slices before performing 2-D tomographic image reconstruction. This can lead to errors in positioning depending on the axial acceptance angle, particularly in the axial direction, as the radial distance from the center increases. Some systems can change the axial acceptance angle by adjusting the septa shielding, while others specify the angle in software. For systems that acquire and reconstruct 3-D measurements, it is assumed that the volume imaged can be sliced into parallel planes for data analysis.

The acceptance angle shall be that recommended by the manufacturer and shall remain fixed for all NEMA measurements of tomograph performance.

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The amount of scattered radiation for a point source in air is considerably less than in a patient; however, there is nevertheless some scatter from the lead shielding which is not eliminated with the coincidence requirement. Moreover, the ability to locate the position of events properly depends on the energy of the event, particularly for systems which use crystal-to-photomultiplier tube coding.

Therefore, the energy window used for these measurements must be specified. The window setting shall be that recommended by the manufacturer and shall remain fixed during all of the NEMA measurements of a tomograph's performance.

For all of the measurements using the test phantom, it is assumed that only the test phantom is in the field-of-view of the scanner. Placing any other attenuating material, such as a fixation device, in the field-of-view may adversely affect the test results.

Therefore, the test phantom shall be suspended in the field-of-view while performing any measurement using the phantom. It shall not be placed on a headholder or patient table.

2.4 EQUIVALENCY

^{18}F is required for all of the tests. For some measurements, substitution of another radionuclide such as ^{68}Ga can lead to significantly different results, due to such factors as positron range and activity calibration. No accommodation for using radionuclides other than ^{18}F is made in these procedures.

It is assumed that the dose calibrator or well counter used for these measurements has been calibrated using either a National Institute of Standards and Technology reference source, or one whose activity has been closely related or traceable to a reference source.

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Section 3
SPATIAL RESOLUTION

3.1 GENERAL

The spatial resolution of a system represents its ability to distinguish between two points after image reconstruction. The measurement is performed by imaging point (or line) sources in air, and then reconstructing images using a sharp reconstruction filter. Although this does not represent the condition of imaging a subject in which tissue scatter and a limited number of acquired events require the use of a smooth reconstruction filter, the measured spatial resolution provides a best-case comparison among scanners, indicating the highest achievable performance.

3.2 PURPOSE

The purpose of this measurement is to characterize the widths of the reconstructed image point spread functions (PSF) of compact radioactive sources, or the widths of line spread functions (LSF) of extended sources placed perpendicular to the direction of measurement. Either point or line sources can be used. The width of the spread function is measured by its full-width at half-maximum amplitude (FWHM).

In addition, there are two measures of how well objects can be distinguished in the axial direction. One of these, the axial resolution is made with a stationary point and is applicable only to scanners with sufficiently fine axial sampling (at least three times smaller than the FWHM of the axial profile) to yield a valid number. The second measure, the axial slice width (commonly referred to as the "slice thickness"), is made with a point source stepped through the scanner axially in small increments. This measure is applicable to all scanners.

3.3 METHOD

For all systems, the spatial resolution shall be measured in the transverse plane in two directions (e.g. radially and tangentially). In addition, for those systems having axial sampling at least three times smaller than the FWHM of the axial response function, an axial resolution also shall be measured.

The transverse field-of-view and image matrix size determine the pixel size in the transverse plane. In order to measure the width of the spread function accurately, its FWHM should span at least ten pixels. A typical imaging study of a brain, however, requires a 260 mm FOV, which together with a 128 x 128 image matrix and 6 mm spatial resolution, results in a FWHM of only three pixels. Therefore, the pixel size should be made close to one-tenth the expected FWHM during reconstruction and should be indicated as a condition for the transverse spatial resolution measurement.

For volume imaging systems, the voxel dimensions in both the transverse and axial directions should be close to one-tenth the expected FWHM, and should be indicated as a condition for the spatial resolution measurement.

For all systems, the axial slice width is measured by moving a source in small increments to sample the response function adequately. For the axial slice width measurement, the step size should be close to one-tenth the expected FWHM. It is assumed that a computer-controlled bed will be used for accurate positioning of the source.

3.3.1 Radionuclide

The radionuclide for this measurement shall be ^{18}F, with an activity less than that at which either the percent dead-time losses exceed 5% or the random coincidence rate exceeds 5% of the total event rate.

3.3.2 Source Distribution

Point and line sources meeting the requirements as defined in Section 1.1 are to be used.

3.3.2.1 TRANSVERSE RESOLUTION

Line sources, suspended in air (to minimize scatter), shall be used for measurements of transverse spatial resolution. The sources shall be fixed parallel to the long axis of the tomograph, and located radially at 50 millimeter intervals along Cartesian axes in a plane

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perpendicular to the long axis of the tomograph (see Figure 3-1). For tomographs having a transverse field-of-view smaller than 310 mm, the sources shall be positioned at the radial positions (r = 10, 50, 100 mm); tomographs with up to a 410 mm field-of-view shall use seven positions (r = 10, 50, 100, 150 mm); larger tomographs shall use nine positions (r = 10, 50, 100, 150, 200 mm). Each of these positions yields two measurements of FWHM, which shall be distinguished by being in the radial and tangential directions.

3.3.2.2 AXIAL SLICE WIDTH

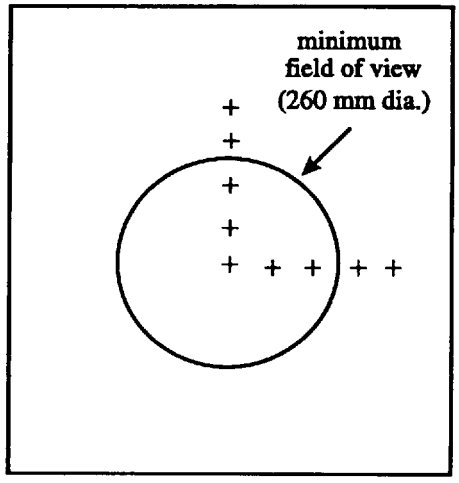
The response of point sources suspended in air shall be measured for all systems. The point sources shall be moved in small increments along the axial direction over the length of the tomograph. For tomographs having a transverse field-of-view smaller than 310 mm, the sources shall be positioned at three locations (r = 0, 50, 100 mm); for tomographs with up to a 410 mm field-of-view, the sources shall be positioned at four positions (r = 0, 50, 100, 150 mm); for larger tomographs, the sources shall be positioned at five positions (r = 0, 50, 100, 150, 200 mm) (see Figure 3-2). The sources are stepped in the axial direction in increments of one-tenth the expected FWHM of the axial response function.

3.3.2.3 AXIAL RESOLUTION

For those tomographs with an axial sampling interval one-third or less than the FWHM of the axial response function, axial spatial resolution is to be determined from measurements of point source suspended in air.

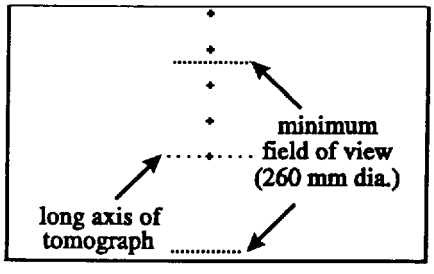
The sources are located at radial intervals of 50 mm, starting at the center, to a distance which depends on the transverse field-of-view, as described in the measurement of axial slice profile width.

Tomographs with a transverse field-of-view smaller than 310 mm shall use three positions (r = 0, 50, 100 mm); tomographs with up to a 410 mm field-of-view shall use four positions (r = 0, 50, 100, 150 mm); larger tomographs shall use five positions (r = 0, 50, 100, 150, 200 mm). Each point source shall be imaged at axial intervals of 20 mm, starting at the center of the scanner and extending to within 10 mm from the edge of the axial FOV.



(The 260 mm minimum field of view boundary is shown as a solid circle.)

Figure 3-1
GRID OF LINE SOURCES FOR TRANSVERSE RESOLUTION IN A TRANSVERSE PLANE



(The 260 mm minimum field of view boundary is shown as dotted lines.)

Figure 3-2
GRID OF POINT SOURCES FOR AXIAL RESOLUTION

3.3.3 Data Collection

Measurements shall be collected for all sources in all of the positions specified above. At least 50,000 counts shall be acquired in each response function and 50,000 counts for each source per slice. Measurements can be taken with multiple sources except for the slice width measurement.

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3.3.4 Data Processing

Data shall be corrected for dead-time losses and random coincidences. Reconstruction using a ramp filter with the cutoff at the Nyquist frequency as determined in projection space, shall be employed for all spatial resolution data. No reconstruction is done for axial slice width.

3.4 ANALYSIS

The transverse spatial resolution (FWHM) of the line source response function in two directions shall be determined by forming one-dimensional response functions, along profiles through the transverse image in two orthogonal directions, through the peak of the distribution.

Axial spatial resolution (FWHM) of the point sources are determined by forming one-dimensional response functions, along profiles through the volume image in the axial direction, through the peak of the distribution in the slice nearest to the source.

The slice widths (FWHM) are determined by forming one-dimensional response functions by recording the counts collected for each plane at each axial location of the source. This is repeated for each radial source location. These are the axial response functions.

Each FWHM shall be determined by linear interpolation between adjacent pixels at half the maximum pixel value, the peak of the response function (see Figure 3-3). Values shall be converted to distance in millimeters by multiplication by the pixel size.

3.5 REPORT

Radial and tangential resolutions (FWHM) for each radius, averaged over all slices, shall be calculated and reported as values of system resolution.

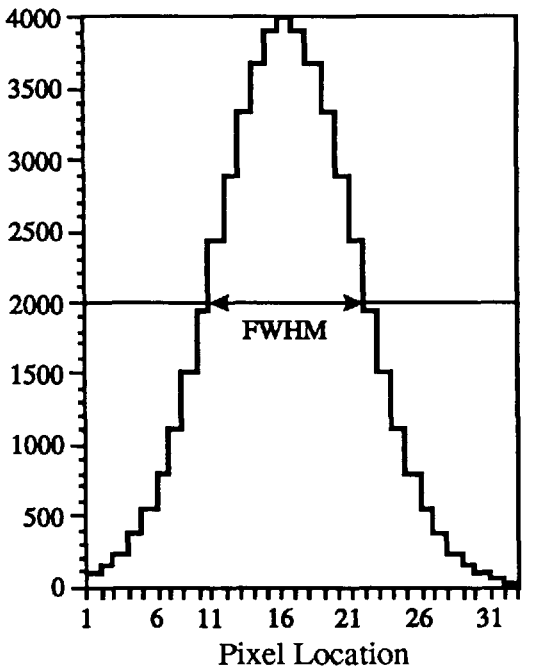


Figure 3-3
A TYPICAL RESPONSE FUNCTION WITH FWHM DETERMINED GRAPHICALLY BY INTERPOLATION

Axial slice widths for each radius, averaged over all slices for each type (e.g. odd, even), shall be reported. Transverse pixel dimensions and axial step increments in millimeters shall also be reported.

Axial resolutions at each radius, averaged over all slices, shall be reported for systems in which axial resolution is to be measured. For these systems, the axial pixel dimension in mm shall also be reported.

The dimensions of the fillable sources shall be reported.

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Section 4
SCATTER MEASUREMENT

4.1 GENERAL

The scattering of gamma rays emitted by the annihilation of positrons results in falsely located coincidence events. Variations in design and implementation cause positron emission tomographs to have different sensitivities to scattered radiation.

4.2 PURPOSE

The purpose of this procedure is to measure the relative system sensitivity to scattered radiation. Scatter is expressed by the scatter fraction, SF, for the entire tomograph and by the values for scatter fraction in each slice.

4.3 METHOD

The measurement shall be performed by imaging a single-line source (see Section 1.2) at three radial positions within a water-filled test phantom.

Unscattered events are assumed to lie within a 40 mm wide strip centered on the image in each sinogram of the line source. This width is arbitrarily chosen because the scatter value is relatively insensitive to the exact width of the region, and few unscattered events lie more than 20 mm from the line image in most positron emission tomographs (see Figure 4-1).

A linear interpolation across the strip from the points of intersection of the scatter tails and the edges of the 40 mm wide strip is used to estimate the amount of scatter present in the strip. The area under the line, plus the contributions outside of the strip equals the estimated scatter.

Estimates of scatter fraction for uniform source distributions are made by assuming a slowly varying radial dependence exists. In this assumption, the measure of scatter fraction for a line source along the central axis of the tomograph is applied to a cross-sectional area out to a radius of 22.5 mm. The scatter fraction for a line source 45 mm off-axis is applied to an annulus between 22.5 and 67.5 mm. Likewise, the scatter fraction for a line source 90 mm off-axis is applied to an annulus between 67.5 and 100 mm (see Figure 4-2). The three values for scatter fraction are weighted by the areas to which they are applied, yielding a weighted average. The annular areas are in the ratios of 1:8:10.75, respectively.

4.3.1 Radionuclide

The radionuclide for the measurement shall be ^{18}F, with an activity less than that at which either the percent dead-time losses exceed 5% or the random coincidence rate exceeds 5% of the total event rate.

4.3.2 Source Distribution

The test phantom shall be filled with non-radioactive water as a scatter medium. The test phantom line source insert shall be inserted, parallel to the axis of the cylinder, in three steps: at radii of 0, 45, and 90 mm. The phantom shall be centered both axially and transaxially in the field-of-view.

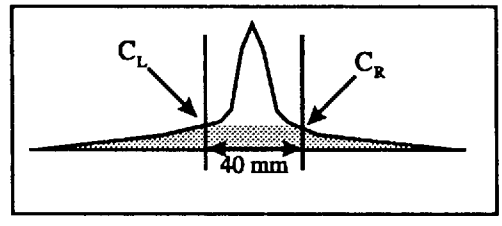


Figure 4-1
SINOGRAM PROJECTION OF COUNT DENSITY DUE TO SOURCE IN A SCATTERING MEDIUM

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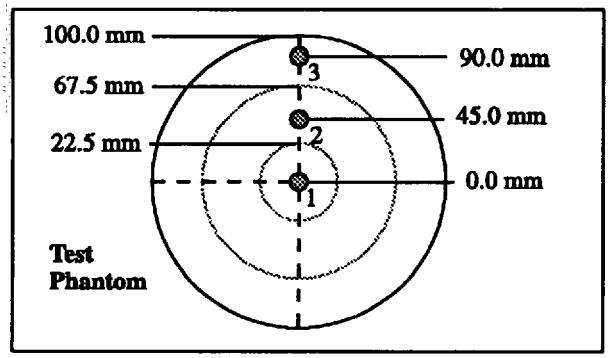


Figure 4-2
ANNULAR REGIONS OF MEASURED LINE SOURCE SCATTER FOR UNIFORM SCATTER CALCULATION

4.3.3 Data Collection

Measurements shall be acquired with the source at each specified radii from the central axis of the tomograph. Sinogram data shall be acquired for each radial location of the line source. At least 200,000 counts per slice shall be acquired for each slice within the lesser of the axial field of view or the center 17.0 cm where the phantom was placed. The same acquisition time shall be used for each acquisition.

4.3.4 Data Processing

Data shall be corrected for dead-time losses and random coincidences, but not for scatter or attenuation.

4.4 ANALYSIS

Sinograms for all slices at least one cm from the ends of the phantom shall be analyzed. Thus for tomographs with an axial field of view less than 17.0 cm, all slices shall be analyzed.

All pixels in each sinogram *i* located farther than 12 cm from the center of the phantom shall be set to zero. For each projection angle *a* within the sinogram, the location of the center of the line source response shall be determined by finding the pixel having the greatest value. Each projection shall be shifted so that the pixel containing the maximum value is aligned with the central pixel of the sinogram. After alignment, a sum projection shall be produced such that a pixel in the sum projection is the sum of the pixels in each angular projection having the same radial offset as the pixel in the sum projection:

$$C_{r,i,k} = \sum_{a} C_{r-max,a,i,k}$$

Where r is the pixel number in a projection and max refers to the location of the maximum value in the projection, i is slice number, and k = 1, 2, and 3 refer to line sources at radii 0, 45, and 90 mm, respectively.

The counts $C_{L,i,k}$ and $C_{R,i,k}$, the left and right pixel intensities at the edges of the 40 mm wide strip at the center of the sinogram, shall be obtained from the sum projection (see Figure 4-1). Linear interpolation shall be employed to find the pixel intensities at ± 20 mm from the central pixel of the projection. The average of the two pixel intensities $C_{L,i,k}$ and $C_{R,i,k}$ shall be multiplied by the number of pixels, including fractional values, between the edges of the 40 mm wide strip, and the product added to the counts in the pixels outside the strip, to yield the number of scatter counts $C_{s,i,k}$ for the slice *i* and the source position *k*.

The total event count $C_{TOT,i,k}$ is the sum of all pixels in the sum projection. The average radioactivity $A_{ave,k}$ during data acquisition over the time interval $T_{acq,k}$ for the line source at position k, shall be calculated (see Section 1.2).

The scatter fraction SF_i for each slice, due to a uniform source distribution is calculated as follows:

$$SF_i = \frac{\left(\frac{C_{s,i,1}}{A_{ave,1}}\right) + 8\left(\frac{C_{s,i,2}}{A_{ave,2}}\right) + 10.75\left(\frac{C_{s,i,3}}{A_{ave,3}}\right)}{\left(\frac{C_{TOT,i,1}}{A_{ave,1}}\right) + 8\left(\frac{C_{TOT,i,2}}{A_{ave,2}}\right) + 10.75\left(\frac{C_{TOT,i,3}}{A_{ave,3}}\right)}$$

Where the subscripts 1, 2, and 3 refer to line sources at radii 0, 45, and 90 mm, respectively.

4.5 REPORT

For each slice measurement that was analyzed, tabulate the value of SF_i. The average, SF, of the SF_i shall also be reported as the system scatter fraction for uniform sources.

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Section 5
SENSITIVITY MEASUREMENT

5.1 GENERAL

Sensitivity defines the rate at which coincidence events are detected in the presence of radioactive sources of activity levels where count rate losses are negligible. For some tomographs, sensitivity varies with axial location. The relative sensitivity profile test quantifies this non-uniformity.

5.2 PURPOSE

Two procedures are defined. The purpose of the first procedure is to measure themean sensitivity per image plane for a positron emission tomograph before any corrections for variations in detector sensitivity have been applied. The purpose of the second procedure is to characterize the uniformity of sensitivity in the axial direction.

These tests are performed at low count rates so that corrections for randoms and dead time can be neglected. The test does not address the issue of noise propagation in image reconstruction nor the impact on image noise from reconstruction algorithms. Thus the sensitivity measurements cannot predict the noise in reconstructed images.

5.3 METHOD

In the sensitivity test, a known volume of water containing a known quantity of radioactivity is placed in the field-of-view of a positron emission tomograph. The resulting count rate is measured. The system sensitivity is calculated from these. The test depends upon accurate assays of radioactivity by a dose calibrator or well counter. It is difficult to maintain an absolute calibration of such counting instruments to accuracies better than 10% rms. Absolute reference standards using positron emissions should be considered if higher degrees of absolute accuracy are required.

The relative sensitivity profile test uses measurements from the axial slice width measurement of Section 3.

Measurements shall be corrected for scatter fraction to obtain true coincidence sensitivity in units of counts per decay-per-ml.

5.3.1 Radionuclide

The radionuclide used for these measurements shall be ^{18}F. The amount of radioactivity used for the sensitivity test shall not exceed that at which either percent dead-time losses exceed 2% or the random coincidence rate exceeds 2% of the total event rate. The initial activity concentration in the phantom shall be determined either by measuring the total amount of radioactivity injected into the phantom (measured in a dose calibrator) and the volume of the phantom, or from samples from the phantom counted in a calibrated well counter. The time between the calibration and the sensitivity measurement shall be minimized.

5.3.2 Source Distribution

The source distributions for the sensitivity test and for the relative sensitivity profile test are described in the following sections.

5.3.2.1 SENSITIVITY TEST

The test phantom shall be filled with non-aerated water, to which a measured amount of radioactivity has been added. The phantom shall be centered both axially and transaxially in the field-of-view.

5.3.2.2 RELATIVE SENSITIVITY PROFILE TEST

All systems shall measure the response of a point source suspended in air and moved in small increments along the entire axial length of the tomograph. The source is positioned transaxially in the center of tomograph and is stepped in the axial direction in increments of one-tenth the expected FWHM of the axial response function.

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5.3.3 Data Collection

5.3.3.1 SENSITIVITY TEST

For the sensitivity test, at least 200,000 counts per slice shall be acquired for each slice within the lesser of the axial field of view or the center 17.0 cm where the phantom was placed. The data shall be assembled into sinograms; it is not necessary to reconstruct these data.

5.3.3.2 RELATIVE SENSITIVITY PROFILE TEST

For the relative sensitivity profile test, at least 50,000 counts shall be acquired in each profile. The data from the axial slice width test specified in Section 3 may be used.

5.3.4 Data Processing

Sinograms are to be formed with randoms correction and dead-time correction but without detector normalizations, attenuation correction, or scatter correction. Coincidence events shall each be recorded as an event count only once throughout the field-of-view of the tomograph. The axial response functions are determined by forming one-dimensional response functions by summing the counts collected at each axial location.

5.4 ANALYSIS

5.4.1 Sensitivity Test

The activity concentration in the phantom shall be corrected for decay to determine the average amount of activity, a_{ave}, in the phantom during the data acquisition time interval (see section 1.2). The total counts $C_{i,TOT,120\ mm}$ in each slice within a radius of 120 mm shall be obtained by summing the values of all such pixels in each sinogram.

The slice sensitivity S_i for unscattered events shall be found by evaluation of the following equation:

$$S_i = \frac{C_{i,TOT,120mm}}{T_{acq}} \left(\frac{1-SF_i}{a_{ave}} \right)$$

The total system sensitivity S_{TOT} shall be the sum of S_i over all slices of the tomograph, within the center 17.0 cm or the axial field of view whichever is less.

5.4.2 Relative Sensitivity Profile Test

The relative point slice sensitivity shall be calculated by summing the counts in each response function. The axial response function for each slice shall be normalized for differences in slice sensitivity by dividing the number of counts collected at each step by the relative point slice sensitivity. The normalized axial response functions shall be plotted against distance in mm and displayed on a single graph.

No interpolation or deconvolution of the slice thickness shall be employed to correct for undersampling by the tomograph.

The normalized axial response functions shall be analyzed to determine the maximum value of the profile when the source is near the center of each slice. A maximum value shall be recorded for each slice. The pixel values at which the profiles for pairs of slices cross shall be recorded as a minimum (valley).

The peak to valley ratio shall be determined for each minimum (cross over) value *i* by the following equation:

$$PV_i = \left(\frac{Maximum_i + Maximum_{i+1}}{2\ Minimum_i} \right)$$

The average value PV_{ave} shall be calculated.

5.5 REPORT

5.5.1 Sensitivity

For each slice, tabulate the value of S_i within the center 17.0 cm or the axial field of view whichever is less. S_{TOT} shall also be reported.

5.5.2 Relative Sensitivity Profile

Plot the normalized axial response function for all slices. Report the relative point slice sensitivity, and the peak to valley ratio, PV_i, for each valley, *i*. Also report the average peak to valley ratio, PV_{ave}.

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Section 6
COUNT LOSSES AND RANDOMS MEASUREMENTS

6.1 GENERAL

The measurements of count losses and random rates express the ability of a positron emission tomograph to measure highly radioactive sources with accuracy and repeatability.

6.2 PURPOSE

The purpose of this procedure is to measure losses of events due to: (1) system dead-time, and; (2) the generation of random events, at several levels of source activity.

6.3 METHOD

To begin the test, a source of relatively high activity is placed in the field of view of the positron emission tomograph. As the source activity decays, random event rates decline more rapidly than do true event rates. The random rate eventually becomes negligible. As the activity decays, the efficiency of the system in processing coincident events improves, eventually resulting in negligible count losses. Measurement of the true coincidence count rates with negligible randoms rates and count losses calibrate the response of the system for estimating count losses at higher activity levels. The accuracy of this method is limited by the count rate losses and rate of randoms during the calibration measurements.

6.3.1 Radionuclide

The radionuclide used for this measurement shall be ^{18}F. The amount of radioactivity shall be great enough to cause the true event rate to reach 50 % dead-time loss value, and also to allow for one of the following two rates to be measured:

a. $R_{t,peak}$ true event rate at peak count rate
b. $R_{t=r}$ true event rate when random event rate equals true event rate

The initial concentration of activity in the phantom shall be determined either from the activity injected into the phantom (as measured in a calibrated dose calibrator) and the internal volume of the phantom, or from samples drawn from the phantom counted in a calibrated well counter.

6.3.2 Source Distribution

The test phantom shall be filled with deaerated water, plus the measured amount of radioactivity, and centered in the transverse and axial fields-of-view.

6.3.3 Data Collection

Data shall be acquired at intervals more frequent than half the radionuclide half-life, $T_{1/2}$, until count loss rates of true events are less than 1.0% of the total, and the random rates are less than 1.0% of true rates. The individual acquisition durations, $T_{acq,j}$, shall be less than one-fourth of $T_{1/2}$.

It is important that the last three measurements be acquired at a high enough count rate, and of sufficiently long duration, to provide adequate statistics to avoid inaccuracies in the analysis. Therefore, it is expected that manufacturers will recommend a protocol for their scanners that includes starting activity concentration, acquisition times and the duration.

6.3.4 Data Processing

For tomographs with an axial field of view of 17.0 cm or less, sinograms shall be generated for each acquisition *j* for each slice *i*. For tomographs with an axial field of view greater than 17.0 cm, sinograms shall be generated for each acquisition for slices within the central 17.0 cm. No corrections for variations in detector sensitivity, detector motions such as wobble, randoms, scatter, dead-time, or attenuation shall be applied to the measurements.

6.4 ANALYSIS

The average activity $A_{ave,j}$, and the average activity concentration, $a_{ave,j}$, for each acquisition *j* shall be calculated (see Section 1.2).

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6.4.1 Dead Time Measurement

The counts in each sinogram shall be summed over the entire physical field-of-view. Depending upon the design of the tomograph, this procedure will yield either $C_{t+s+r,i,j}$ or $C_{t+s,i,j}$, the counts in the i^{th} slice of the j^{th} acquisition. In the former case, randoms counts $C_{r,i,j}$ shall be subtracted from $C_{t+s+r,i,j}$ to obtain $C_{t+s,i,j}$.

The randoms counts, $C_{r,i,j}$, shall be obtained using a standard processing technique such as measured singles or delayed coincidences, as recommended by the manufacturer.

Calculate the trues plus scatter count rates $R_{t+s,i,j}$ as follows:

$$R_{t+s,i,j} = \frac{C_{t+s,i,j}}{T_{acq,j}}$$

For each slice *i*, calculate the rate $R_{Extr,i,j}$ which would have been measured for acquisition *j* if there had been no dead-time losses. To minimize the effects of statistics, $R_{Extr,i,j}$ shall be obtained by the following equation:

$$R_{Extr,i,j} = \frac{A_{ave,j}}{3} \sum_{k=1}^{3} \frac{R_{t+s,i,k}}{A_{ave,k}}$$

Where k = 1 is the acquisition with the lowest activity.

For each slice *i* of each acquisition *j* the percent dead time $PDT_{i,j}$ in percentage units shall be calculated by the following equation:

$$PDT_{ij} = 100 - 100\left(\frac{R_{t+s,i,j}}{R_{Extr,i,i}}\right)\%$$

For each slice *i*, linear interpolation shall be used to determine the activity concentration at which the percent dead time, $PDT_{i,j}$ is 50%.

The values for each slice are summed to obtain system values. Calculate the system trues plus scatter count rates $R_{t+s,sys,j}$ as follows:

$$R_{t+s,sys,j} = \sum_{i=1}^{I} R_{t+s,i,j}$$

Where I is the number of slices within 17.0 cm or the axial field of view, whichever is less.

For the system, calculate the rate $R_{Extr,sys,j}$ which would be obtained for acquisition *j* had there been no dead-time losses.

$$R_{Extr,sys,j} = \sum_{i=1}^{I} R_{Extr,i,j}$$

Where I is the number of slices within 17.0 cm or the axial field of view, whichever is less.

For each acquisition *j* the system percent dead time $PDT_{sys,j}$ in percentage units shall be calculated by the following equation:

$$PDT_{sys,j} = 100 - 100\left(\frac{R_{t+s,sys,j}}{R_{Extr,sys,j}}\right)\%$$

Linear interpolation shall be used to determine the activity concentration at which the system percent dead time $PDT_{sys,j}$ is 50%.

6.4.2 True Event Rate Measurement

A rectangular region of interest, ROI_i, centered over the radial axis of the sinogram, of width 240 mm and spanning all angles shall be drawn for each slice *i*. The counts within the ROI in each of the sinograms shall be totaled. Depending upon the design of the tomograph, this procedure will yield either $C_{ROI,t+s+r,i,j}$ or $C_{ROI,t+s,i,j}$, the counts in the i^{th} slice of the j^{th} acquisition. In the former case, the randoms count $C_{ROI,r,i,j}$ shall be subtracted from $C_{ROI,t+s+r,i,j}$ to obtain $C_{ROI,t+s,i,j}$. The true count rates $R_{ROI,t,i,j}$ shall be calculated as follows:

$$R_{ROI,t,i,j} = \frac{C_{ROI,t+s,i,j}}{T_{acq,j}}(1 - SF_i)$$

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Where SF_i is the scatter fraction obtained from Section 4 measurements.

The randoms count rate shall be calculated as:

$$R_{ROI,r,i,j} = \frac{C_{ROI,r,i,j}}{T_{acq,j}}$$

For each slice *i* calculate the rate $R_{ROI,Extr,i,j}$ which would have been measured for acquisition *j* were there no dead-time losses. To minimize the effects of statistics, $R_{ROI,Extr,i,j}$, shall be obtained by the following equation:

$$R_{Extr,i,j} = \frac{A_{ave,j}}{3}\sum_{k=1}^{3}\frac{R_{ROI,t,i,k}}{A_{ave,k}}$$

Where k = 1 is the acquisition with the lowest activity.

For each slice *i*, linear interpolation shall be used to calculate the rate and activity concentration where the trues rate equals the randoms rate.

Calculate the system true count rates $R_{ROI,t,sys,j}$ as follows:

$$R_{ROI,t,sys,j} = \sum_{i=1}^{I} R_{ROI,t,i,j}$$

Where I is the number of slices within 17.0 cm or the axial field of view, whichever is less.

Calculate the system random count rates $R_{ROI,r,sys,j}$ as follows:

$$R_{ROI,r,sys,j} = \sum_{i=1}^{I} R_{ROI,r,i,j}$$

Where I is the number of slices within 17.0 cm or the axial field of view, whichever is less.

Linear interpolation shall be used to calculate the rate and activity concentration where the system trues rate equals the system randoms rate.

Calculate the system $R_{ROI,Extr,sys,j}$

$$R_{ROI,Extr,sys,j} = \sum_{i=1}^{I} R_{ROI,Extr,i,j}$$

Where I is the number of slices within 17.0 cm or the axial field of view, whichever is less.

6.5 REPORT

6.5.1 Dead Time Measurement

For each slice *i*, tabulate the activity concentration at which the percent dead time, PDT_i, equals 50%.

For the system, plot the percent dead time as a function of activity concentration. and report the activity concentration at which the system percent dead time, PDT_{sys}, equals 50%.

6.5.2 True Event Rate Measurement

For each slice *i*, tabulate the smaller of the following two sets of parameters:

a. true rate $R_{ROI,t,i}$ at which $R_{ROI,t,i} = R_{ROI,r,i}$ (true rate equals randoms rate)
b. true rate $R_{ROI,t,peak,i}$, at which $R_{ROI,t,i}$ peaks or saturates. Report the corresponding activity concentration for each rate.

For the system, plot the following three quantities as a function of source activity concentration $a_{ave,j}$:

a. $R_{ROI,t,sys,j}$ the system trues rate
b. $R_{ROI,r,sys,j}$ the system randoms rate
c. $R_{ROI,Extr,sys,j}$ the extrapolated system trues rate

For the system, also report the smaller of the following two parameters:

a. true rate $R_{ROI,t,sys}$ at which $R_{ROI,t,sys} = R_{ROI,r,sys}$ (true rate equals randoms rate)
b. true rate $R_{ROI,t,peak,sys}$ at which $R_{ROI,t,sys}$ peaks or saturates

along with the corresponding activity concentration.

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Section 7
UNIFORMITY MEASUREMENTS

7.1 GENERAL

The uniformity of a system describes the ability to measure the same activity independent of its location within the imaging field-of-view. Deviations from a uniform response to a uniform field of radioactivity in the field-of-view of a positron emission tomograph are artifacts which may limit the ability to quantitate distributions of radioactive substances. A measure of these deviations indicates the degree of nonuniformity; smaller values indicate better uniformity than do larger values.

7.2 PURPOSE

The purpose of this procedure is to provide a measure of the extrema of deviations as detected in certain image planes and volumes, as well as the average deviation.

7.3 METHOD

Illumination of the tomograph by a uniform distribution of radioactivity contained within a right circular cylindrical phantom of limited diameter extending throughout the axial field of the tomograph is a challenging test of uniformity of response.

Correction for self-attenuation must be applied prior to analysis of the measurements. There are at least two methods of attenuation correction: measurement by transmission from an external source or sources, and estimation by a mathematical representation of the cylinder, deriving attenuation corrections from knowledge of the attenuation rate in the medium. This calculated attenuation method, being less subject to externally generated nonuniformities, then is the measured correction method, is the method chosen in this test to reveal more accurately the intrinsic uniformity of positron emission tomographs.

7.3.1 Radionuclide

The radionuclide for the measurement shall be ^{18}F, with an activity less than that at which either the percent dead-time losses exceed 20% or the random coincidence rate exceeds 20% of the total event rate at the beginning of the acquisition.

7.3.2 Source Distribution

The test phantom shall be filled with de-aerated water, to which is added a measured amount of radioactivity. It shall be centered axially in the field-of-view but displaced vertically 25 mm off axis.

7.3.3 Data Collection

The phantom shall be imaged for a length of time sufficient to assure an average of no fewer than 20 million counts contribute to each plane.

7.3.4 Data Processing

For tomographs having an axial field of view less than 17.0 cm, all slices shall be reconstructed. For tomographs with larger than 17.0 cm axial field of view, only slices falling in the central 17.0 cm shall be reconstructed. All corrections (normalization, slice-sensitivity, dead-time, randoms, and scatter) shall be applied, if available. Calculated attenuation correction shall also be applied. The assumed attenuation coefficient shall be the same as used in other tests and the value shall be reported as indicated below. Images shall be reconstructed using the standard matrix and pixel size and using a ramp filter with cutoff at the Nyquist frequency as determined in projection space.

7.4 ANALYSIS

Relative sensitivity shall be measured in non-overlapping regions formed by the orthogonal grid of approximately 10 mm spacing circumscribed by a circle 175 mm in diameter centered in the phantom image. Each square region shall be an integral number of pixels with overall length less than or equal to 10 mm. Only fully circumscribed square regions shall be measured (see Figure 7-1). Partial squares around the edges shall be neglected.

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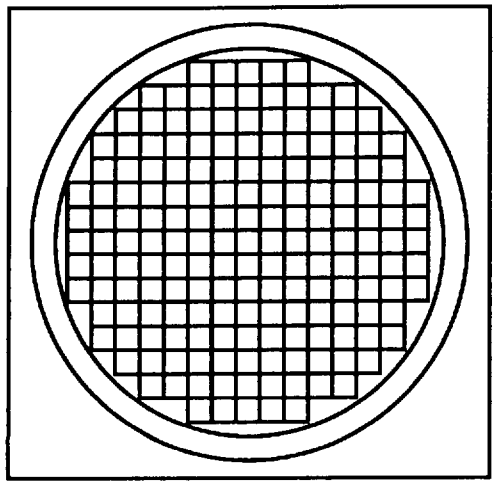


Figure 7-1
GRID OF REGIONS FOR RELATIVE SENSITIVITY MEASUREMENTS WITHIN THE ROI

7.4.1 Slice Uniformity

To examine intra-slice uniformity, the maximum and minimum percent non-uniformity, NU_i, shall be calculated for each reconstructed slice *i*:

$$NU_i = \begin{pmatrix} +100\dfrac{Max(C_k) - Ave(C_k)}{Ave(C_k)}\,\% \\ \\ -100\dfrac{Ave(C_k) - Min(C_k)}{Ave(C_k)}\,\% \end{pmatrix}$$

Where, with respect to any square region *k* in slice *i*:
$Max(C_k)$ = greatest number of counts
$Ave(C_k)$ = average number of counts
$Min(C_k)$ = least number of counts

The standard deviation and coefficient of variation shall be calculated for each reconstructed slice *i*:

$$SD_i = \sqrt{\frac{1}{(K-1)}\sum_{k=1}^{k}(C_k - Ave(C_k))^2}$$

and

$$CV_i = \frac{100\ SD_i}{Ave(C_k)}\,\%$$

Where K is the number of square ROI's in slice *i*.

7.4.2 Volume Uniformity

To examine uniformity throughout the tomograph's entire field-of-view (volume), the maximum and minimum percent non-uniformity of the volume, NU_{vol}, shall be calculated:

$$NU_{vol} = \begin{pmatrix} +100\dfrac{Max(C_j) - Ave(C_j)}{Ave(C_j)}\,\% \\ \\ -100\dfrac{Ave(C_j) - Min(C_j)}{Ave(C_j)}\,\% \end{pmatrix}$$

Where, with respect to any square region j in any of the reconstructed slices:
$Max(C_j)$ = greatest number of counts
$Ave(C_j)$ = average number of counts
$Min(C_j)$ = least number of counts

The standard deviation and coefficient of variation shall be calculated for the volume:

$$SD_{vol} = \sqrt{\frac{1}{(J-1)}\sum_{J=1}^{J}(C_j - Ave(C_j))^2}$$

and

$$CV_{vol} = \frac{100\ SD_{vol}}{Ave(C_j)}\,\%$$

Where J is the number of ROI's in the volume.

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7.4.3 System Uniformity

To examine inter-slice (among slices) uniformity, the maximum and minimum percent non-uniformity of the system, NU_{sys}, shall be calculated:

$$NU_{sys} = \begin{pmatrix} +100\,\dfrac{Max(C_i) - Ave(C_i)}{Ave(C_i)}\ \% \\ -100\,\dfrac{Ave(C_i) - Min(C_i)}{Ave(C_i)}\ \% \end{pmatrix}$$

Where, with respect to any reconstructed slice *i*:

$Max(C_i)$ = greatest number of counts averaged over all regions in slice *i*, $Max(Ave(C_k))$

$Ave(C_i)$ = average number of counts in all regions of slice *k* averaged over all slices *i*, $Ave(Ave(C_k))$

$Min(C_i)$ = least number of counts averaged over all regions in slice *i*, $Min(Ave(C_k))$

The standard deviation and coefficient of variation shall be calculated for the system:

$$SD_{sys} = \sqrt{\frac{1}{(I-1)}\sum_{i=1}^{I}(C_i - Ave(C_i))^2}$$

and

$$CV_{sys} = \frac{100\ SD_{sys}}{Ave(C_i)}\ \%$$

Where I is the number of reconstructed slices.

7.5 REPORT

A list of corrections which were applied to the measurement shall be made, indicating which of the possible corrections were applied.

For each slice, slice non-uniformities, NU_i, and slice coefficient of variation, CV_i, shall be reported. The volume non-uniformity NU_{vol}, volume coefficient of variation, CV_{vol}, system non-uniformity value, NU_{sys}, and system coefficient of variation, CV_{sys}, shall be reported.

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Section 8
ACCURACY: SCATTER CORRECTION

8.1 GENERAL

The measurement of scatter fraction as described in Section 4 indicates the sensitivity of the positron emission tomograph to scattered coincidences. Methods of scatter correction attempt to remove this scatter. The accuracy with which scatter is removed is indicated by the residual scatter remaining in the reconstructed images after correction. Residual scatter may vary with the axial location of slices.

8.2 PURPOSE

The purpose of this procedure is to measure the accuracy of the scatter correction method incorporated in the positron emission tomograph's software.

8.3 METHOD

8.3.1 Radionuclide

The radionuclide for the measurement shall be ^{18}F, with an activity less than that at which either the percent dead-time losses exceed 5% or the random coincidence rate exceeds 5% of the total event rate.

8.3.2 Source Distribution

The test phantom shall be centered axially in the field-of-view but displaced 25 mm off-axis radially. It shall be used with 50 mm diameter cylinder insert placed 60 ± 3 mm from the axis of the phantom at 240° as shown in Figure 8-1. The hollow insert shall be filled with non-radioactive de-aerated water. A measured amount of radioactivity shall be added to the phantom and thoroughly mixed with the water.

8.3.3 Data Collection

At least 2 million events per slice shall be acquired during a single emission acquisition.

8.3.4 Data Processing

For tomographs with an axial field of view of 17.0 cm or less, all slices shall be reconstructed. For tomographs with an axial field of view greater than 17.0 cm, only slices in the central 17.0 cm shall be reconstructed.

Corrections for dead-time, randoms, and scatter shall be applied, if available.

Images shall be reconstructed using the standard matrix and pixel size and using a ramp filter with cutoff at the Nyquist frequency as determined in projection space.

Calculated attenuation correction shall be also applied. The assumed attenuation coefficient value shall be that used in other tests. The value shall be reported as indicated below.

8.4 ANALYSIS

In each reconstructed slice, define twelve regions of interest, each 30 ± 2 mm in diameter, each containing the same number of pixels. One of the ROIs shall be centered over the image of the non-radioactive insert. The other eleven ROIs shall be positioned without overlapping one another with their edges at least 20 mm from the perimeter of the test phantom image and from the perimeter of the insert image (see Figure 8-1). The number of counts in each ROI of each slice *i* shall be measured.

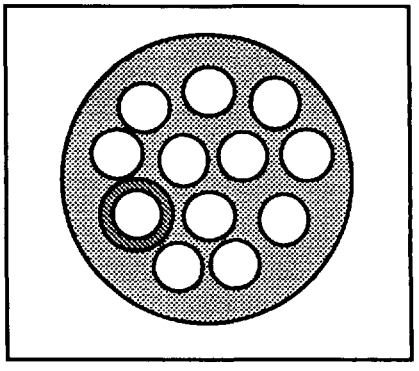


Figure 8-1
GEOMETRY OF TEST PHANTOM AND INSERT, WITH ROIs FOR MEASUREMENT OF REMNANT SCATTER

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For each slice *i*, the remnant scatter fraction after scatter correction, $\Delta SF_{corr,i}$, shall be calculated in percentage units using the following equation:

$$\Delta SF_{corr,i} = 100 \frac{C_{cyl,i}}{C_{ave,i}} \%$$

where $C_{cyl,i}$ is the number of counts in the ROI inside the cylinder insert in slice *i*, and $C_{ave,i}$ is the average number of counts in the other eleven ROIs in slice *i*.

The remnant scatter fraction ΔSF_{corr} for the system shall be found by calculating the average value of $\Delta SF_{corr,i}$.

8.5 REPORT

A table shall be made indicating which of the possible corrections were actually applied to the measurements. The assumed attenuation coefficient shall also be reported.

A table of remnant scatter fraction values in each slice $\Delta SF_{corr,i}$ shall be made. The remnant system scatter fraction value ΔSF_{corr} shall also be reported.

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Section 9
ACCURACY: COUNT RATE CORRECTION

9.1 GENERAL

To achieve quantitative measurements of source activity distribution under widely varying conditions, positron emission tomographs usually have a capability to compensate for dead time losses and random events. The accuracy of these corrections, particularly at the highest counting rates encountered in clinical imaging, is reflected by the bias with which the tomograph reports counts. The following test uses a simple activity distribution and clearly is not representative of a wide variety of imaging conditions. However, such a test requires a considerable amount of time to perform and requires handling large amounts of radioactivity.

9.2 PURPOSE

The purpose of this procedure is to measure the accuracy of corrections for dead-time losses and random event counts in images.

9.3 METHOD

The test phantom data of Section 6.3.3, acquired for measurements of random rates and dead time losses, can also be used to measure the net error in count rate after correction for dead-time and for random coincidences.

The comparison is between the corrected true count rate and the extrapolation of count rate from low count rate data. It is assumed that errors from dead-time and randoms are insignificant at low count rates. All corrections are to be applied.

9.3.1 Radionuclide

The radionuclide used for this measurement shall be ^{18}F. The amount of radioactivity shall be great enough to cause the true event rate to reach 50% dead-time loss value, and also to allow for one of the following two rates to be measured:

a. $R_{t,peak}$ true event rate at peak count rate
b. $R_{t=r}$ true event rate when random event rate equals true event rate

The initial concentration of activity in the phantom shall be determined either from the activity injected into the phantom (as measured in a calibrated dose calibrator) and the internal volume of the phantom, or from samples drawn from the phantom counted in a calibrated well counter.

9.3.2 Source Distribution

The test phantom shall be filled with non-aerated water, to which a measured amount of radioactivity has been added. The phantom is to be centered in the field-of-view.

9.3.3 Data Collection

Measurements shall be acquired at time intervals less than half the half-life, $T_{1/2}$, until count loss rates of true events are less than 1.0% of the total, and random rates are less than 1.0% of true rates. The individual acquisition durations. $T_{acq,j}$, shall be shorter than to one-fourth of $T_{1/2}$.

The final three acquisitions must be at a sufficiently high count rate and of sufficiently long duration to provide adequate statistics to avoid inaccuracies in the analysis. Manufacturers will recommend a protocol for their scanners that includes starting activity concentration, acquisition times and duration.

9.3.4 Data Processing

For tomographs with an axial field of view of 17.0 cm or less, all slices shall be reconstructed. For tomographs with an axial field of view greater than 17.0 cm, only slices in the central 17.0 cm shall be reconstructed. All corrections shall be applied to the data. Images shall be reconstructed using the standard matrix and pixel size and using a ramp filter with cutoff at the Nyquist frequency as determined in projection space.

9.4 ANALYSIS

All analyses shall be performed on each reconstructed image *i*. The average source activity

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concentration, $a_{ave,j}$, for each acquisition *j* shall be calculated (see Section 1.2).

A circular region of interest, ROI, centered on the image of the phantom and 180 mm in diameter shall be drawn in the reconstructed image for each slice *i*. The number of true counts $C_{ROI,i,j}$ for each slice *i* and acquisition *j* shall be measured. Calculate the trues rates $R_{ROI,i,j}$ as follows:

$$R_{ROI,i,j} = \frac{C_{ROI,i,j}}{T_{acq,j}}$$

For each slice *i*, calculate the extrapolated true counting rate $R_{Extr,i,j}$ which would have been obtained for acquisition *j* were there no dead-time losses. To minimize the effects of statistics, $R_{Extr,i,j}$, shall be obtained by the following equation:

$$R_{Extr,i,j} = \frac{A_{ave,j}}{3} \sum_{k=1}^{3} \frac{R_{ROI,i,k}}{A_{ave,k}}$$

Where k = 1 is the acquisition with the lowest activity.

For each slice *i* of each acquisition *j* the relative count rate error $\Delta r_{i,j}$ in percentage units shall be calculated by the following equation:

$$\Delta r_{i,j} = 100 - 100\left(\frac{R_{ROI,i,j}}{R_{Extra,i,j}}\right)\%$$

9.5 REPORT

For each slice, tabulate the values of $\Delta r_{i,j}$ and $a_{ave,j}$. Plot a graph of the highest and lowest values among the slices of $\Delta r_{i,j}$ versus $a_{ave,j}$, choosing linear graphical axes. The data points may be joined to form a true continuous curve. Linear interpolation shall be used to calculate for each curve the bias Δr_i at the lowest of the three values $a_{t,peak}$, $a_{t,50\%}$, and $a_{t=r}$ as determined in Section 6.4.1.

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Section 10
ACCURACY: ATTENUATION CORRECTION

10.1 GENERAL

Positron emission tomography has a valid theoretical basis for attenuation correction for arbitrarily distributed attenuating media within the field-of-view of a tomograph. The basis for the correction is a measurement of the transmission of annihilation radiation through the field-of-view. The accuracy by which this is actually done is an important measure of its quantitative ability.

10.2 PURPOSE

The purpose of this procedure is to measure the accuracy of the transmission method of attenuation correction.

10.3 METHOD

Transmission of external radiation through a non-uniform attenuating media is processed for attenuation correction matrices which are applied to projection data as part of the reconstruction process. Conformance with true activity values is an indicator of the accuracy of attenuation correction.

10.3.1 Radionuclide

The radionuclide for the measurement shall be ^{18}F, with an activity less than that at which either the percent dead-time losses exceed 5% or the random coincidence rate exceeds 5% of the total event rate.

10.3.2 Source Distribution

The test phantom shall be centered in the field-of-view but displaced 25 mm off-axis, and shall be used with the three 50 mm diameter cylinder inserts placed 60 ± 3 mm from the axis of the phantom at 120° angular increments, arranged as in Figure 10-1.

For the transmission measurement, the phantom shall be filled with non-radioactive water. One hollow insert is filled with non-radioactive air and the other with water.

For the emission measurement, a measured amount of radioactivity shall be added to the test phantom and thoroughly mixed with the water. The contents of the inserts are not changed.

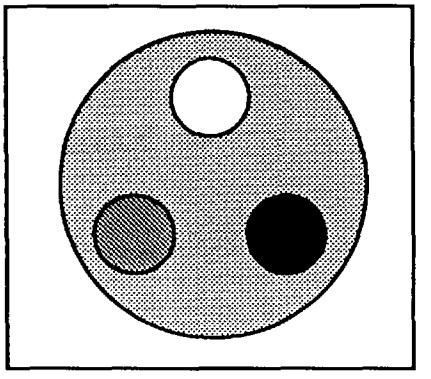


Figure 10-1
TEST PHANTOM CONTAINING AN AIR-FILLED INSERT ABOVE, A WATER-FILLED HOLLOW INSERT LEFT, AND A SOLID INSERT RIGHT

10.3.3 Data Collection

Transmission scanning of the test phantom shall be measured by the method recommended by the manufacturer of the tomograph. For the emission measurement, the prescribed amount of radioactivity shall be added to the test phantom and a standard image acquisition shall be performed, obtaining at least 2 million counts per slice.

The transmission and emission measurements can be performed in either order provided proper procedures are followed. If the test phantom is removed between measurements, it must be precisely repositioned. If the emission scan is performed first, ten half-lives must elapse before transmission measurements are acquired.

10.3.4 Data Processing

For tomographs with an axial field of view of 17.0 cm or less, all slices shall be reconstructed. For tomographs with an axial field of view greater than

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17.0 cm, only slices in the central 17.0 cm shall be reconstructed. Images shall be reconstructed using the standard matrix and pixel size and using a ramp filter with cutoff at the Nyquist frequency as determined in projection space. The emission data shall be reconstructed applying all corrections—including the attenuation correction obtained from the transmission measurement.

10.4 ANALYSIS

In the emission images, define three circular ROIs 30 mm in diameter centered on the air, solid, and water insert images, and nine circular ROIs 30 mm diameters in the uniform activity area, in each slice image, as shown in Figure 10-2. The radii to the outer six 30 mm ROIs from the axis of the phantom shall all equal 60 mm. Record the total counts in each of the ROIs in each slice *i*.

$$C_{air,i}, C_{solid,i}, C_{water,i}, C_{1,i} \cdots C_{9,i}$$

The numerical indexes identify the nine ROIs in the uniform activity areas.

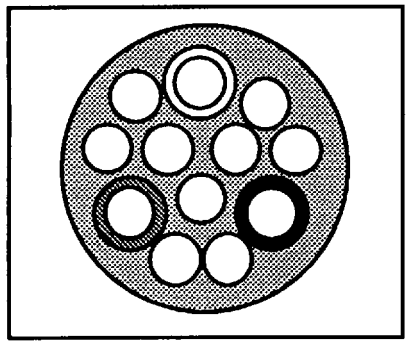


Figure 10-2
THREE 30-MM REGIONS CENTERED ON THE INSERTS, AND NINE 30-MM REGIONS FOR NORMALIZATION AND UNIFORMITY

Calculate the normalized counts $C_{N,i}$ in each slice.

$$C_{N,i} = \sum_{k=1}^{9} \frac{C_{k,i}}{9}$$

The relative errors $\Delta C_{insert,i}$ in percentage units for each of the inserts in each of the slices shall be calculated as follows:

$$\Delta C_{insert,i} = 100 \frac{C_{insert,i}}{C_{N,i}} \%$$

Where insert = air, solid, and water.

The non-uniformity of attenuation correction for each slice *i* shall be calculated as follows:

$$NU_{A,i} = \begin{pmatrix} +100 \dfrac{Max(C_{k,i}) - C_{N,i}}{C_{N,i}} \% \\ -100 \dfrac{C_{N,i} - Min(C_{k,i})}{C_{N,i}} \% \end{pmatrix}$$

10.5 REPORT

For each slice, tabulate the values of $\Delta C_{air,i}$, $\Delta C_{solid,i}$, $\Delta C_{water,i}$. The averages of these counting errors shall be reported.

For each slice, tabulate the values of $NU_{A,i}$.

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The purpose of NEMA standards, their classification, and status are set forth in certain clauses of the NEMA *Standardization Policies and Procedures* manual and are referenced below:

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National Electrical Manufacturers Association Standards are adopted in the public interest and are designed to eliminate misunderstandings between the manufacturer and the purchaser and to assist the purchaser in selecting and obtaining the proper product for their particular needs. Existence of a National Electrical Manufacturers Association Standard does not in any respect preclude any member or nonmember from manufacturing or selling products not conforming to the standard.

Definition of a Standard

A standard of the National Electrical Manufacturers Association defines a product, process, or procedure with reference to one or more of the following: nomenclature, composition, dimensions, tolerances, safety, operating characteristics, performance, rating, testing, and the service for which they are designed.

(Standardization Policies and Procedures, p. 1)

Dimensions

Where dimensions are given for interchangeability purposes, alternate dimensions satisfying the other provisions of the Standards Publication may be capable of otherwise equivalent performance.

(Standardization Policies and Procedures, p. 6)

Categories of Standards

National Electrical Manufacturers Association Standards are of three classes, which have received the affirmative vote of at least two-thirds of the Subdivision votes cast in the affirmative or negative:

1. NEMA Standard, which relates to a product, process, or procedure commercially standardized and subject to repetitive manufacture.
2. Suggested Standard for Future Design, which may not have been regularly applied to a commercial product, but which suggests a sound engineering approach to future development.
3. Adoptive Standard, which is adopted in whole or in part from the standards of another organization, either domestic, regional, or international.

(Standardization Policies and Procedures, pp. 5)

Authorized Engineering Information

Authorized Engineering Information consists of explanatory data and other engineering information of an informative character not falling within the classification of NEMA Standard or Suggested Standard for Future Design, which standard has received the affirmative vote of at least two-thirds of the Subdivision votes cast in the affirmative or negative.

(Standardization Policies and Procedures, pp. 5)

Identification of Status

Standards in NEMA Standards Publications are identified as "NEMA Standard," "Suggested Standard for Future Design," or "Adoptive Standard." These indicate the status of the standard. A statement incorporating the auxiliary verb "shall" indicates that compliance with a requirement is mandatory for compliance with the standard. These classes of standards are identified in the foreword or throughout the text.

The material identified as "Authorized Engineering Information" is designated similarly. Statements incorporating other auxiliary verbs such as "should," "may," etc. refer to the authorized engineering information and not to procedures required for compliance with the standard.

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