# NEMA NU 2

# PERFORMANCE MEASUREMENTS OF POSITRON EMISSION TOMOGRAPHS

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# NEMA Standards Publication NU 2-2001

*Performance Measurements of Positron Emission Tomographs*

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# TABLE OF CONTENTS

SECTION 1 DEFINITIONS, SYMBOLS, AND REFERENCED PUBLICATIONS....1
1.1 Definitions....1
1.2 Standard Symbols....1
SECTION 2 GENERAL....5
2.1 Purpose....5
2.2 Purview....5
2.3 Units of Measure....5
2.4 Consistency....5
2.5 Equivalency....6
SECTION 3 SPATIAL RESOLUTION....7
3.1 General....7
3.2 Purpose....7
3.3 Method....7
3.3.1 Symbols....7
3.3.2 Radionuclide....7
3.3.3 Source Distribution....7
3.3.4 Data Collection....8
3.3.5 Data Processing....8
3.4 Analysis....8
3.5 Report....9
SECTION 4 SCATTER FRACTION, COUNT LOSSES, AND RANDOMS MEASUREMENT....11
4.1 General....11
4.2 Purpose....11
4.3 Method....11
4.3.1 Symbols....12
4.3.2 Radionuclide....12
4.3.3 Source distribution....12
4.3.4 Data collection....12
4.3.5 Data processing....13
4.4 Analysis....13
4.4.1 Scatter fraction....14
4.4.2 Total event rate measurement....14
4.4.3 True event rate measurement....14
4.4.4 Random event rate measurement....15
4.4.5 Scatter event rate measurement....15
4.4.6 Noise equivalent count rate measurement....15
4.5 Report....15
4.5.1 Count rate plot....15
4.5.2 Peak count values....16
4.5.3 System scatter fraction....16
SECTION 5 SENSITIVITY....17
5.1 General....17
5.2 Purpose....17
5.3 Method....17
5.3.1 Symbols....17
5.3.2 Radionuclide....17
5.3.3 Source distribution....17
5.3.4 Data Collection....18
5.4 Calculations and Analysis....18
5.4.1 System Sensitivity....18
5.4.2 Axial Sensitivity Profile....18
5.5 Report....18
SECTION 6 ACCURACY: CORRECTIONS FOR COUNT LOSSES AND RANDOMS....21
6.1 General....21

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6.2 Purpose....21
6.3 Method....21
6.3.1 Symbols....21
6.3.2 Radionuclide....21
6.3.3 Source Distribution....21
6.3.4 Data Collection....22
6.3.5 Data Processing....22
6.4 Analysis....22
6.5 Report....23
Section 7 IMAGE QUALITY, ACCURACY OF ATTENUATION AND SCATTER CORRECTIONS....25
7.1 General....25
7.2 Purpose....25
7.3 Method....25
7.3.1 Symbols....25
7.3.2 Radionuclide....25
7.3.3 Source Distribution....26
7.3.4 Data Collection....26
7.3.5 Data Processing....27
7.4 Analysis....27
7.4.1 Image Quality....27
7.4.2 Accuracy of Attenuation and Scatter Corrections....28
7.5 Report....28
APPENDIX NU 2-1994 SCATTER FRACTION AND COUNT RATE TESTS....33
A.1 Phantom Description....33
A.2 Scatter Fraction Measurement....33
A.2.1 General....33
A.2.2 Purpose....33
A.2.3 Method....34
A.2.4 Analysis....35
A.3 Count Loss and Randoms Measurements....36
A.3.1 General....36
A.3.2 Purpose....36
A.3.3 Method....36
A.3.4 Analysis....37
A.3.5 Report....39

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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, multi-planar and volume reconstruction models, and dedicated positron emission tomographs and other coincidence-capable imaging systems. It is assumed that every system to be tested under this standard is able to create sinograms and transverse slice 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 transverse fields 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 the isotope $^{18}F$ 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.

The philosophy and rationale of the standards measurements, and illustrative examples of the analysis and results, are presented by Karp, *et al*. submitted for publication in the *Journal of Nuclear Medicine.*

This standards publication was developed by the Coincidence Imaging Task Force chartered by the Nuclear Standards and Regulatory Committee. Committee approval of the standard does not necessarily imply that all committee members voted for its approval or participated in its development. At the time it was approved, the task force was composed of the following members:

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# Section 1
# DEFINITIONS, SYMBOLS, AND REFERENCED PUBLICATIONS

## 1.1 DEFINITIONS

**axial field-of-view (FOV):** The maximum length parallel to the long axis of a positron emission tomograph along which the instrument generates transaxial tomographic images.

**prompt counts:** Coincidence events acquired in the standard coincidence window of a positron emission tomograph. Prompt counts include true, scattered, and random coincidence events.

**sinogram:** A two dimensional projection space representation of a transaxial image where one dimension refers to radial distance from the center, and the second dimension refers to projection angle.

**transverse field-of-view (FOV):** The maximum diameter circular region perpendicular to the long axis of a positron emission tomograph within which objects might be imaged.

**test phantom:** Components for each measurement are defined in the description of that measurement.

## 1.2 STANDARD SYMBOLS

Symbolic expressions for certain quantities are used throughout this standards publication. Symbols that use any one of the standard subscripts to further specify a basic quantity are identified by the subscript string $_{xxx}$. All quantities expressed as a function of some 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.

Only those symbols that are used in multiple sections of the standard are listed in this section. Symbols that are only used in one section are described in that section.

**counts ($C_{xxx}$):** The number of coincidence events:

a. $C_{ROI}$ – events in a planar region of interest
b. $C_{TOT}$ – total number of events
c. $C_m$ – maximum number of events
d. $C_{r+s}$ – random plus scatter event count
e. $C_L$ – event count at left edge of projection area of interest
f. $C_R$ – event count at right edge of projection area of interest
g. $C_H$ – counts in a hot region of interest
h. $C_B$ – counts in a background region of interest
i. $C_C$ – counts in a cold region of interest

**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. $A_{ave,j}$ – average radioactivity for $j^{th}$ acquisition
c. $A_{cal}$ – radioactivity at time $T_{cal}$

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The initial radioactivity at the beginning $T_0$ of an acquisition shall be found using the activity $A_{cal}$ as recorded in the dose calibrator or well counter at time $T_{cal}$ according to:

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

Where $T_{1/2}$ is the half-life of the radioisotope.

The average radioactivity for a particular acquisition shall be found using the activity, $A_0$, at the beginning of the acquisition, the half-life of the radionuclide, $T_{1/2}$, and the duration of the acquisition, $T_{acq}$, according to:

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

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

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

**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. $a_{t,peak}$ – radioactivity concentration at peak true event rate
b. $a_{eff}$ – effective average activity concentration of a line source in a solid cylinder
c. $a_H$ – radioactivity concentration in a hot sphere
d. $a_B$ – radioactivity concentration in the background
e. $a_{NEC,peak}$ – radioactivity concentration at the peak NECR rate

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

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

The average radioactivity concentration is thus

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

Note that in computing the effective radioactivity concentration, $a_{eff}$, the volume to be used is the volume of the solid cylinder, not the volume of its line source insert.

**radioisotopic half-life ($T_{1/2}$):** The interval of time during which half of the nuclei of a radionuclide are likely to decay. For the isotope $^{18}F$, the half-life is 6588 seconds (or 109.8 minutes or 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 planar region of interest
b. $R_{TOT}$ – total event rate
c. $R_{Extr}$ – potential event rate (no losses)

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d. $R_t$ – true event rate
e. $R_s$ – scatter event rate
f. $R_r$ – random event rate
g. $R_{t,peak}$ – true event rate where $R_t$ saturates
h. $R_{NEC}$ – noise equivalent count rate
i. $R_{NEC,peak}$ – peak noise equivalent count rate
j. $R_{CORR}$ – decay-corrected count rate

**time ($T_{xxx}$):** A time measured in seconds:

a. $T_{1/2}$ – a time interval of one half-life
b. $T_{acq}$ – duration of an acquisition
c. $T_j$ – starting time of acquisition j
d. $T_{cal}$ – time of well counter measurement
e. $T_{T,E}$ – the total time interval of transmission and emission acquisitions

**volume (V):** A physical volume measured in milliliters.

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# Section 2
# GENERAL

## 2.1 PURPOSE

The intent of this standards publication 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 standard measurement procedures can be used by customers for acceptance-testing of tomographs before and after installation of the equipment.

## 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, and other coincidence-capable imaging systems. Wherever possible, future developments that could be readily anticipated were taken into account.

The tomographs being evaluated are assumed to have transverse fields of view suitable for human subjects. For all of the procedures, except for the Image Quality test, the scanner must have an accessible diameter of at least 260 millimeters. The test phantom for all of the procedures, except for the Image Quality test, is 70.0 cm in length and is suitable for performing measurements in all slices of tomographs with an axial field of view of less than 65 cm. The Image Quality test, which requires a different test phantom, can only be performed on a scanner with an accessible diameter of at least 350 millimeters. While this precludes the performance of the Image Quality test on some brain-only scanners, it is important to note that the Image Quality test is designed to emulate whole-body imaging performance, and therefore is not appropriate for a brain-only tomograph.

The measurements described in this standards publication have been designed with a primary focus on whole body imaging for oncologic applications. As such, these measurements may not accurately represent the performance of a positron emission tomograph in brain imaging applications. The scatter fraction and count rate performance measurements from the NU-2 1994 standard are included as an Appendix; these measurements may be used to better assess the performance of a positron emission tomograph for brain imaging.

## 2.3 UNITS OF MEASURE

Système International d'Unités (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 that are mutually exclusive, unless otherwise directed for a particular measurement. These include, but are not limited to the following parameters: energy discrimination windows (including the utilization of multiple energy windows in photopeak-Compton imaging modes), coincidence timing window(s), pulse integration time, reconstruction algorithm with associated parameters, pixel size, slice thickness, axial acceptance angle, and axial averaging or smoothing. If multiple operating modes are supported by the instrument, the operating mode for a particular measurement shall be clearly specified.

For instruments with movable detector elements the detector positions and trajectories shall be those recommended by the manufacturer and shall remain the same for all acquisitions. These motions include,

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but are not limited to, the detector separation distance, orbit trajectory around the patient to produce a full tomographic data set, and motions to increase sampling such as detector wobble or table displacements. The reconstruction algorithm, with its associated parameters, matrix, and pixel size shall be that recommended by the manufacturer and shall remain fixed for all of the 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 a 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 oriented into transaxial slices for data analysis.

Some measurements explicitly require volumetric data to be resorted into transverse sinograms using the single-slice rebinning method, as described in Daube-Witherspoon, M.E. and Muehllehner, G., *Treatment of axial data in three-dimensional PET, J Nucl Med* 28:1717-1724, 1987; for all other measurements, the manufacturer's recommended treatment of volumetric data shall be used.

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

The energy window or windows used for these measurements must be specified. If multiple windows are used in a photopeak-Compton imaging mode, that mode shall also be specified. These window settings shall be those recommended by the manufacturer and shall remain fixed during all of the NEMA measurements of a tomograph's performance.

Each measurement procedure specifies the method of source support, whether the source is to be suspended in the field of view or supported by some means. For those measurements in which the source is to be supported, the source shall be placed on the patient table.

Unless specified otherwise in the description of a particular measurement, phantom positioning instructions carry a nominal tolerance of 5 mm in both the transaxial and the axial directions.

## 2.5 EQUIVALENCY

$^{18}$F is specified 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. If, for quality assurance or other purposes, a manufacturer employs measurement methods other than those prescribed, the manufacturer shall demonstrate traceability between the methods prescribed for the measurement and those employed for testing.

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 sources in air, and then reconstructing images with no smoothing or apodization. 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. The width of the spread function is measured by its full width at half-maximum amplitude (FWHM) and full width at tenth-maximum amplitude (FWTM).

## 3.3 METHOD

For all systems, the spatial resolution shall be measured in the transverse slice in two directions (e.g. radially and tangentially). In addition, an axial resolution also shall be measured.
The transverse field-of-view and image matrix size determine the pixel size in the transverse slice. In order to measure the width of the point spread function as accurately as can practically be achieved, its FWHM should span at least three pixels. The pixel size should be made no more than one-third of the expected FWHM in all three dimensions during reconstruction and should be indicated as a condition for the spatial resolution measurement.

### 3.3.1 Symbols

**Resolution** (RES) — The measurement of the size of the reconstructed image of a point source. Resolution is specified as the **full width at half maximum** (FWHM) or **full width at tenth maximum** (FWTM) of the point source response.

### 3.3.2 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.

### 3.3.3 Source Distribution

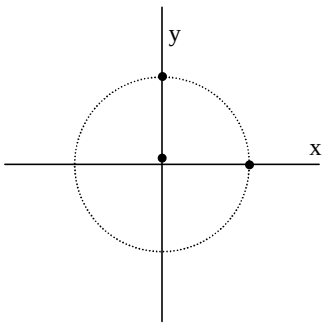
The point shall consist of a small quantity of concentrated activity inside a glass capillary with an inside diameter of 1 mm or less and an outside diameter of less than 2 mm. The axial extent of the activity in the capillary shall be less than 1 mm.

The sources shall be fixed parallel to the long axis of the tomograph and located at 6 points as follows:

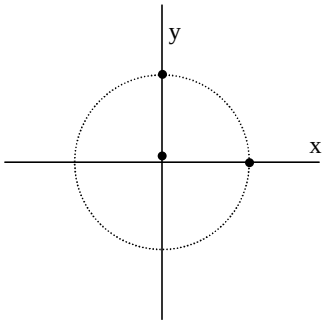
- In the axial direction, along planes (1) at the center of the axial FOV and (2) one-fourth of the axial FOV from the center of the FOV.
- In the transverse direction the source shall be positioned (1) 1 cm vertically from the center
- (to represent the center of the FOV, but positioned to avoid any possible inconsistent results at the very center of the FOV), (2) at x=0 and y=10 cm, and (3) at x=10 cm and y=0.

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The source arrangement is shown diagrammatically in Figure 3-1.




Axial Position = 0




Axial Position = ¼of axial FOV

**Figure 3-1**
**POSITIONS OF SOURCE FOR**
**RESOLUTION MEASUREMENT**

### 3.3.4 Data Collection

Measurements shall be collected at all six positions specified above. At least one hundred thousand counts shall be acquired in each response function. Measurements can be taken with multiple sources. Finer sample size may be selected than typically used in clinical studies.

### 3.3.5 Data Processing

Reconstruction by filtered backprojection with no smoothing or apodization shall be employed for all spatial resolution data.

## 3.4 ANALYSIS

The spatial resolution (FWHM and FWTM) of the point source response function in all three directions shall be determined by forming one-dimensional response functions, along profiles through the image volume in three orthogonal directions, through the peak of the distribution. The width of the response functions in the two directions at right angles to the direction of measurement shall be approximately two times the FWHM.

Each FWHM (and FWTM) shall be determined by linear interpolation between adjacent pixels at half (or one-tenth) the maximum value of the response function (see Figure 3-2). The maximum value shall be determined by a parabolic fit using the peak point and its two nearest neighboring

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points respectively. Values shall be converted to distance in millimeters by multiplication by the pixel size.

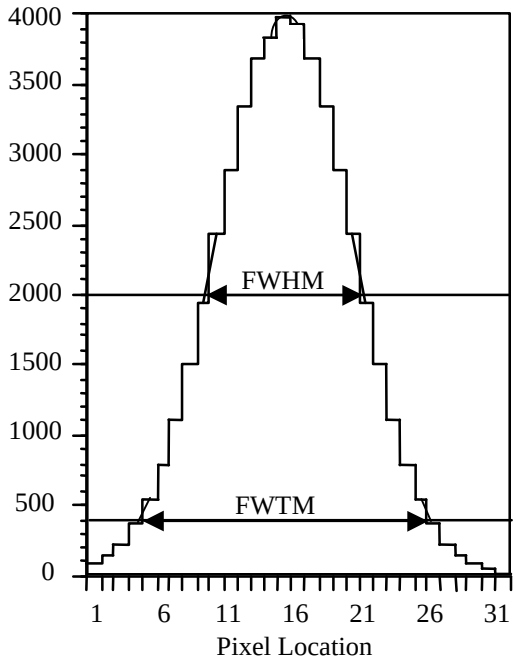



**Figure 3-2**
**A TYPICAL RESPONSE FUNCTION WITH FWHM AND FWTM DETERMINED GRAPHICALLY BY INTERPOLATION**

### 3.5 REPORT

Radial and tangential resolutions (FWHM and FWTM) for each radius (center and 10cm), averaged over both axial positions, shall be calculated and reported as values of system resolution according to Table 3-1.

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| | Description | Formula |
|---|---|---|
| At 1 cm radius | | |
| Transverse | Average x & y for both z positions (4 numbers) | $RES = \left( \begin{array}{l} RESx_{x=0,y=1,z=center} + RESy_{x=0,y=1,z=center} + \\ RESx_{x=0,y=1,z=1/4FOV} + RESy_{x=0,y=1,z=1/4FOV} \end{array} \right) \Big/ 4$ |
| Axial | Average of 2 z positions (2 numbers) | $RES = \left( RESz_{x=0,y=1,z=center} + RESz_{x=0,y=1,z=1/4FOV} \right) \Big/ 2$ |
| At 10 cm radius | | |
| Transverse radial | Average 2 transverse for both z positions (4 numbers) | $RES = \left( \begin{array}{l} RESx_{x=10,y=0,z=center} + RESy_{x=0,y=10,z=center} + \\ RESx_{x=10,y=0,z=1/4FOV} + RESy_{x=0,y=10,z=1/4FOV} \end{array} \right) \Big/ 4$ |
| Transverse tangential | Average 2 transverse for both z positions (4 numbers) | $RES = \left( \begin{array}{l} RESy_{x=10,y=0,z=center} + RESx_{x=0,y=10,z=center} + \\ RESy_{x=10,y=0,z=1/4FOV} + RESx_{x=0,y=10,z=1/4FOV} \end{array} \right) \Big/ 4$ |
| Axial resolution | Average 2 transverse for both z positions (4 numbers) | $RES = \left( \begin{array}{l} RESz_{x=10,y=0,z=center} + RESz_{x=0,y=10,z=center} + \\ RESz_{x=10,y=0,z=1/4FOV} + RESz_{x=0,y=10,z=1/4FOV} \end{array} \right) \Big/ 4$ |

**Table 3-1**
**FORMULAS FOR COMPUTING SPATIAL RESOLUTION REPORT VALUES.**
**( RESx, RESy, and RESz refer to the spatial resolution measured in the x, y, and z-directions)**

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# Section 4
# SCATTER FRACTION, COUNT LOSSES, AND RANDOMS 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.

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

The measurement of noise equivalent count rates is based on work described in Strother, S.C., Casey, M.E. and Hoffman, E.J., *Measuring PET Scanner Sensitivity: Relating Count-Rates to Image Signal-to-Noise Ratios Using Noise Equivalent Counts*, *IEEE Trans Nucl Sci,* NS-37(2):783-788, 1990.

## 4.2 PURPOSE

The first 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.

The second purpose of this procedure is to measure the effects of system dead-time and the generation of random events at several levels of source activity.

The true event rate is the total coincident event rate minus the scattered event rate and minus the randoms event rate. The method of randoms estimation includes misplaced events as part of the randoms measurement. Furthermore, shifts in the energy peak may influence the results for the randoms, since it is assumed that the scatter fraction is constant as a function of countrate.

## 4.3 METHOD

The test phantom is a solid right circular cylinder composed of polyethylene with a specific gravity of 0.96 ± 0.01, with an outside diameter of 203 ± 3 mm (8”), and with an overall length of 700 ± 5 mm. A 6.4 ± 0.2 mm (1/4”) hole is drilled parallel to the central axis of the cylinder, at a radial distance of 45 ± 1 mm. For ease of fabrication and handling, the cylinder may consist of several segments that are assembled together during testing. However, in both design and assembly of the completed phantom one must *insure a tight fit between adjacent segments*, as even very small gaps will allow narrow axial regions of scatter-free radiation.

The test phantom line source insert is a clear polyethylene or polyethylene coated plastic tube at least 800 mm in length, with an inside diameter of 3.2 ± 0.2 mm (1/8”) and an outside diameter of 4.8 ± 0.2 mm (3/16”). The central 700 ± 5 mm of this tube will be filled with a known quantity of activity and threaded through the 6.4 mm hole in the test phantom.

To begin the test, a source of relatively high activity is placed in the field of view of the positron emission tomograph. Regular measurements are then taken while the activity in the phantom decays over several half-lives. A decrease in the ratio of the random event rate to the true event rate accompanies the activity decay, eventually falling to less than 1%. In addition, the efficiency of the system in processing coincident events improves as the activity decays, until count losses may be effectively neglected. Thus by waiting long enough one obtains a measurement of the coincidence count rate that is effectively free from both randoms and processing losses. By

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extrapolating this true rate back to higher activity levels and comparing it to the measured rate one may estimate count losses suffered by the system at higher activity levels. The accuracy of this technique depends critically on adequate statistics being gathered at sufficiently low levels of activity. This may require repeated measurements at the lower count rates.

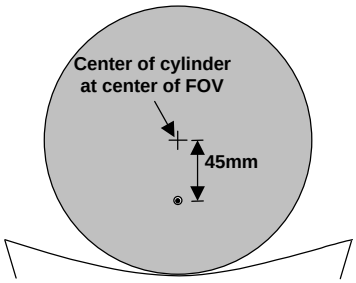



**Figure 4-1**
**POSITIONING OF PHANTOM**

### 4.3.1 Symbols

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

### 4.3.2 Radionuclide

The radionuclide used for this measurement shall be $^{18}F$. The amount of radioactivity shall be great enough to allow the following two rates to be measured:

a. $R_{t,peak}$ – peak true count rate
b. $R_{NEC,peak}$ – peak noise equivalent count rate

Recommendations for the initial activity required to meet these objectives will be supplied by the manufacturer.

The initial activity in the phantom shall be determined from the activity injected into the phantom as measured in a calibrated dose calibrator.

### 4.3.3 Source distribution

The central 700 ± 5 mm of the test phantom line source insert shall be filled with water well mixed with the measured amount of radioactivity and sealed at both ends. This line source shall be inserted into the hole of the test phantom such that the region of activity coincides with the 70 cm length of the phantom. The test phantom with line source is mounted on the standard patient table supplied by the manufacturer and rotated such that the line source insert is positioned nearest to the patient bed (see Figure 4-1). The phantom is centered in the transverse and axial fields-of-view to within 5 mm.

### 4.3.4 Data collection

Data shall be acquired at intervals more frequent than half the radionuclide half-life, $T_{1/2}$, until true events losses are less than 1.0%, and the random rates are less than 1.0% of true rates. The durations of the individual acquisitions, $T_{acq,j}$, shall be less than one-fourth of $T_{1/2}$. Acquisitions shall be fully tomographic; therefore, rotating scanners must rotate to provide complete and uniform angular sampling for each acquisition. In the case of rotating scanners, the acquisition time $T_{acq}$ shall include the time required to rotate the detectors.

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It is essential to the accurate estimation of system dead-time losses that sufficient statistics be acquired with count loss rates and random rates both below 1.0% of true rates. Each acquisition should contain a minimum of 500,000 prompt counts. It is also important that the measurements around the peak count rate be done with sufficient frequency so that the peak rate can be accurately determined. Therefore, it is expected that manufacturers will recommend a protocol for their scanners that includes starting activity, acquisition times, and acquisition durations.

### 4.3.5 Data processing

For tomographs with an axial field of view of 65 cm or less, sinograms shall be generated for each acquisition *j* of slice *i*. For tomographs with an axial field of view greater than 65 cm, sinograms shall be generated for each acquisition for slices within the central 65 cm. No corrections for variations in detector sensitivity or detector motions such as wobble, randoms, scatter, dead-time, or attenuation shall be applied to the measurements. Real-time subtraction of random events shall not be done.

The sinograms must contain the total acquired counts of the scanner without corrections; i.e., the sinograms must contain true, random, and scatter counts. Furthermore, scanners with the capacity for direct measurement of random rates may not use these measurements in the estimation of random count rates detailed below. Oblique sinograms are collapsed into a single sinogram for each respective slice (by single-slice rebinning) while conserving the number of counts in the sinogram.

## 4.4 ANALYSIS

All pixels in each sinogram *i* of acquisition *j* 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:

$$C(r)_{i,j} = \sum_{a} C(r - r_{max}(\phi), \phi)_{i,j}$$

Where:

a. r is the pixel number in a projection,

b. $\phi$ is the projection number in the sinogram (i.e., the sinogram row), and

c. $r_{max}(a)$ refers to the location of the maximum value in projection $\phi$.

The counts $C_{L,i,j}$ and $C_{R,i,j}$ 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 4-2). 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 $C_{L,i,j}$ and $C_{R,i,j}$ 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 random plus scatter counts $C_{r+s,i,j}$ for the slice i of acquisition j.

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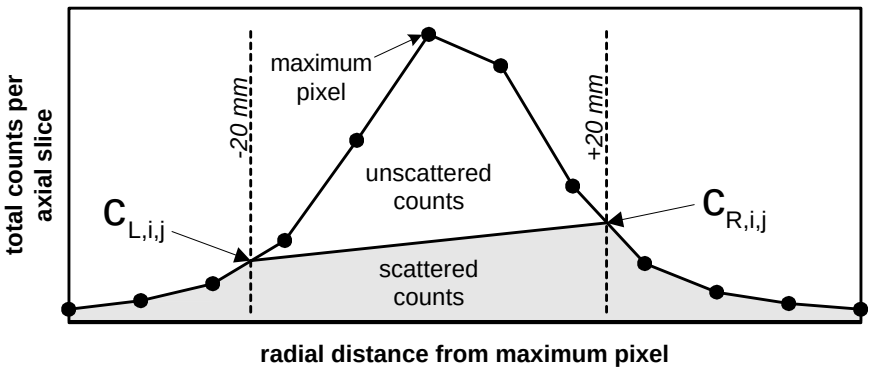



**Figure 4-2**
**INTEGRATION OF BACKGROUND COUNTS INSIDE AND OUTSIDE 40mm STRIP**

The total event count $C_{TOT,i,j}$ is the sum of all pixels in the sum projection for slice i of acquisition j. The average activity $A_{ave,j}$ for each acquisition j shall be calculated (see Section 1.2).

### 4.4.1 Scatter fraction

The final acquisitions $j'$ of the sequence with count loss rates and random rates below 1.0% of the trues rate shall be used to determine the scatter fraction. For these acquisitions, it is assumed that $C_{r+s,i,j'}$ has a negligible number of random counts and consists only of scatter counts, and likewise, $C_{TOT,i,j'}$ consists only of true and scatter counts.

The scatter fraction $SF_i$ for each slice is calculated by summing over the low activity acquisitions as follows:

$$SF_i = \frac{\sum_{j'} C_{r+s,i,j'}}{\sum_{j'} C_{TOT,i,j'}}$$

The system scatter fraction $SF$ is computed as the weighted average of the $SF_i$ values as follows:

$$SF = \frac{\sum_{i}\sum_{j'} C_{r+s,i,j'}}{\sum_{i}\sum_{j'} C_{TOT,i,j'}}$$

### 4.4.2 Total event rate measurement

For each acquisition $j$, the total event rate $R_{TOT,i,j}$ for each slice i is computed as:

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

Where $T_{acq,j}$ is the acquisition time. The system total event rate $R_{TOT,j}$ is computed as the sum of $R_{TOT,i,j}$ over all slices $i$.

### 4.4.3 True event rate measurement

For each acquisition $j$, the true event rate $R_{t,i,j}$ for each slice $i$ is computed as:

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$$R_{t,i,j} = \frac{\left(C_{TOT,i,j} - C_{r+s,i,j}\right)}{T_{acq,j}}$$

Where $T_{acq,j}$ is the acquisition time. The system true event rate $R_{t,j}$ is computed as the sum of $R_{t,i,j}$ over all slices *i*.

#### 4.4.4 Random event rate measurement

For each acquisition *j*, the random event rate $R_{r,i,j}$ for each slice *i* is computed as:

$$R_{r,i,j} = R_{TOT,i,j} - \left(\frac{R_{t,i,j}}{1 - SF_i}\right)$$

The system random event rate $R_{r,j}$ is computed as the sum of $R_{r,i,j}$ over all slices *i*.

#### 4.4.5 Scatter event rate measurement

For each acquisition *j*, the scatter event rate $R_{s,i,j}$ for each slice i is computed as:

$$R_{s,i,j} = \left(\frac{SF_i}{1 - SF_i}\right) R_{t,i,j}$$

The system scatter event rate $R_{s,j}$ is computed as the sum of $R_{s,i,j}$ over all slices *i*.

#### 4.4.6 Noise equivalent count rate measurement

For each acquisition *j*, on all systems *except* those which perform direct randoms subtraction, the noise equivalent count rate $R_{NEC,i,j}$ for each slice *i* is computed as:

$$R_{NEC,i,j} = \frac{R_{t,i,j}^2}{R_{TOT,i,j}}$$

Systems that use direct randoms subtraction should instead compute $R_{NEC,i,j}$ for each slice *i* as:

$$R_{NEC,i,j} = \frac{R_{t,i,j}^2}{R_{TOT,i,j} + R_{r,i,j}}.$$

The system noise equivalent count rate $R_{NEC,j}$ is computed as the sum of $R_{NEC,i,j}$ over all slices *i*.

### 4.5 REPORT

#### 4.5.1 Count rate plot

For the system, plot the following five quantities as a function of the average effective radioactivity concentration $a_{ave,j}$, as defined in Section 1.2, where the volume *V* is the total volume of the cylindrical phantom (22,000 $cm^3$):

a. $R_{t,j}$ – system true event rate
b. $R_{r,j}$ – system random event rate
c. $R_{s,j}$ – system scatter event rate
d. $R_{NEC,j}$ – system noise equivalent count rate
e. $R_{TOT,j}$ – system total event rate

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### 4.5.2 Peak count values

Report the following values, derived from the above plot:

a. $R_{t,peak}$ – peak true count rate
b. $R_{NEC,peak}$ – peak noise equivalent count rate
c. $a_{t,peak}$ – the activity concentration at which $R_{t,peak}$ is reached
d. $a_{NEC,peak}$ – the activity concentration at which $R_{NEC,peak}$ is reached

### 4.5.3 System scatter fraction

Report the value of *SF*.

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# Section 5
# SENSITIVITY

## 5.1 GENERAL

Sensitivity of a positron emission tomograph is expressed as the rate in counts per second that true coincidence events are detected for a given source strength. Since the emitted positrons annihilate and create a pair of gamma rays, a significant amount of material must surround the source to insure annihilation. This surrounding material also attenuates the created gamma rays, prohibiting a measurement without interfering attenuation. To arrive at an attenuation free measurement, successive measurements are made with a uniform line source surrounded by known absorbers. From these measurements, the sensitivity with no absorber can be extrapolated.

This measurement technique is based on work described in Bailey, D.L., Jones, T., and Spinks, T.J., *A Method for Measuring the Absolute Sensitivity of Positron Emission Tomographic Scanners*, *Eur J Nucl Med,* 18: 374-379, 1991.

## 5.2 PURPOSE

The purpose of this procedure is to measure the sensitivity or ability of the scanner to detect positrons.

## 5.3 METHOD

The test equipment required for this measurement is the sensitivity phantom shown in Figure 5-1.

### 5.3.1 Symbols

**Accumulated Sleeve Wall Thickness** (X) – the combined thickness of the metal sleeve walls used in the sensitivity measurement.

**Attenuation Coefficient** ($\mu$) – a measure of the likelihood that a photon will undergo an interaction while traveling through a material, expressed in units of reciprocal distance (such as $mm^{-1}$).

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

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

### 5.3.2 Radionuclide

The radionuclide employed for these measurements shall be $^{18}F$. The activity used shall be low enough so that the counting losses are less than one percent, and the random event rate is less than 5% of the trues rate.

The initial activity in the phantom shall be determined by measurement in a dose calibrator.

### 5.3.3 Source distribution

A 700 ± 5 mm portion of plastic tubing shall be filled with water, well mixed with a measured amount of radioactivity, and sealed at both ends. This activity, $A_{cal}$ in MBq, and the time of the assay, $T_{cal}$, should be recorded. The phantom is suspended in the center of the transaxial field of view, aligned with the axis of the tomograph in such a way that any supporting mechanism is external to the field of view.

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### 5.3.4 Data Collection

Data are collected for a period of time to ensure that at least 10,000 trues per slice are collected. Single slice rebinning shall be used to assign counts in oblique lines-of-response (LORs) to the image slice where the LOR crosses the scanner axis. The time of the measurement, $T_1$, is recorded along with the duration, $T_{acq}$, and the number of counts collected. In the case of scanners whose detectors must be moved to acquire a full tomographic data set, the acquisition time $T_{acq}$ shall include the time required to move the detectors. The rate, $R_{1,i}$, in counts per second, shall be determined by dividing the counts collected in the slice by the duration. In succession, each of the four sleeves are added to the phantom and the measurement repeated, recording values for $T_j$ and $R_{j,i}$ for each measurement.

To assess the sensitivity at different radial positions, the process described in the preceding paragraph shall be repeated at a 10 cm radial offset from the center of the transaxial field of view.

## 5.4 CALCULATIONS AND ANALYSIS

### 5.4.1 System Sensitivity

For each measurement associated with each of the five sleeves, and for each slice, correct the count rate for isotope decay by the following formula:

$$R_{CORR,j,i} = R_{j,i} \cdot 2^{(T_j - T_{cal})/T_{1/2}}$$

Once the isotope decay has been corrected, calculate $R_{CORR,j}$ by summing the $R_{CORR,j,i}$ from each slice. The data are then fit to the following equation using regression:

$$R_{CORR,j} = R_{CORR,0} \cdot \exp(-\mu_M \cdot 2 \cdot X_j)$$

Where $R_{CORR,0}$ and $\mu_M$ are the unknowns, and $X_j$ represents the accumulated sleeve wall thickness. The term $R_{CORR,0}$ represents the count rate with no attenuation. The value for attenuation in metal, $\mu_M$, is allowed to vary to compensate for the small amount of scattered radiation.

The same procedure shall be followed for the sensitivity measurements done at 10 cm offset from the tomograph center.

The system sensitivity shall be computed by the following formula:

$$S_{tot} = \frac{R_{CORR,0}}{A_{cal}}$$

### 5.4.2 Axial Sensitivity Profile

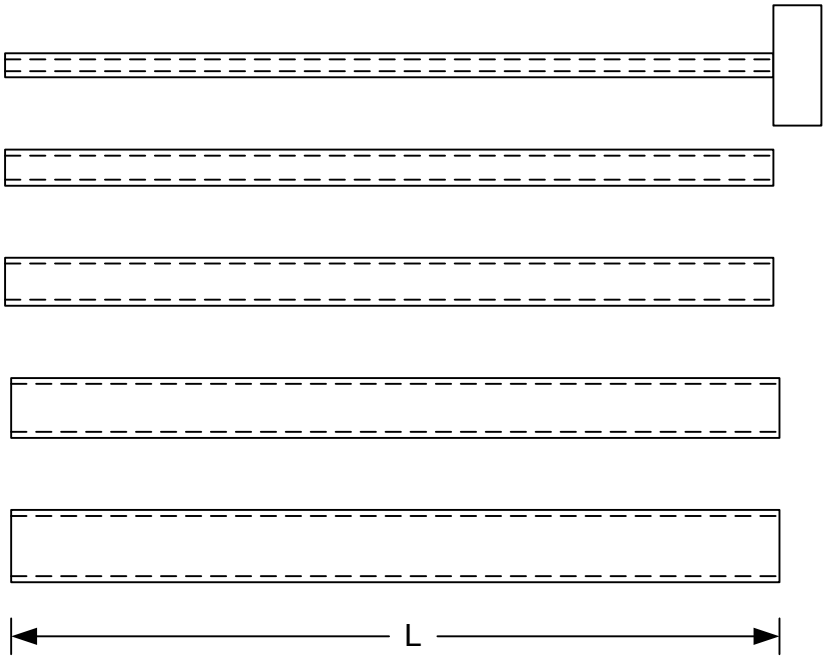
Using the data collected for the smallest tube, $C_{1,Plane}$, at the 0 centimeter radial offset, compute the sensitivity for each slice by the following:

$$S_i = \frac{R_{CORR,1,i}}{R_{CORR,1}} \cdot S_{tot}$$

## 5.5 REPORT

Report the sensitivity for each of the radial offsets in counts/sec/MBq. Also report the axial sensitivity profile by plotting the sensitivity, $S_i$, for each slice. Both the system sensitivity and the axial sensitivity profile shall be reported.

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| Tube Number | Inside Diameter (mm) | Outside Diameter (mm) | Length L (mm) |
|---|---|---|---|
| 1 | 3.9 | 6.4 | 700 |
| 2 | 7.0 | 9.5 | 700 |
| 3 | 10.2 | 12.7 | 700 |
| 4 | 13.4 | 15.9 | 700 |
| 5 | 16.6 | 19.1 | 700 |

**Figure 5-1**
**SENSITIVITY MEASUREMENT PHANTOM**

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# Section 6
# ACCURACY: CORRECTIONS FOR COUNT LOSSES AND RANDOMS

## 6.1 GENERAL

To achieve quantitative measurements of source activity distributions 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 count 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.

## 6.2 PURPOSE

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

## 6.3 METHOD

The test phantom data of Section 4.3, 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 losses and randoms subtraction.

The comparison is between the corrected true count rate and the expected count rate extrapolated from low count rate data. Errors from dead-time and randoms are assumed to be insignificant at low count rates. All corrections are to be applied.

### 6.3.1 Symbols

**Relative count rate error** ($\Delta r$) — the difference between the expected count rate and the measured count rate, expressed as a percentage of the expected rate.

### 6.3.2 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 a 50% dead-time loss value and also to allow the following two rates to be measured:

a. $R_{t,peak}$ – peak true count rate
b. $R_{NEC,peak}$ – peak noise equivalent count rate

Recommendations for the initial activity required to meet these objectives will be supplied by the manufacturer.

The initial activity in the phantom shall be determined from the activity injected into the phantom as measured in a calibrated dose calibrator.

### 6.3.3 Source Distribution

The central 700 ± 5 mm of the test phantom line source insert shall be filled with water, well mixed with the measured amount of radioactivity, and sealed at both ends. This line source shall be inserted into the hole of the test phantom such that the region of activity coincides with the 70 cm length of the phantom. The test phantom with line source is mounted on the standard patient

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table supplied by the manufacturer and rotated such that the line source insert is positioned nearest to the patient bed. The phantom is centered in the transverse and axial fields-of-view.

### 6.3.4 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 durations of the individual acquisitions, $T_{acq,j}$, shall be less than one-fourth of $T_{1/2}$. Acquisitions shall be fully tomographic; therefore, rotating scanners must rotate to provide complete and uniform angular sampling for each acquisition.

It is essential to the accurate estimation of system dead-time losses that sufficient statistics be acquired with count loss rates and random rates both below 1.0% of true rates. Each acquisition should contain a minimum of 500,000 prompt counts. Therefore, it is expected that manufacturers will recommend a protocol for their scanners that includes starting activity, acquisition times, and the duration.

### 6.3.5 Data Processing

For tomographs with an axial field of view of 65 cm or less, all slices shall be reconstructed. For tomographs with an axial field of view greater than 65 cm, only slices in the central 65 cm shall be reconstructed. Randoms and deadtime corrections shall be applied to the data. Images shall be reconstructed using the standard means; that method shall be reported.

## 6.4 ANALYSIS

All analyses shall be performed on each reconstructed image *i*. The average activity $A_{ave,j}$ for each acquisition *j* shall be calculated (see Section 1.2). The average effective activity concentration $a_{eff,j}$ for each acquisition *j* shall be computed by dividing $A_{ave,j}$ by the volume of the test phantom (22,000 $cm^3$).

A circular region of interest, ROI, centered on the transverse field of view (*not* centered on the line source) 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 rate $R_{ROI,i,j}$:

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

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 or randoms. 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 $Dr_{i,j}$ in percentage units shall be calculated by the following equation:

$$\Delta r_{i,j} = 100\left(\frac{R_{ROI,i,j}}{R_{Extr,i,j}} - 1\right)\%$$

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### 6.5 REPORT

For each slice, tabulate the values of $Dr_{i,j}$ and $a_{eff,j}$. Plot a graph of the highest and lowest values among the slices of $Dr_{i,j}$ versus $a_{eff,j}$, choosing linear graphical axes. The data points may be joined to form a true continuous curve.

Report the maximum value of the bias $|Dr_{i,j}|$ at activity values at or below $a_{NEC,peak}$ as determined in Section 4.5.2.

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# Section 7
# IMAGE QUALITY, ACCURACY OF ATTENUATION AND SCATTER CORRECTIONS

## 7.1 GENERAL

Because of the complex interplay of different aspects of system performance, it is desirable to be able to compare the image quality of different imaging systems for a standardized imaging situation that simulates a clinical imaging condition. Due to variations in the uptake of radiopharmaceuticals and in patient sizes and shapes, it is difficult to simulate clinical imaging conditions using a phantom. For these reasons, the results of a single phantom study can only give indications of image quality for that particular imaging situation.

## 7.2 PURPOSE

The purpose of this measurement is to produce images simulating those obtained in a total body imaging study with both hot and cold lesions. Spheres of different diameters are imaged in a simulated body phantom with non-uniform attenuation; activity is also present outside the scanner. Image contrast and signal-to-noise ratios for both hot and cold spheres are used as measures of image quality. In addition, the accuracy of the attenuation and scatter corrections is determined from this measurement.

## 7.3 METHOD

### 7.3.1 Symbols

**Contrast** ($Q_{xxx}$) – the contrast of a sphere in a warm background:

a. $Q_H$ – hot sphere contrast
b. $Q_C$ – cold sphere contrast

**Background variability** ($N_{xxx}$) – used as part of the image quality measurement:

a. $N_j$ – coefficient of variation for all ROIs of size *j* in the image volume.

**Relative count error** ($\Delta C$) — the difference between the expected count and the measured counts, expressed as a percentage:

a. $\Delta C_{lung}$ – relative error in lung insert

**Standard deviation** (SDxxx) — used as part of the background variability measurement:

a. $SD_j$ – standard deviation for all ROIs of size *j* in the image volume

### 7.3.2 Radionuclide

The radionuclide for this measurement shall be $^{18}F$. The concentration of the background activity in the phantom shall be 5.3 kBq/cc (0.14 μCi/cc) within +/- 5% as calibrated at the start of imaging. This activity concentration corresponds to 370 MBq (10 mCi) per 70,000 cc, a typical injected dose for total body studies. If the manufacturer suggests a lower injected activity for total body imaging, a corresponding lower background activity concentration may be used for this study. The background activity concentration used and the manufacturer's recommended injected dose for total body imaging shall be reported. The cold lesions shall be filled with water containing no radioactivity. The hot lesions shall be filled with a concentration of N times that of the background, where N = 4 and 8. The line source of the test phantom shall be filled with 116 MBq (3.08 mCi) of

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$^{18}$F to yield an effective activity "concentration" equal to the background activity concentration; if a lower background activity is used in the phantom, then a corresponding lower activity shall be used in the line source, as well.

### 7.3.3 Source Distribution

The imaging phantom consists of four parts:

a. a body phantom of at least 180 mm interior length, with a cross section as shown in Figure 7-1;

b. six fillable spheres with internal diameters of 10, 13, 17, 22, 28, and 37 mm with a wall thickness of less than or equal to 1mm (see Figure 7-2);

c. to simulate the attenuation of lung, a cylindrical insert filled with a low atomic number materialwith an average density of 0.30 ± 0.10 g/cc, 50±2 mm in outside diameter with a wall thickness less than 4 mm, that is centered inside the body phantom and that extends through the entire axial extent of the phantom; and

d. the test phantom (line source in solid polyethylene cylinder) used for the Scatter Fraction, Count Losses, and Randoms Measurement described in Section 4.

Parts (a), (b), and (c) are described in IEC Publication 61675-1, *Radionuclide Imaging Devices – Characteristics and Test Conditions. Part 1: Positron Emission Tomographs*, 1998.

The two largest spheres (28 mm and 37 mm) shall be filled with water for cold lesion imaging, and the four smallest spheres (10 mm, 13 mm, 17 mm, and 22 mm) with $^{18}$F for hot lesion imaging. The centers of the spheres shall be placed 68 mm from the body phantom endplate so that they are axially in the same transverse slice. The transverse positioning of the spheres shall be so that the centers of the spheres are positioned at a radius of 5.72 cm from the center of the phantom, as shown in Figure 7-2. The 17mm diameter sphere shall be positioned along the horizontal axis of the phantom.

The body phantom shall be filled with the background activity concentration and placed on the imaging table. The body phantom shall be positioned axially in the scanner so that the center of the spheres is at the middle slice of the scanner and positioned transaxially so that the center of the phantom is centered in the scanner. The phantom shall be aligned so that the plane through the centers of the spheres is coplanar to the middle slice of the scanner to within 3 mm throughout the extent of the phantom. A 700 ± 5 mm length of the line source of the test phantom shall be filled with $^{18}$F and threaded through the 6.4 mm hole in the test phantom. The test phantom shall then be placed at the head end of the body phantom and abutting the body phantom in order to approximate the clinical situation of having activity that extends beyond the scanner.

### 7.3.4 Data Collection

The data acquisition time shall be determined considering the axial distance the bed is translated between positions in a total body study (typically less than the axial field-of-view of the scanner) and the total axial imaging distance being simulated. The imaging time shall be set so as to simulate a total body scan, 100 cm total axial imaging distance, in 60 minutes. This time shall include both emission and transmission imaging times assuming attenuation correction is performed at each bed position. The total scan time for emission and transmission scans $T_{T,E}$ is calculated as

$$T_{T,E} = \frac{60\,\text{min}}{\text{dist}} \times \text{axial step}$$

Where dist = 100 cm, and axialstep is the distance the bed is moved between positions in a total body study. This time shall include both emission and transmission scan durations, as well as any transition times (e.g., for moving the transmission source or uploading data).

Additional measurements may be taken where the imaging time is increased to simulate a longer total imaging time or a decreased total axial imaging distance. Specifically, one may choose an

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imaging time that corresponds to a total axial imaging distance of 50 cm in 60 minutes. The actual emission and transmission imaging times are to be reported as well as the total axial imaging distance being simulated. Because the scans have limited counts, it is recommended that 3 replicate scans be acquired in order to improve the reliability of the results. The durations of the subsequent replicate scans should be adjusted for physical decay in order to acquire the same number of events.

### 7.3.5 Data Processing

All slices shall be reconstructed with all available corrections applied to the data. Images shall be reconstructed using the standard parameters (e.g., image matrix size, pixel size, slice thickness, reconstruction algorithm, filters, or other smoothing applied) for whole-body studies, as recommended by the manufacturer. These reconstruction parameters shall be reported.

## 7.4 ANALYSIS

### 7.4.1 Image Quality

A transverse image centered on the cold and hot spheres shall be used in the analysis. The same slice shall be used for all spheres. Regions of interest (ROIs) shall be drawn on each hot and cold sphere. A circular ROI shall be used with a diameter as close as possible to the inner diameter of the sphere being measured. The ROI analysis tool should take into account partial pixels and also permit movement of the ROI in increments of 1 mm or smaller.

ROIs of the same sizes as the ROIs drawn on the hot and cold spheres shall be drawn in the background of the phantom on the slice centered on the spheres. Twelve 37 mm diameter ROIs shall be drawn throughout the background at a distance of 15 mm from the edge of the phantom but no closer than 15 mm to any sphere (see Figure 7-3). ROIs of the smaller sizes (10, 13, 17, 22, and 28 mm) shall be drawn concentric to the 37-mm background ROIs. The ROIs shall also be drawn on the slices as close as possible to +/-1 cm and +/-2 cm on either side of the central slice. A total of 60 background ROIs of each size, 12 ROIs on each of five slices, shall thus be drawn. The locations of all ROIs shall be fixed between successive measurements (e.g., replicate scans). The average counts in each background ROI shall be recorded. The percent contrast $Q_{H,j}$ for each hot sphere $j$ is calculated by:

$$Q_{H,j} = \frac{\frac{C_{H,j}}{C_{B,j}} - 1}{\frac{a_H}{a_B} - 1} * 100\%$$

Where:

a. $C_{H,j}$ is the average counts in the ROI for sphere $j$,

b. $C_{B,j}$ is the average of the background ROI counts for sphere $j$,

c. $a_H$ is the activity concentration in the hot spheres, and

d. $a_B$ is the activity concentration in the background.

The percent contrast $Q_{C,j}$ for each cold sphere $j$ is calculated by

$$Q_{C,j} = \left(1 - \frac{C_{C,j}}{C_{B,j}}\right) * 100\%$$

Where:

a. $C_{C,j}$ is the average counts in the ROI for sphere $j$

b. $C_{B,j}$ is the average of the background ROI counts for sphere $j$

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The percent background variability $N_j$ for sphere $j$ is calculated as:

$$N_j = \frac{SD_j}{C_{B,j}} * 100\%$$

Where $SD_j$ is the standard deviation of the background ROI counts for sphere $j$, calculated as:

$$SD_j = \sqrt{\sum_{k=1}^{K} \left(C_{B,j,k} - C_{B,j}\right)^2 \Big/ (K-1)}, K = 60$$

### 7.4.2 Accuracy of Attenuation and Scatter Corrections

A circular ROI, 30 ± 2 mm in diameter, shall be centered on the lung insert. Record the average pixel value within the ROI, $C_{lung,i}$, for each slice $i$. Twelve circular background ROIs, 30 ± 2 mm in diameter, shall be placed on each slice at the locations specifies for the background ROIs in Section 7.4.1. Record the average pixel values within the ROIs, $C_{B,i}$, for each slice $i$.

To measure the residual error in scatter and attenuation corrections, the relative error $DC_{lung,i}$ in percentage units for each slice $i$ shall be calculated as follows:

$$\Delta C_{lung,i} = \frac{C_{lung,i}}{C_{B,i}} * 100\%$$

Where:

a. $C_{lung,i}$ is the average counts in the lung insert ROI
b. $C_{B,i}$ is the average of the 60 37-mm background ROIs drawn for the image quality analysis

### 7.5 REPORT

The following items are to be reported:

a. Background concentration used to fill the phantom and manufacturer's recommended injected dose for total body studies.
b. Acquisition parameters including emission imaging time, transmission imaging time, axial step size, and total axial imaging distance simulated.
c. The method of reconstruction, including the reconstruction filters and other smoothing applied in both the transaxial and axial directions, and any corrections that are applied (e.g. scatter, randoms, attenuation, deadtime, decay, normalization), pixel size, image matrix size, and slice thickness.
d. The percent contrast and percent background variability for each sphere size and for both concentration ratios. If replicate scans are acquired, the average and SD of the percent contrast and percent background variability over the replicates shall be reported.
e. The value of $DC_{lung,i}$ for each slice. The average of these errors shall also be reported.
f. For each activity ratio imaged, the transverse image through the center of all the spheres, and a coronal image through the center of the 17 mm sphere.

Items (b), (d), and (f) shall be reported for each set of scan conditions (i.e., value of N and axial scan length).

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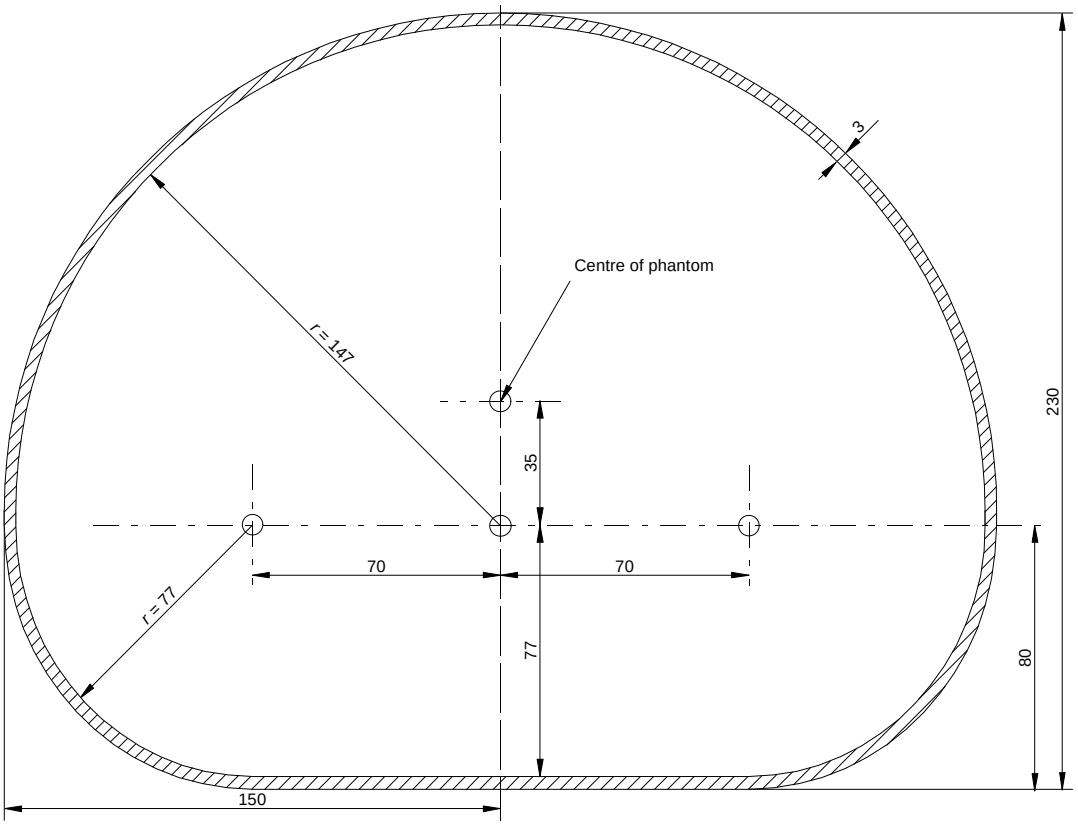



**Figure 7-1**
**CROSS-SECTION OF BODY PHANTOM**

All dimensions are in millimeters and are given within ±1 mm. The phantom material is polymethylmethacrylate. (From IEC Standard 61675-1; used with permission)

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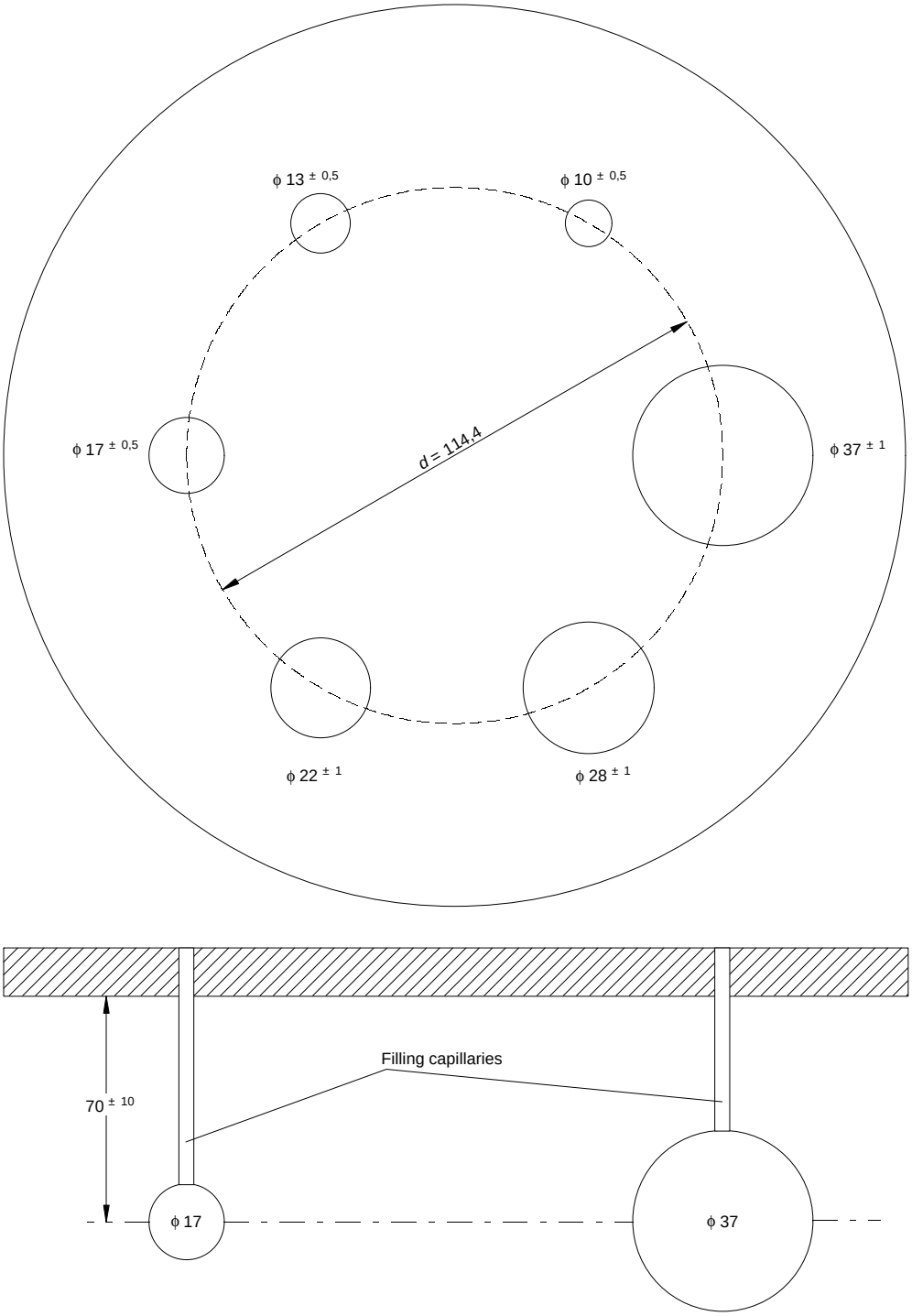



**Figure 7-2**
**PHANTOM INSERT WITH HOLLOW SPHERES**

All diameters given are inside diameters. The wall thickness of the spheres shall be less than or equal to 1 mm. The centers of the spheres shall be 70 ± 10 mm from the inside surface of the mounting plate so they are axially all in the same transverse slice. Phantom material is polymethylmethacrylate, although the spheres may alternatively be made from glass. (From IEC Standard 61675-1; used with permission)

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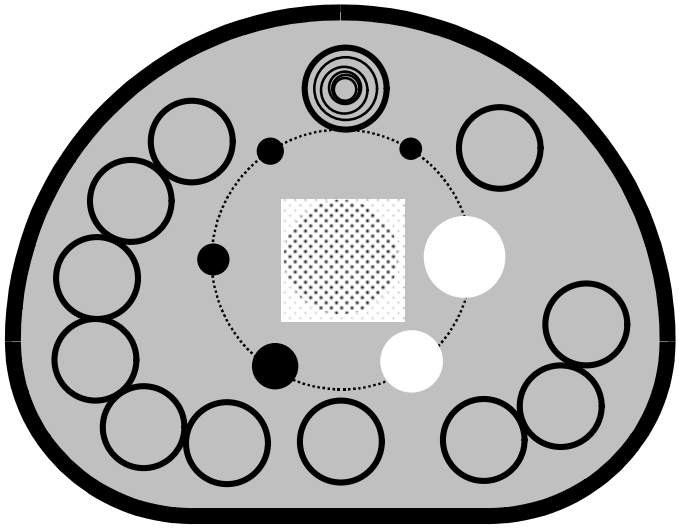


**Figure 7-3**
**BACKGROUND REGION OF INTEREST PLACEMENT FOR IMAGE QUALITY ANALYSIS**

Regions of interest (ROIs) shall be drawn on the spheres. The diameters of the ROIs shall be as close as possible to the physical inner diameters of the spheres. In addition, twelve ROIs of each size shall be drawn in the background.

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# APPENDIX
# NU 2-1994 SCATTER FRACTION AND COUNT RATE TESTS

The measurements described in this standards publication have been designed with a primary focus on whole body imaging for oncologic applications. As such, these measurements may not accurately represent the performance of a positron emission tomograph in brain imaging applications. In order to maintain consistency with NU 2-1994, it is suggested that the scatter fraction test and count rate test from NU 2-1994 be performed with the original NEMA phantom (20-cm diameter by 19-cm long), in addition to the new tests in the present standard. In general, the original (smaller) phantom will yield higher count-rates and a lower scatter fraction than the new (larger) phantom used in the updated standard. Neither phantom can predict the exact performance of a patient study; however, the smaller phantom tends to better predict the performance of a brain study, while the larger phantom tends to better predict the performance of a whole-body study. This is particularly noticeable for 3-D scanners with a large axial field-of-view.

To avoid confusion when reporting values measured according to the methods described in this appendix, such results must be clearly identified as arising from the NU 2-1994 measurement methods, and distinguished from values measured according to the measurements described in the present standard.

## A.1 PHANTOM DESCRIPTION

**Test phantom** is a right circular cylinder composed of virgin polymethyl methacrylate, PMMA, with an outside diameter of 203 ± 3 mm, having a wall thickness of 3 ± 1 mm, and having 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.

**Test phantom line source insert** is a phantom insert element having a fillable cavity of at least 185 mm in length and 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.

## A.2 SCATTER FRACTION MEASUREMENT

### A.2.1 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.

### A.2.2 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 the values for scatter fraction in each slice.

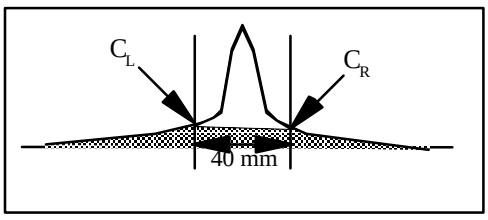



**Figure A-1**
**SINOGRAM PROJECTION OF COUNT DENSITY DUE TO SOURCE IN A SCATTERING MEDIUM**

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### A.2.3 Method

The measurement shall be performed by imaging a single-line source 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 A-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 A-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.

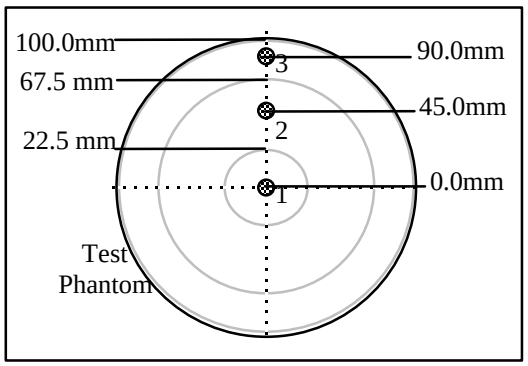



**Figure A-2**
**ANNULAR REGIONS OF MEASURED LINE SOURCE SCATTER FOR UNIFORM SCATTER CALCULATION**

#### A.2.3.1 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.

#### A.2.3.2 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.

#### A.2.3.3 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

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view or the center 17.0 cm where the phantom was placed. The same acquisition time shall be used for each acquisition.

### A.2.3.4 Data Processing

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

### A.2.4 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 processed.

All pixels in each sinogram *i* located further 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 with 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:

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

Where r is the pixel number in a projection, and max refers to the location of the maximum value in the projection, *i* is the slice number, and *k* = 1, 2, and 3 refer to the 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 A-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.

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 k =1, 2, and 3 refer to line sources at radii 0, 45, and 90 mm, respectively.

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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## A.3 COUNT LOSS AND RANDOMS MEASUREMENTS

### A.3.1 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.

### A.3.2 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.

### A.3.3 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.

#### A.3.3.1 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 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.

#### A.3.3.2 Source Distribution

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

#### A.3.3.3 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 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.

#### A.3.3.4 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 *n* detector sensitivity or detector motions such as wobble, randoms, scatter, dead-time, or attenuation shall be applied to the measurements.

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### A.3.4 Analysis

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

#### A.3.4.1 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:

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

For each slice i, linear interpolation shall be used to determine the activity concentration where 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* if there had 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.

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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 where the system percent dead time $PDT_{sys,j}$ is 50%.

**A.3.4.2 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 in the sinogram 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:

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

Where $SF_i$ is the scatter fraction obtained from Section A.2 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.

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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.

### A.3.5 Report

#### A.3.5.1 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%.

#### A.3.5.2 True Event Rate Measurement

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

a. true rate $R_{ROI,t,i}$ where $R_{ROI,t,i} = R_{ROI,r,i}$ (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 $R_{ROI,t,peak,sys}$ where $R_{ROI,t,sys}$ peaks or saturates

along with the corresponding activity concentration.

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