EXPERIENCE ON PERFORMANCE MEASUREMENTS OF POSITRON EMISSION TOMOGRAPHS: NEMA NU2 – 2018

P Pasawang[1], T Sontrapornpol[1], A Krisanachinda[2]

[1]King Chulalongkorn Memorial Hospital, [2]Chulalongkorn University, Bangkok, Thailand

I.Introduction

The major role and responsibility of the clinically qualified medical physicist, CQMP in nuclear medicine[1] are the installation design, technical specification, acceptance and commissioning of equipment, including the establishment of criteria for acceptable performance. The others are the radiation safety and protection of patients, staff and general public, patient internal dosimetry, optimization of the physical aspects of the diagnostic procedure, quality management of the physical and technical aspects of nuclear medicine and collaboration with other clinical professionals. CQMPs have the leading role in preparation of equipment specification according to the needs of nuclear medicine facility. Following the installation of new equipment, CQMPs are responsible for specifying the basic standards to be applied for the acceptance and subsequent commissioning. They ensure that all units and systems function according to their technical specifications and guide on any deviation of equipment performance from acceptable criteria. In this study, after the installation and calibration of the positron emission tomographic system, the CQMPs perform the acceptance test using NEMA Standards Publication NU 2-2018[2]. The performance measurements of the PET system consist of the tomographic resolution, system sensitivity, the scatter fraction, count losses and randoms, the image quality and time- of- flight resolution.

II.Materials and methods

Positron Emission Tomograph system manufacturer Siemens Healthineers Model Biograph mCT 64 had been tested after the installation of the hardware and software, by the team of clinically qualified nuclear medicine medical physicists, local nuclear medicine technologists and Siemens service engineers. Performance measurement of the PET systems follows NEMA, National Electrical Manufacturers Association, Standards Publication NU-2 2018 which consist of

1. Spatial resolution

The purpose of the spatial resolution test is to measure the full width at half maximum (FWHM) and the full width at tenth maximum (FWTM) of the image reconstructed point spread function (PSF) of ^{18}F. The method starts from the preparation of a point source of ^{18}F at the activity of 2.22 MBq (60 μCi) at small quantity of less than or equal to 1 mm in a capillary tube and fix it in the FOV at six positions of (0,1,1/8FOV$_z$), (0,1,1/2 FOV$_z$), (0,10, 1/8 FOV$_z$), (0,10,1/2 FOV$_z$), (0,20,1/8 FOV$_z$), and (0,20,1/2 FOV$_z$). The acceptable offset on x, y axes is $\pm$2 mm for the source at 1cm offset, and $\pm$5 mm for the sources at offset 10 and 20 cm, and on z axis is $\pm$0.25 mm.

III Results

NEMA NU-2 2018 Resolution Test

Image Size: Full (No Zoom)

Average Net Trues: 2,701,710.3 counts

Corrections applied: normalization, dead time, radial-arc-correction, decay-correction, frame-length-correction, FORE and Randoms-subtraction

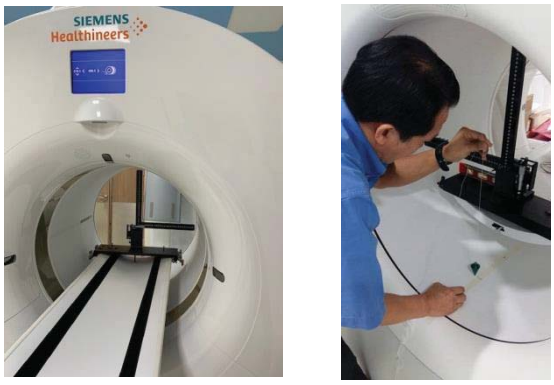


Figure 1: Position of point source in capillary tube for measurement of spatial resolution

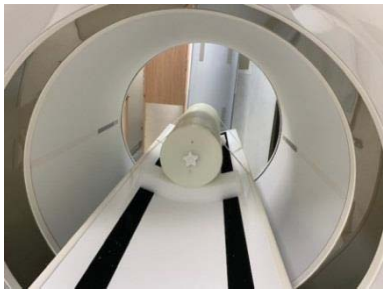
Table 1: The spatial resolution determined from the full width at half maximum (FWHM) and the full with at tenth msximum (FWTM) of ^{18}F activity 2.22 MBq(60 μCi)

Radial Distance	Direction	FWHM (mm)	FWTM (mm)	FWHM System Specification (mm)
1 cm	Radial	4.32	8.88	4.5
	Tangential	4.69	9.37	
	Axial	4.51	10.05	4.7
10 cm	Radial	5.61	10.81	5.2
	Tangential	4.92	9.50	
	Axial	6.18	12.67	6.1
20 cm	Radial	6.38	11.82	6.1
	Tangential	5.75	10.58	
	Axial	8.07	9.53	8.3

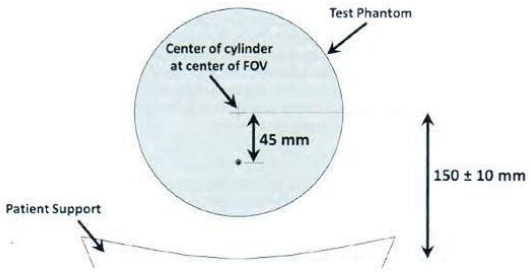
2. Scatter fraction, count loss and randoms

The purpose of this procedure is to measure the relative system sensitivity to scattered radiation. Scatter is expressed as the scatter fraction. SF, for the entire tomograph. Another purpose of this test 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 test phantom is a solid circular cylinder made of polyethylene with outside diameter of 203± 3 mm.and the length of 700± 5 mm. A 6.4mm hole is drilled parallel to the central axis of the cylinderat the radial distance at 45 mm

Source preparation and acquisition protocol The line source was filled with ^{18}F 1441.228 MBq (38.952 mCi), volume 5.5 cc, and inserted into the cylindrical scattered phantom. The phantom was centered in the transaxial field of view, and also in the axial field of view using a CT scout scan. The total number of acquired frames was 45.



A



B

Figure 2 A) The scattered phantom during data acquisition B) Drawing of a scattered phantom and a hole for inserted 700 mm length of polyethylene line source.

Count rates and noise equivalent count rate (NECR). For each acquisition j, the system event rate can be calculated as the followings:

a. The total event rate $R_{TOT,j}$:

$$R_{TOT,j} = \frac{1}{T_{acq,j}} \sum_i C_{TOT,i,j}$$

b. The true event rate $R_{t,j}$:

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

c. The random event rate $R_{r,j}$:

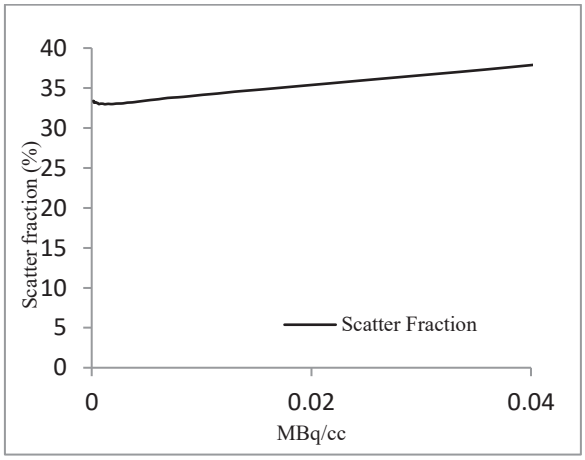
$$R_{r,j} = \frac{1}{T_{acq,j}} \sum_i C_{r,i,j}$$

d. and the scatter event rate $R_{s,j}$:

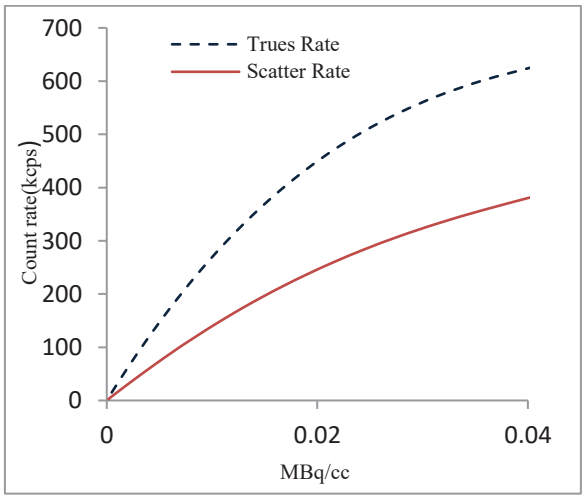
$$R_{s,j} = \frac{1}{T_{acq,j}} \sum_i \left(C_{r+s,i,j} - C_{r,i,j}\right)$$

The system scatter fraction can be determined from the equation

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



A



B

Figure 3 A) A graph plot between Scatter fraction and the average activity concentration (MBq/cc)

B) A graph plot between true and scatter counting rate (cps) and the average activity concentration (MBq/cc)

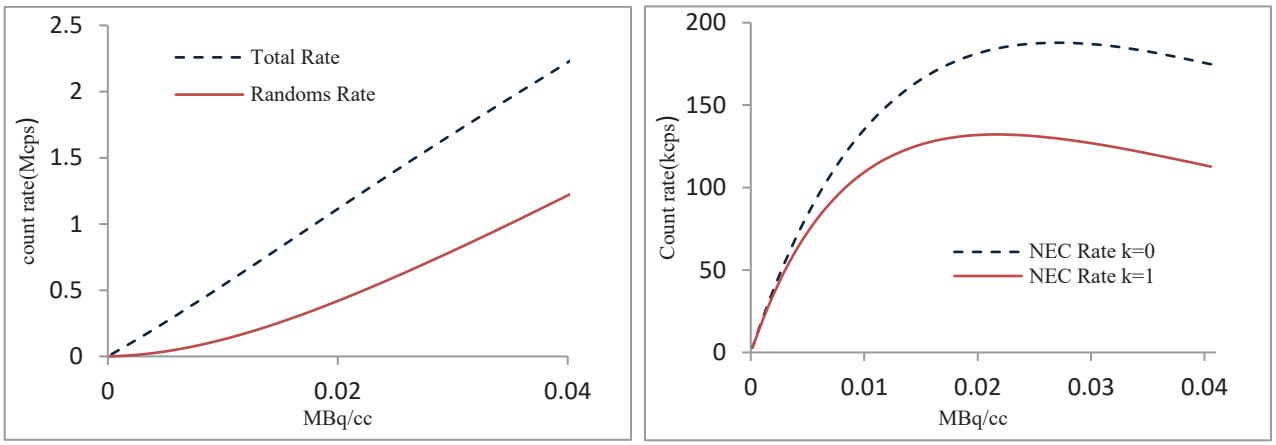


Figure 4 A) The graph plot between Total and Randoms Rate and average concentration (MBq/cc)
B) The graph plot between Noise Equivalent Count Rate and average concentration (MBq/cc)

Table 2: Calculated and measured peak true count rate, peak NECR, and scatter fraction

Quantity	Value	System Specification
Calculated Peak Trues Rate, cps	657	610@< 40 kBq/cc
Calculated Effective Activity Concentration	53.9 kBq/cc	
Measured Peak Trues Rate, cps	627	
Measured Effective Activity Concentration	40.6 kBq/cc	
Calculated Peak NEC Rate, cps	188	180@< 28 kBq/cc
Calculated Effective Activity Concentration	27.2 kBq/cc	
Measured Peak NEC Rate, cps	188	
Measured Effective Activity Concentration	278 kBq/cc	
Scatter fraction (%)	33.3	37

3. Sensitivity

The purpose of the tomographic sensitivity relates the count rate measured by the PET scanner to the amount of radioactivity within the FOV. The sensitivity measurement is therefore to determine the rate of detected true coincidence events per unit of radioactivity concentration for a standard source configuration.

Source preparation and acquisition protocol

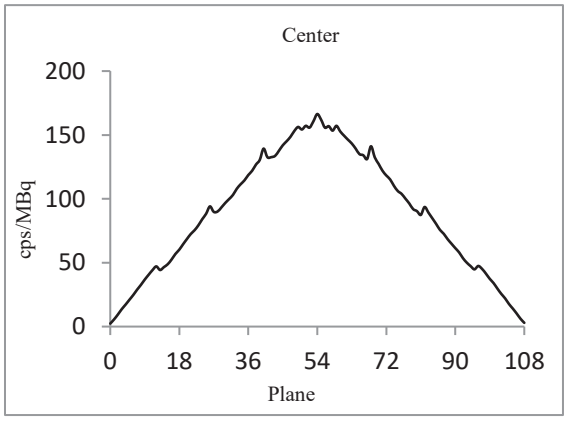
An innermost polyethylene tube at 700± 20 mm. length was filled with ^{18}F solution of 4. 421MBq (119 µCi). It was then inserted into the bore of the sensitivity phantom that consists of five concentric metal cylinders, and mounted on the scanning bed at the center of the transverse axial field of view. A series of acquisitions was then performed, each lasting 5 minutes (300 seconds). The aluminum sleeves were removed one at a time, and the phantom was scanned with 5, 4, 3, 2 and 1 cylinders. Each scan was also repeated at a distance of 10 cm from the center of the field of view.

Table 3: Sensitivity phantom of 5 sleeves at various inside and outside diameters. .

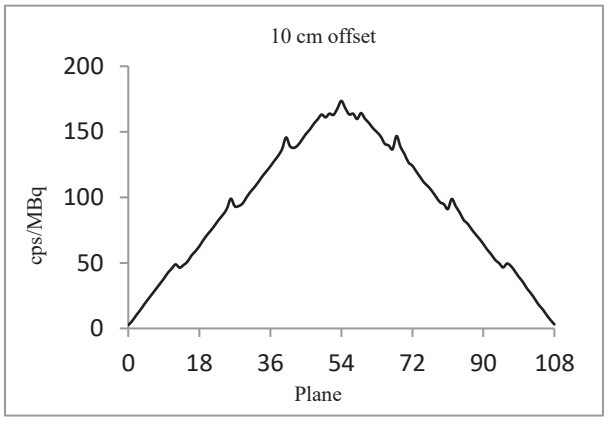
Sleeve No.	Inside Dia.(mm)	Outside Dia.(mm)	Length(mm)
1	3.9	6.4	700
2	7.0	9.5	700
3	10.2	12.7	700
4	13.4	15.9	700
5	16.6	19.1	700

Figure 5 Sensitivity phantom 5 layers of metallic cylinder inserted by polyethylene tube of 700± 20 mm filled with ^{18}F solution. Acquisitions of 5,4,3,2 and 1 layers at center and 10 offset of FOV

Results

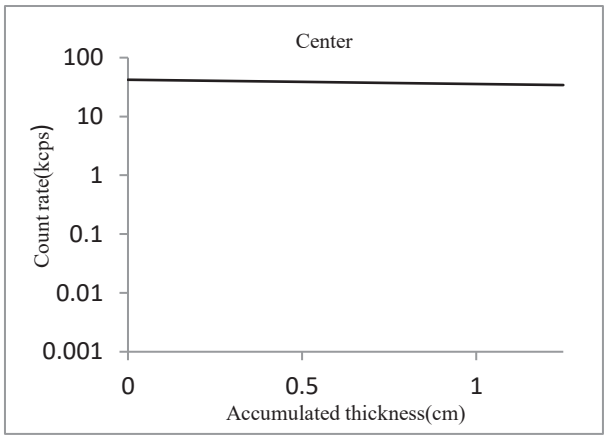


A

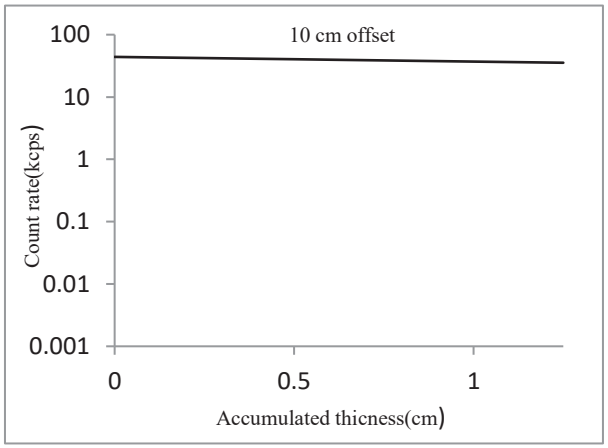


B

Figure 6 A) Axial sensitivity profile at center of FOV B) at 10 cm off center



A



B

Figure 7 A) Semi Log graphs of sensitivity at center of FOV B) Sensitivity at 10 cm off center (right)

Table 4: System sensitivity of ^{18}F at center FOV and 10cm from center FOV

	Center (0 cm) (%Diff)	Offset (10 cm) (%Diff)	System Specification
System Sensitivity (STOT) (cps/MBq)	9616.4 (5.72%)	10040.5 (3.6%)	10200
Detector Efficiency (%)	0.96	1.0	
Effective mu (cm^{-1})	0.167	0.173	
Lower Level Discriminators (keV)	435	435	
Upper Level Discriminators (kev)	650	650	
Source Length (cm)	70.40	70.40	
Initial Activity (MBq, mCi)	4.20, 0.11	3.34, 0.09	
Average Net Trues (Counts)	9744189.2	8031871.2	

4. Image quality

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 background variability 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.

Methods

Data has been acquired and analyzed according to the NEMA NU 2-2018 Standard Publication, Section 7 (Image Quality). The NEMA NU 2-2018 protocol states the concentration of the background activity concentration in the phantom should be 5.8 kBq/cc, corresponding to an injected dose of 460 MBq for a total body study; however, a lower injected activity may be used if recommended by the manufacturer.

Twelve 37 mm diameter circular ROIs were drawn throughout the background at a distance of 15 mm from the edge of the phantom. The percent contrast (Q_H) in hot sphere can be calculated from

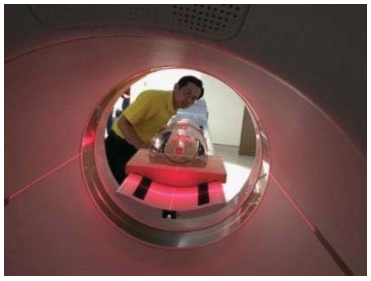


Figure 8 Setup for IEC/2001 body phantom and line source in scattered phantom for image quality acquisition

$$Q_H = \frac{(C_{hot} - C_{bg})/C_{bg}}{(a_{hot} - a_{bg})/a_{bg}} \times 100$$

where C_{hot} is the average counts in the ROI for each hot sphere, C_{bg} is the average counts of the twelve 37 mm in the background ROI, a_{hot} is the radioactivity concentration in the hot spheres and a_{bg} is the activity concentration in the background. The percent contrast in cold sphere (Q_C) can be calculated from

$$Q_C = \frac{(C_{bg} - C_{cold})}{C_{bg}} \times 100$$

where C_{cold} is the average of the counts in the ROI for each cold sphere. The percent background variability (N) can be calculated from

$$N = \left(SD/C_{bg}\right) \times 100$$

where SD is the standard deviation of the background ROI counts for sphere. To measure the residual error in scatter and attenuation corrections, the relative error (ΔClung) in percentage units for each slice can be calculated from

$$\Delta C_{lung} = \left(C_{lung} / C_{bg}\right) \times 100$$

where C_{lung} is the average counts in the ROI placed over the lung insert and ???

Acquisition Parameters

Emission Imaging Time	226 s
Axial step size	0 cm
Axial Imaging Distance Simulated	100 cm

Reconstruction Parameters

Correction Applied	NORM, DTIM, SCAT, DECAY, RAN
Reconstruction Method	PSF+TOF 3i21s, XYZ Gauss 5.00
Pixel size	4.07 mm
Imaging Matrix Size	200 x 200
Slice Thickness	3 mm

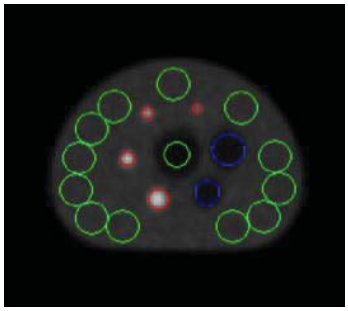


Figure 9 The torso phantom image and placement of ROIs for quantitative analysis

Result

Source-Background Ratio 4:1

Background Concentration	7.51 kBq/cc
Hot Sphere Concentration	32.40 kBq/cc 226 sec

Table 5: Image quality of IEC Phantom in terms of percent contrast of various sphere diameter and percent background variability

Sphere diameter (mm)	Contrast (%)	Background variability (%)
Hot 10	29.91	3.22
Hot 13	47.03	2.97
Hot 17	54.42	2.58
Hot 22	64.87	2.22
Cold 28	67.56	1.87
Cold 37	74.96	1.61
Average lung residual error (%)	14.28	

Source-Background Ratio 8:1

Background Concentration	5.8 kBq/cc
Hot Sphere Concentration	46.4 kBq/cc 226 sec

Table 6: Image quality of IEC Phantom in terms of percent contrast of various sphere diameter and percent background variability

Sphere diameter (mm)	Contrast (%)	Background variability (%)
Hot 10	45.87	3.14
Hot 13	62.87	2.80
Hot 17	68.54	2.39
Hot 22	77.54	2.07
Cold 28	68.28	1.75
Cold 37	75.88	1.44
Average lung residual error (%)	13.98	

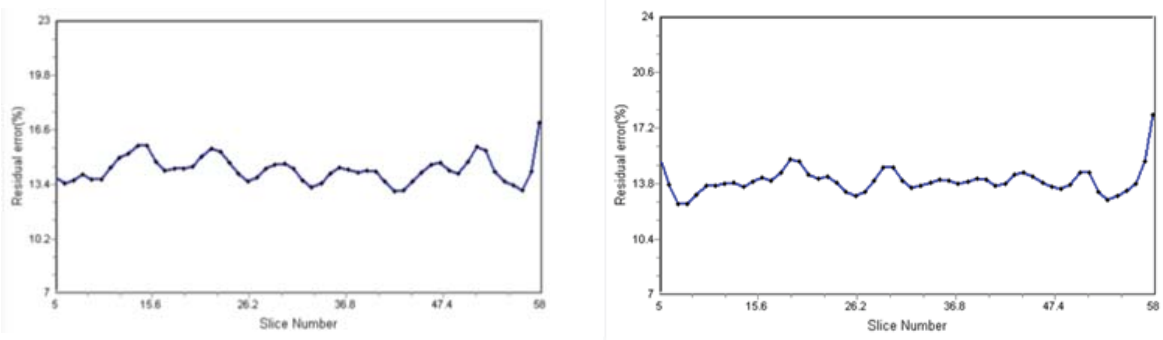


Figure 10 A) The slice number and lung residual error (average 14.28%) in Source-Background ratio 4:1
B) The slice number and lung residual error (average 13.98%) in Source-Background ratio 8:1

IV Discussion and Conclusion

The acceptance test of PET system is a series of measurement performed by the clinically qualified medical physicists in nuclear medicine to verify that the system conforms to vendor specification. The purposes of the tests are:

- To ensure that equipment performs to the manufacturer's specification prior of final payment for the equipment
- To establish the baseline performance of the equipment to which future quality tests will be compared
- To provide data that can give guidance in the determination of optimal operating parameters for routine use
- To ensure that the PET system meets regulatory requirement for radiation safety.

Before the acceptance test, all calibrations required as part of the installation and commissioning must be performed to ensure that the PET system is operating as expected. It should be verified that the daily QC had been passed and there are no problems apparent in the sonograms.

Acceptance test had been completed within three days of the test on spatial resolution, sensitivity, scatter fraction, count losses and randoms measurement and finally, the image quality. Time of flight resolution had been acquired to PET scanner operating in the TOF mode. Characterization of timing resolution is an important test that determines the capability of the system to estimate the difference in time of arrival of the two coincidence photons, and hence obtain information about the likely location of the annihilation along the LOR. The result of the test is in completed according to some errors in the correction files.

Tolerance levels:

Spatial resolution

Calculated FWHM should not exceed the specification given by the vendor. An appropriate tolerance criterion for FWHM is:

$$FWHM_{observed} < 1.05\ FWHM_{expected}$$

$$FWTM/FWHM = 1.82\text{-}2.0$$

Sensitivity

The system sensitivity should be equal to or greater than the vendor's specification.

$$Sensitivity_{measured} > 0.95\ Sensitivity_{expected}$$

Scatter fraction, count losses and random measurement

Calculated scatter fraction, peak NEC and peak radio-activity concentration for peak NEC should meet or exceed the vendor's specification.

$$SF_{observed} < 1.05\ SF_{expected}$$

The NEC curve, NEC peak value and peak radioactive concentration should be reported for future comparison.

Image quality

There are no manufacturer specifications; the reference value should be set. A 5% tolerance criterion with respect to the baseline established values for all image quality parameters based on 3 measurements is recommended.

Timing resolution

Measured values of timing resolution, R_T, should not exceed the specification given by the vendor. The reference values, tolerances and action levels should be set. An appropriate tolerance criterion for timing FWHM is: $R_{T\ measured} < 1.05\ R_{T\ expected}$. Corrective action: The timing resolution is expected to be a highly constant parameter. If the tolerance criteria are exceeded, the results should be checked and the testing procedure repeated to confirm the finding. If the result is still outside the tolerance criteria, a recalibration of the system should be performed by appropriate service personnel.

V. References

1. IAEA Human Health Series No.25. Roles and Responsibility and Education and Training Requirement for Clinical Medical Physicists IAEA 2013
2. NEMA Standards Publication. NEMA NU202018. Performance measurement for Positron Emission Tomographs (PET). National Electrical Manufacturer Association 2018: VA, USA
3. IAEA Human Health Series No.1. Quality Assurance for PET and PET/CT Systems IAEA 2009