ISSN: 2577-2996

PROGRESS IN MEDICAL SCIENCES, 2023
VOL 7, NO. 2, PAGE 1 – 9
DOI: doi.org/10.47363/PMS/2023(7)E161

RESEARCH ARTICLE

Open Access

Commissioning of PET/CT- Acceptance Testing and Quality Assurance of the PET Component

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ABSTRACT

This study focuses on the commissioning and validation of the PET component of PET/CT systems, Model uMI780 PET/CT system from United Imaging Healthcare, Shanghai. The aim is to explain the standardized procedures for acceptance testing and quality assurance (QA) to ensure optimal performance and reliability. The study outlines simplified PET quality control (QC) tests for evaluating spatial resolution, PET/CT alignment, sensitivity, and count rate performance, accuracy of corrections, image contrast, scatter/attenuation correction, and image uniformity. These tests are designed to be reproducible and comparable across different scanner platforms and manufacturers. The results are evaluated against the standards provided by the manufacturer and local regulatory guidelines, Atomic Energy Regulatory Board (AERB). The study emphasizes the importance of a thorough and ongoing QA program to maintain the accuracy and reliability of PET/CT imaging, which is essential for diagnostic and therapeutic applications in oncology, cardiology, and neurology.

ARTICLE HISTORY

Received March 02, 2023
Accepted March 09, 2023
Published March 30, 2023

KEYWORDS

PET/CT, Quality Assurance, Acceptance Testing, Spatial Resolution, Sensitivity, Scatter Fraction, Noise Equivalent Count Rate, Energy Resolution, Image Uniformity, Attenuation Correction, Scatter Correction, Quantitative Accuracy, Co-Registration, Normalization, uMI780, Shanghai United Imaging Healthcare

Introduction

Positron emission tomography/computed tomography (PET/CT) imaging plays an important role in the practice of medicine by its singular ability to visualize and accurately quantify radiotracer distribution. PET-CT provides both metabolic and anatomical information in a single scan. This is particularly useful in oncology for detecting, staging, and monitoring cancer, as it helps differentiate between benign and malignant lesions and assess the effectiveness of treatment.

Commissioning is the initial process of setting up a PET-CT system to ensure it meets the required performance standards. This involves acceptance testing, which verifies that the system meets the manufacturer's specifications and is functioning correctly upon installation. Baseline measurements are established to set reference values for various performance parameters, such as spatial resolution, sensitivity, and image quality. Calibration ensures the system is properly calibrated for accurate quantification of PET data.

A thorough and ongoing quality assurance (QA) program can help ensure the dual modality system provides optimal patient care and outcomes. The QA program should start with acceptance testing to ensure that the equipment and software packages meet the manufacturers' specifications, which were agreed upon before purchase and are specified in the procurement contract. QA is an ongoing process that involves regular checks and maintenance to ensure the PET-CT system continues to perform optimally. Key components include routine quality control (QC), which involves regular tests to monitor system performance, including daily, weekly, and monthly checks. Performance assessment involves periodic evaluations of system performance against established baseline measurements to detect any deviations or issues. Preventive maintenance includes scheduled maintenance activities to prevent system failures and prolong the lifespan of the equipment.

Implementing a rigorous QA program helps maintain the accuracy and reliability of PET-CT imaging, which is essential for diagnostic and therapeutic applications in oncology, cardiology, and neurology. The Atomic Energy Regulatory Board (AERB), Regulatory Authority of India, has specific protocols and guidelines for commissioning PET-CT facilities. To establish a PET-CT facility, one must comply with the Atomic Energy (Radiation Protection) Rules, 2004, and AERB Safety Codes and must obtain the necessary regulatory consent from AERB4. This includes quality assurance tests such as spatial resolution, sensitivity, scatter fraction, and noise equivalent count rate (NECR). The QA program is then maintained by periodic daily, weekly, quarterly, semi-annual, and annual monitoring to ensure compliance with regulatory bodies and to evaluate if the scanner performance has deviated from its initial assessment. This document provides commissioning procedures as per AERB requirements for quality Assurance (QA) of clinical PET/CTs, data acquisition, resolution recovery, or time-of-flight etc

Methods and Materials

After the acceptance testing phase, the PET-CT scanner was commissioned for operation. Task Group 126 (TG 126) was assigned the responsibility of developing acceptance testing and quality assurance (QA) procedures for PET/CT systems. The goal of TG 126 was to create standardized evaluation procedures for existing short-axis cylindrical-bore PET/CT systems, adhering to the principles of NEMA NU 2 standards [1,2].

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Acceptance Testing and QA Overview

This paper focuses on simplified PET quality Assurance (QA) tests for evaluating various parameters, including spatial resolution, PET/CT alignment, sensitivity, count rate performance, accuracy of corrections, image contrast, scatter/attenuation correction, and image uniformity [1-8]. The reports generated from these tests must compare the measured results to the standards set by the manufacturer and local regulatory guidelines. They should also summarize whether the tests passed or failed and recommend any necessary corrective actions. The following tests are specifically related to the PET component (Model: uMI780 PET CT. Manufacturer: -SHANGHAI UNITED IMAGING HEALTHCARE)

Spatial Resolution (FWHM & FWTM) in 3D Modes

Spatial resolution of a system defines its ability to depict two-point sources as distinct in a reconstructed image [7]. It is typically defined as the full-width at half-maximum (FWHM) of a point spread function (PSF) and is calculated from the line profile through a reconstructed image of a point source of radioactivity in air. The in-air measurements described below do not account for the effect of scatter or contrast-dependent convergence of iterative reconstruction on scanner resolution. It provides a standardized and reproducible measurement of reconstruction-dependent scanner spatial resolution over time, between scanner platforms, and across manufacturers. Specifically, by measuring the "Full Width at Tenth Maximum (FWTM)" of a reconstructed point source image, which indicates how spread out the signal is from a single point source, essentially giving an estimate of the scanner's spatial resolution. Capillary tube positioning device and 185–370 MBq/ml (5–10 mCi/ml) 18F-FDG are the materials used for these tests. Table 1 shows the test results.

Table 1: The Ratio between FWTM and FWHM should be in the Range 1.8–2.0 if the Manufacturer Reference Value is not Available for the Same

value is not available for the same.

Measurement Information

Axial radial and tangential resolution for 0.5AFOV

Source Location	(-2.55,7.79,-0.13)mm			(-1.25,95.43,1.16)mm			(-0.46,193.42,6.05)mm		
Direction	Tangential	Radial	Axial	Tangential	Radial	Axial	Tangential	Radial	Axial
FWHM (mm)	3.11	3.12	3.11	3.19	3.54	3.24	3.51	4.63	3.35
FWTM (mm)	5.85	6.12	6.23	5.82	6.42	6.34	6.38	8.01	6.43

Axial radial and tangential resolution for 0.125AFOV

Source Location	(-3.29,7.19,113.37)mm			(-1.96,94.79,114.65)mm			(-1.19,192.70,119.93)mm		
Direction	Tangential	Radial	Axial	Tangential	Radial	Axial	Tangential	Radial	Axial
FWHM (mm)	3.17	3.04	3.24	3.23	3.53	3.25	3.36	4.42	3.35
FWTM (mm)	6.08	6.32	6.27	5.99	6.40	6.42	6.49	7.97	6.39

Average resolution over both axial positions

Source Location	(0,10)mm			(0,100)mm			(0,200)mm		
Direction	Tangential	Radial	Axial	Tangential	Radial	Axial	Tangential	Radial	Axial
FWHM (mm)	3.14	3.08	3.17	3.21	3.54	3.24	3.43	4.53	3.35
FWTM (mm)	5.96	6.22	6.25	5.90	6.41	6.38	6.44	7.99	6.41

Sensitivity in 3D Modes

Sensitivity measures the number of counts (coincidence detection events) per second per unit activity within the PET scanner's field of view (FOV). The test is conducted with low activity levels to ensure dead time losses are below 5% and the random coincidence rate is less than 5% of the total prompt count rate. A simplified version of the NEMA NU 2 sensitivity test is used, which involves measuring the system sensitivity with the smallest diameter sleeve of the NEMA sensitivity phantom. This provides a standardized measure of the scanner's intrinsic sensitivity [6,7].

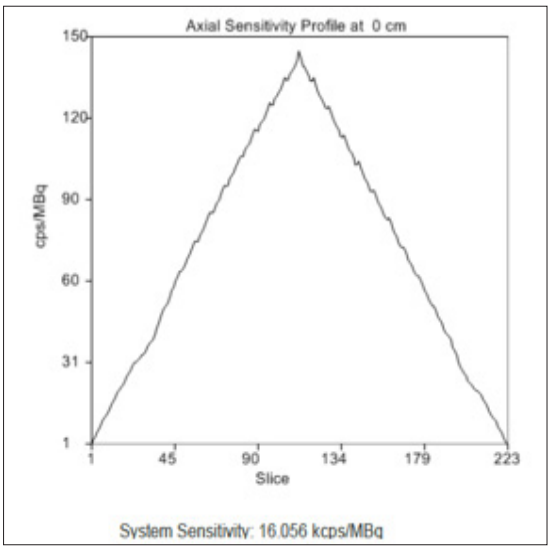


Figure 1: Sensitivity Profile

Table 2: Sensitivity Test Result

Description	Measured	Reference	Tolerance
Sensitivity in CPS/(Bq/ml) for 3 D Mode	16.056 cps/ kBq	>/=14 cps/kBq	≥ 0.95 of Refer-ence

Scatter Fraction in 3D Modes

The scatter fraction (SF) of a PET scanner is a crucial performance metric that quantifies the proportion of total detected photons that have undergone scatter before detection. SF is defined as the fraction of all detected coincidence events in which at least one of the two emitted annihilation photons is scattered prior to detection, provided that the number of random coincidence events is less than 1% of the true event rate. The NEMA NU-2 standard outlines a protocol for measuring scatter fraction using an axially-aligned line source, offset by 45 mm from the central axis, within a cylindrical polyethylene phantom. The measured scatter fraction is 36.56%, which is within the tolerance specified by the regulatory authority (≤ 1.05 of the reference value).

Noise Equivalent Count Rate (NECR) in 3D Modes

The Noise Equivalent Count Rate (NECR) is a crucial performance metric for evaluating PET (Positron Emission Tomography) scanners. It measures the effective signal-to-noise ratio by considering the true, scattered, and random events detected by the scanner. A higher NECR indicates better image quality and more efficient scanner performance. NECR is typically measured using a standardized phantom, such as the NEMA NU 2 scatter phantom, which simulates human tissue. This metric is essential for comparing different PET scanners and optimizing their performance for both clinical and research applications. The results are tabulated below.

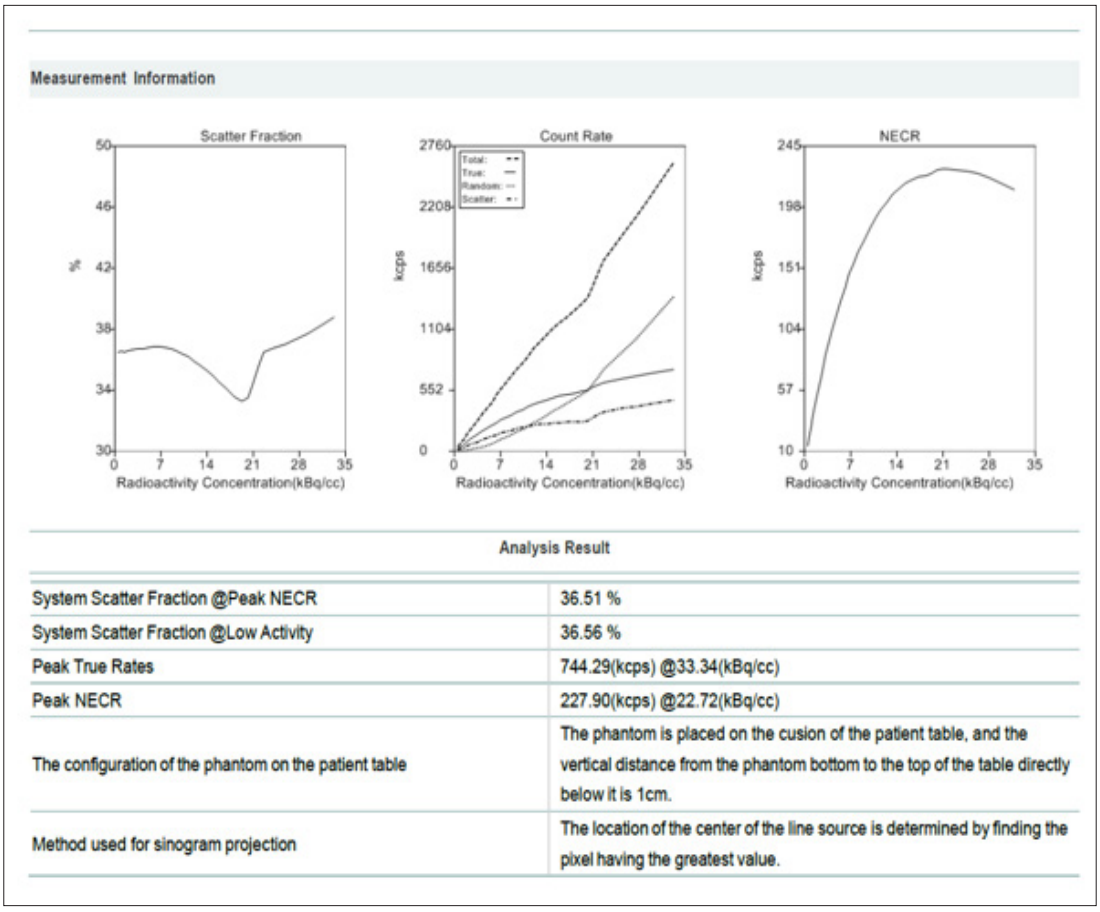


Figure 2: Scatter Fraction, Count Rate and NECR Measurements

Table 3: NECR Measurement Result

Description	3D Mode		
	Measured	Reference	Tolerance
Peak NECR (kcps) in 3 D Mode	227.9	>/=200	≥ 0.95 of Refer-ence
Activity (MBq) at which Peak NECR is achieved in 3D Mode	499.9	>/=400	≥ 0.95 of Refer-ence

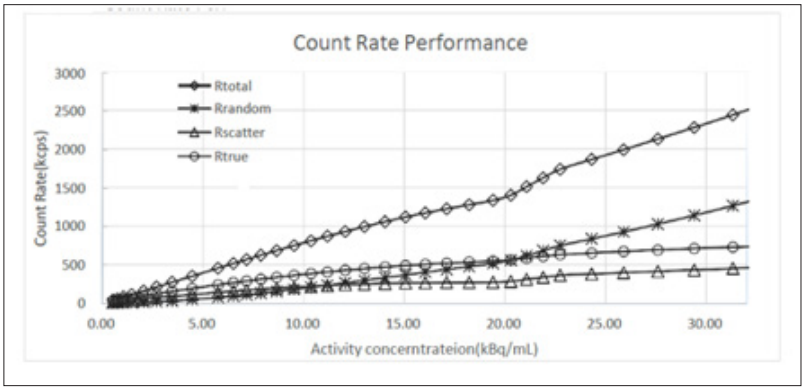


Figure 3: Count Rate Performance

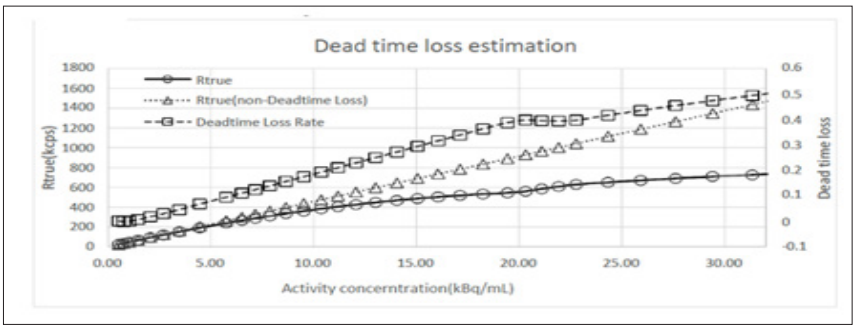


Figure 4: Dead Time Loss Estimation

Parameter List		
Scan Parameter	Scan Time(s)	411.0
Reconstruction Parameter	Matrix Size	192 * 192
	Total Slice	113
	Pixel Size(mm)	3.13 * 3.13
	Slice Thickness(mm)	2.68
	Recon Algorithm	3D iterative TOF PSF
	Correction	DECY\ATTN\SCAT\DTIM\RAN\NORM\DCAL

Energy resolution measures a PET scanner's ability to accurately distinguish between different energy levels of detected photons. This is crucial for improving image quality and reducing noise. Good energy resolution helps differentiate true coincidence events from scattered ones, enhancing overall image clarity. Energy resolution is typically expressed as a percentage of the full width at half maximum (FWHM) of the photo peak, with a lower percentage indicating better energy resolution.

Energy resolution test

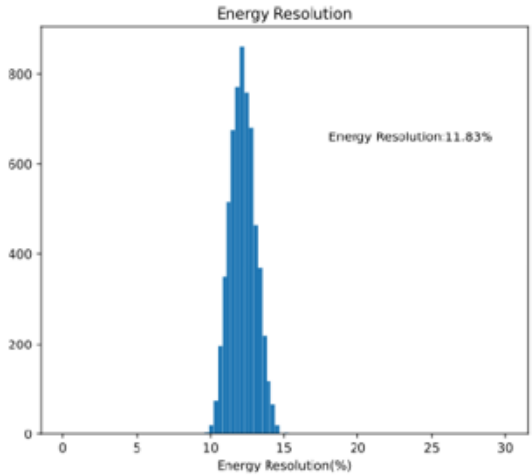
Energy resolution	
Test system	300077
Test methods:	Alignment line source with system axial center and acquire single data to analysis energy spectrum.
Data analysis	
Test results	11.83%

Figure 5: Energy Resolution Test

Image Quality, Accuracy of Attenuation & Scatter Correction and Accuracy of Radioactivity Quantitation

High-quality images are essential for accurate diagnosis and treatment planning. Factors such as the type of scintillation crystal, photodetector quality, and data processing algorithms play crucial roles in determining image quality. Attenuation and scatter correction are vital for accurate PET imaging. Attenuation correction compensates for the loss of photon energy as it passes through the body, while scatter correction addresses the deflection of photons. Techniques for these corrections include CT-based methods, MR-based methods, and advanced algorithms like deep learning [5].

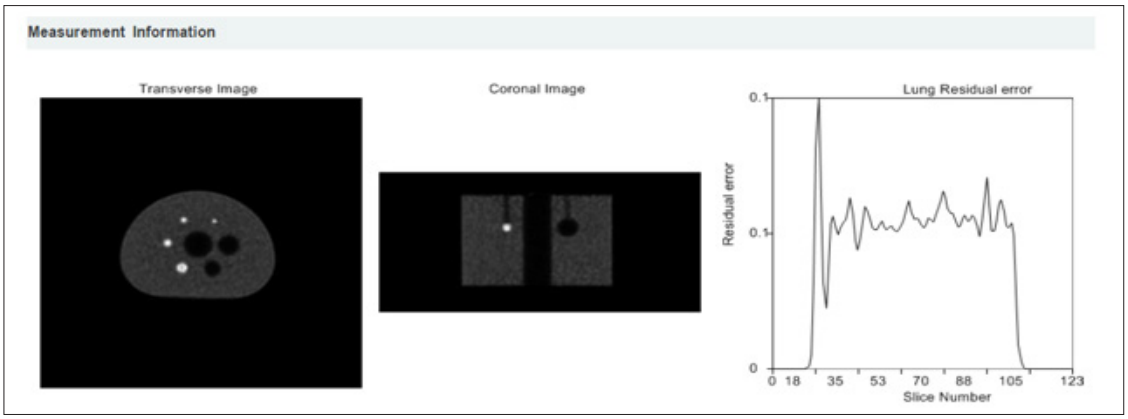
Quantitative accuracy in PET imaging is crucial for measuring the concentration of radiotracers within the body. This accuracy is influenced by factors such as scanner calibration, attenuation and scatter correction, and the reconstruction algorithms used. Standardized uptake values (SUVs) are commonly used to quantify radiotracer uptake, and achieving high accuracy in these measurements is essential for reliable diagnosis and treatment monitoring. The measured parameters are within the tolerance limits.

Measurement Result

Diameter(mm)	10.0	13.0	17.0	22.0	28.0	37.0
Hot Contrast(%)	49.9	64.2	72.0	79.6		
Cold Contrast(%)					81.5	85.3
Background Variability(%)	4.6	3.8	3.0	2.4	2.0	1.6
Mean Lung Relative Error(%)	4.2					

Parameter List

Scan Parameter	Scan Time(s)	405.0
	Activity Ratio	4 : 1
	Axial FOV(mm)	302.84
	Axial Step Size(mm)	227.13
	Background Concentration(kBq/cc)	6.13
Reconstruction Parameter	Matrix Size	256 * 256
	Total Slice	124
	Pixel Size(mm)	2.34 * 2.34
	Slice Thickness(mm)	2.44
	Recon Algorithm	3D OSEM



Injection Dose	3.85 mCi
Measurement Result	Pass

Measurement Item

SUV	Reference Range	Current Value	Measurement Result
Average	0.95-1.05	1.002	Pass

Coincidence Timing Resolution for TOF Positron Emission Tomography

The coincidence timing resolution (CTR) for Time-of-Flight (TOF) Positron Emission Tomography (PET) is a crucial parameter that determines the precision with which the scanner can localize the annihilation event along the line of response. This precision significantly enhances image quality by improving the signal-to-noise ratio and lesion detectability. Better CTR values lead to more accurate localization of annihilation events, which in turn improves image clarity and reduces noise. This is particularly beneficial for imaging larger patients, where the benefits of TOF are more pronounced. The measured value is well within the tolerance limit [8].

TOF resolution and Energy resolution test

Time of Flight (TOF) resolution test

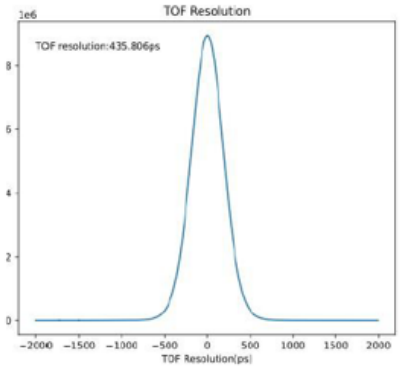
TOF resolution	
Test system	300077
Test methods:	Align line source with system axial center and acquire coincidence data after system calibration.
Data analysis	
Test results	435.806ps

Figure 6: TOF Resolution Test

Non-Uniformity of the Reconstructed Image

Non-uniformity in reconstructed PET images can result from several factors, affecting the accuracy and quality of the images. These factors include attenuation correction errors, scatter correction errors, detector sensitivity variations, and reconstruction algorithms. The results are tabulated below.

Table 4: Non-Uniformity Test Result

Description	Measured	Reference	Tolerance
Mean non-uniformity (% NU)	3.0%, 0.8%	</=10%	≤ 1.05 of Refer-ence

Normalization

Normalization in PET imaging is essential for ensuring uniformity and accuracy in reconstructed images. This process corrects for variations in detector sensitivity and other system inconsistencies, addressing non-uniformities in the detector response. By standardizing the response across all detectors, normalization ensures that the reconstructed images accurately reflect the true distribution of the radiotracer. This enhancement improves the accuracy of quantitative measurements, such as Standardized Uptake Values (SUVs).

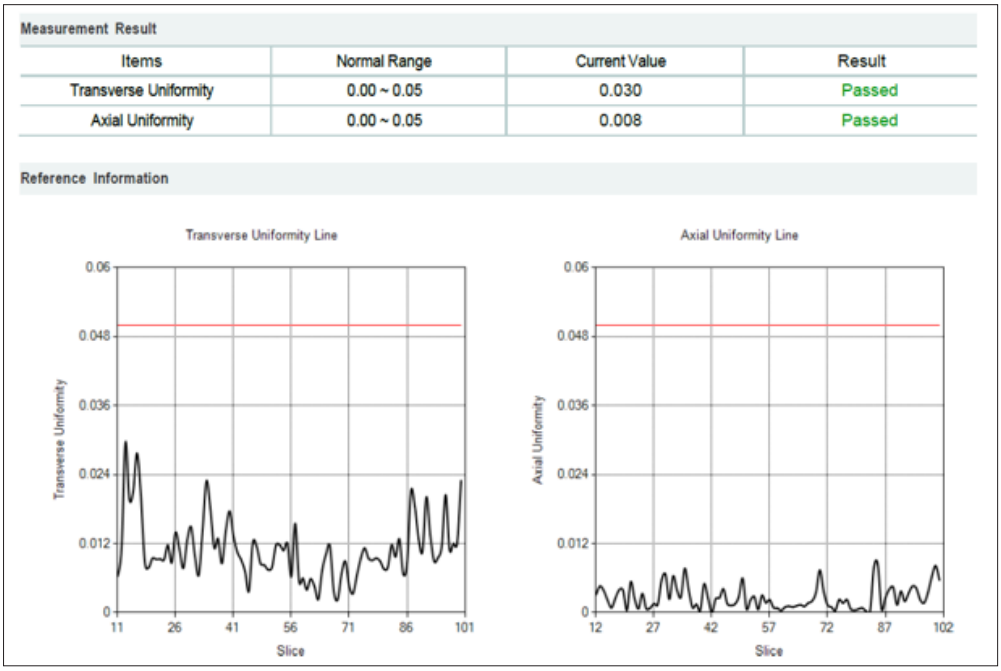


Figure 7: Uniformity Profiles

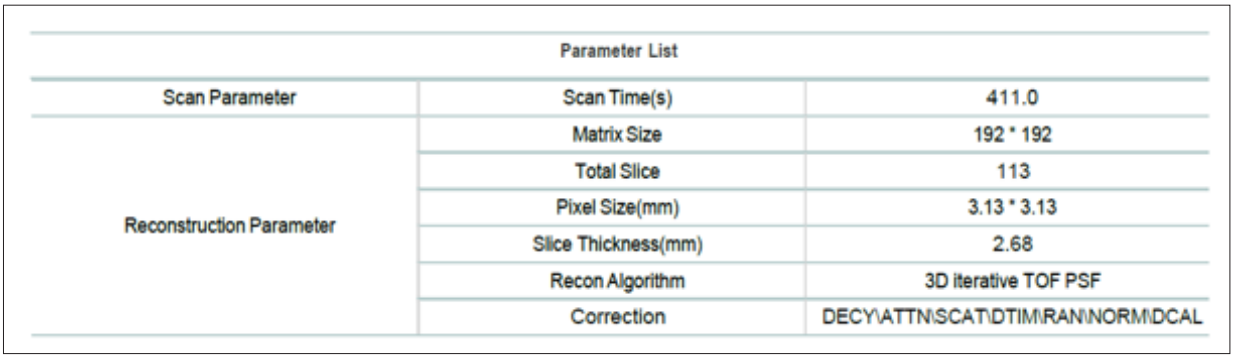


Table 5: Uniformity Measurement Result

Description	Observation	Tolerance
Whether uniformity observed in the normalization sinogram	Yes	Observance of Uniformity in the sinogram

Accuracy of PET/CT Image Registration

Maintaining proper co-registration of PET and CT images is essential for accurate attenuation correction and localization [7,8]. To assess the co-registration of PET and CT images, two additional steps are required beyond the spatial resolution test: 1) adding CT contrast media to the radioactivity and 2) analyzing the PET and CT images to identify any mis-registration. Create axial, coronal, and sagittal fused PET and CT images of the point sources. For the six point sources (three per axial position), measure the distance between the center of the point source on the PET image and the centre of the point source on the CT image. This analysis can be performed either through visual inspection or by measuring the distance between corresponding PET and CT centroids. The same method should be used in follow-up testing. During baseline testing, record the distance values for future comparisons. In follow-up testing, compare these distances to the baseline values to ensure proper co-registration is maintained. Results are tabulated below

Table 6: Accuracy of PET/CT Image Registration Measurement

Description	Measured	Reference	Tolerance
Registration Value for 512x512 matrix	-0.38mm	-1.5</= X</=1.5	±1 pixel (or ±1 mm, whichever is smaller)
	-0.55mm	-1.5</= Y</=1.5	

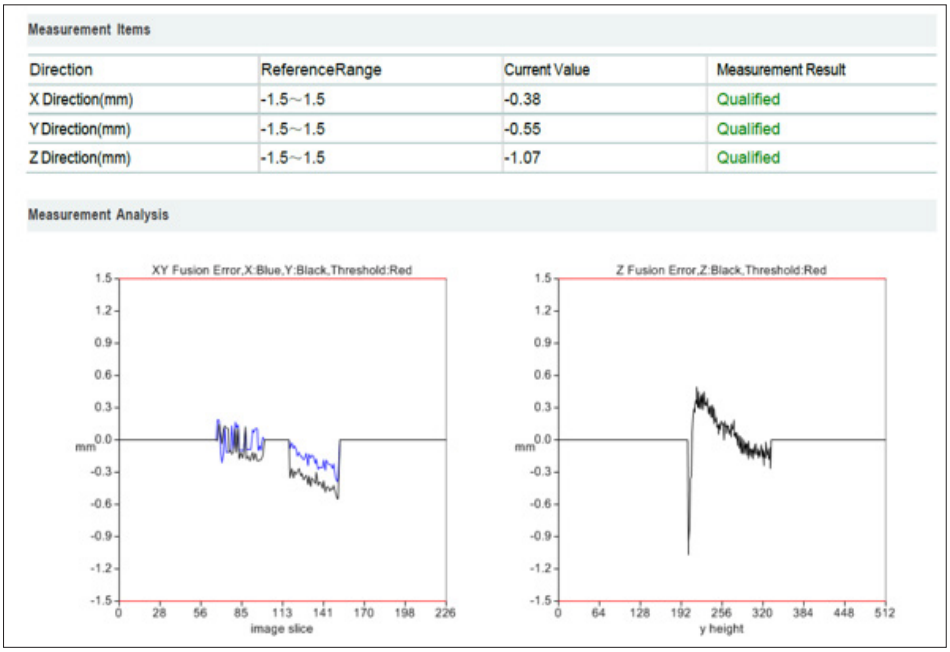


Figure 8: Measurement Analysis

Results

We conducted ten performance evaluations and these evaluations allow clinical physicists to monitor each PET/CT system by comparing periodic follow-up measurements to baseline measurements acquired during acceptance testing. Here is a detailed summary of the evaluations:

For spatial resolution, we used a capillary tube positioning device and 18F-FDG. The pass/fail criteria were based on the Full Width at Half Maximum (FWHM) and Full Width at Tenth Maximum (FWTM) being within specified limits. Sensitivity was evaluated using the NEMA sensitivity phantom and 18F-FDG. The sensitivity values needed to be within the tolerance specified by the manufacturer to pass. The scatter fraction (SF) was measured using a cylindrical polyethylene phantom and a line source. The SF had to be within the specified tolerance (≤ 1.05 of the reference value). For the Noise Equivalent Count Rate (NECR), we used the NEMA NU 2 scatter phantom. The NECR values needed to be within the specified limits. Energy resolution was assessed using a standardized energy source. The energy resolution (FWHM) percentage had to be within specified limits. Image uniformity was evaluated using a uniform phantom. The uniformity values needed to be within specified limits. Attenuation and scatter correction were tested using CT contrast media and standardized phantoms. The corrected images had to show minimal artifacts and accurate attenuation values. Quantitative accuracy was measured using phantoms with known radiotracer concentrations. The Standardized Uptake Values (SUVs) needed to be within specified accuracy limits. Co-registration of PET and CT images was assessed using CT contrast media and point sources. The distance between PET and CT centroids had to be within specified limits. Normalization was evaluated using a standardized normalization phantom. The normalized response across all detectors needed to be within specified limits.

For each evaluation, we provided a summary of materials necessary, and the recommended pass/fail criteria. This comprehensive approach ensures that the PET/CT system maintains optimal performance and delivers accurate and reliable imaging results.

Conclusion

Our report offers a comprehensive guideline for the periodic evaluation of clinical PET/CT systems, specifically focusing on the PET component. By simplifying the procedures and requirements outlined by other agencies, we aim to make the evaluation process more accessible and standardized. This approach not only streamlines the quality assurance process but also ensures that performance comparisons can be made across different vendors, models, and institutions.

The standardized evaluation procedures we have developed allow for consistent monitoring of PET/CT systems, ensuring that they maintain optimal performance over time. Furthermore, our guidelines facilitate the comparison of performance metrics across different PET/CT systems. This is particularly important for institutions that may use multiple scanner models or those looking to upgrade their equipment. By providing a clear framework for performance evaluation, our report helps ensure that all systems meet the necessary standards for accurate and reliable imaging.

In addition to aiding in performance comparisons, our guidelines also support regulatory compliance. By aligning with the standards set by manufacturers and local regulatory bodies, our procedures help institutions meet the required performance criteria and maintain the safety and efficacy of their imaging systems. Overall, our report serves as a valuable resource for clinical physicists and healthcare institutions, promoting the consistent and accurate evaluation of PET/CT systems. By simplifying the evaluation process and providing clear guidelines, we contribute to the ongoing improvement of imaging quality and patient care in the field of medical imaging.

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