J of Nuclear Medicine Technology, first published online February 4, 2016 as doi:10.2967/jnmt.115.168492

Acceptance test of Gemini TF 16 PET scanner based on NEMA NU-2 and performance characteristic assessment for eighteen months in a high volume department

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Running title:

Performance assessment of PET/CT over 18 month duration

Abstract:

We perform on an average 30 PET/CT scans daily. A new PET/CT scanner Gemini TF 16 installed in our department in the month of September 2012 has a PET component capable of Time of Flight imaging by using lutetium-yttrium oxyorthosilicate crystals and operates in a 3-dimensional mode. Our aim was to evaluate the system before acceptance and observe the system performance for eighteen month post installation for its consistency during high volume work. **Methods:** Acceptance tests for a PET/CT scanner are a set of quality control tests performed after installation to verify various parameters specified by the manufacturer before utilizing the scanner for clinical use. We have performed the NEMA NU-2 2007 quality control test of this system and analyzed the results of continuous evaluation of gain calibration, timing resolution and energy resolution for a subsequent period of eighteen months. **Results:** Gemini TF 16 whole-body PET/CT scanner passed the entire NEMA NU-2 acceptance testing and there were not many fluctuations observed in energy and timing resolutions during this period of observation. **Conclusions:** Our study shows that Gemini TF 16 whole-body PET/CT scanner is able to perform excellently for the study period of eighteen months despite high volume work.

Key Words: PET; PET/CT; Time-Of-Flight; fully 3-dimensional whole-body imaging; LSO; LYSO; NEMA QC

Introduction:

The performance assessment of any newly installed medical device is important to ensure the quality of clinical outcome. Likewise, the daily quality control tests assure the consistency and reproducibility of the equipment. The final diagnostic outcome of a medical imaging device largely depends on the quality of image produced by the medical imaging system. [1] So reliability of images produced by the system should initially be judged in a non-clinical condition by means of a battery of tests called quality assurance tests. Various agencies like NEMA, IAEA and Medical Physicist Association of various countries prescribe the guidelines for performance assessment testing of medical equipment. NEMA publishes guidelines for quality assurance of various medical equipments from time to time. NEMA NU-2 is the series of guidelines published by NEMA for the performance assessment of PET scanners. [2-3] There are various quality assurance tests as prescribed by these agencies to check the performance of medical imaging equipment during its life cycle. Acceptance testing of equipment is performed after the installation and after any major repair to accept the system for medical use. Periodic quality control tests are performed at regular time intervals to assure the quality of equipment during clinical use. We installed a Gemini TF 16 PET/CT (Philips Medical Systems) scanner in the Department of nuclear medicine and molecular imaging, Tata memorial Hospital, Mumbai, India in September 2012. This equipment is a high performance PET System with 16-slice Brilliance CT. This system is capable of acquiring data only in three-dimensional mode as septa rings are not available between the PET detector rings. [4-5]

This system acquires and stores data in list mode and is capable of Time of Flight (TOF) Imaging. Lutetium yttrium oxyorthosilicate (LYSO) crystals are the scintillation detectors used in this system. LYSO crystal has an almost similar characteristic as lutetium oxyorthosilicate (LSO) and shows an excellent timing resolution with dead time of 470 ps. In LYSO crystal, lutetium and yttrium are present in a 9:1 ratio. LYSO Crystal contains intrinsic radioactive Lu-177 in trace amount, which is a positron emitter and contributes to significant amount of intrinsic random coincidence at low count rate. [6] We performed all prescribed performance acceptance test in NEMA NU-2 as acceptance testing and got the system licensed by competent authority i.e., Atomic Energy Regulatory Board (AERB), India before putting the system for clinical use. As part of our quality control program daily quality control tests are performed on the system every morning. System is allowed for clinical use only if all the quality control parameters are found to be within the limits prescribed. In our study we also evaluated the system performance for eighteen months on the basis of daily quality control report.

Material and Methods:

A. PET scanner descriptions: The PET system of Gemini TF 16 consists of 28336 LYSO crystal elements arranged on 28 flat modules in an array of 23 X 44 per module. PET modules are arranged in a complete ring topology. There are 44 detector rings consisting of 644 crystals per ring. Size of each detector is 4 X 4 X 22 mm^3. The diameter of the ring is 906 mm and axial length is 180 mm. Patient bore has a diameter of 716 mm with active transverse and axial field of view (FOV) of 675 mm and 180 mm, respectively. PET and CT acquisitions are performed in sequential mode one after the other and PET acquisition is performed in step and shoot mode keeping 50% overlap for axial FOV. The system works in TOF mode and acquires data in list mode. [7-8] Reconstruction of acquired data is performed by highly advanced iterative algorithm and CT attenuation correction map is used to perform attenuation correction of PET images.

B. Phantom descriptions:

B.1. PET Daily quality control phantom: This phantom is used for timing calibration and daily PET quality control.

B.2. SUV phantom: This phantom is used for standardized uptake value (SUV) calibration.

B.3. PET-CT alignment phantom: This phantom is used for alignment of CT image with PET image to achieve proper co registration of PET/CT fusion image.

B.4. Spatial resolution phantom: This is a triangular shape phantom made up of plastic sheet and designed to enable placement of point source at various positions in the FOV as specified by NEMA.

B.5. Scatter phantom: This is a solid cylindrical phantom used to measure Scatter, random, dead time, count loss and NECR. The outer dimension of cylinder is 203 mm diameter and 700 $\pm$ 3 mm length. There is a 6.4 mm hole across the length at 45 mm offset, which is used to place line source in the phantom. Inner and outer diameters and length of line source are 3.2mm, 5mm and 800mm respectively.[9]

B.6. Sensitivity phantom: Five internally stacked concentric aluminum tubes – all 700 mm in length. Inside and outside diameters of 1st Tube are 3.9 mm and 6.4 mm; 2nd Tube, 7.0 mm and 9.5 mm; 3rd Tube, 10.2 mm and 12.7 mm; 4th Tube, 13.4 mm and 15.9 mm; 5th Tube, 16.6 mm and 19.1 mm respectively. The Innermost fillable polyethylene tube has an inside diameter of 1 mm and outside diameter of 3 mm.[10]

B.7. Image quality body phantom: This is a NU-2 NEMA Standard image quality PET phantom. Interior depth of phantom is 180 mm. there are six spherical inserts with inner diameter of 10mm, 13mm, 17mm, 22mm, 28mm and 37mm respectively. Distance from sphere plane to inside wall is 70 mm. Volume of empty D shaped cylinder is 9.7 L. There is cylindrical lung insert filled with polystyrene balls in the middle of the phantom having outer diameter of 51 mm and length 180mm. [11]

C. Quality Control Tests: Various acceptance tests were performed and results were compared with the reference value provided by manufacturer before accepting the system for clinical use. Non NEMA tests were performed by using manufacturer's test protocol. And NEMA performance measurements were performed using the NEMA NU2 2007 procedures for spatial resolution, scatter fraction, sensitivity, count rate loss and random coincidence, noise equivalent count rate (NECR) and image quality.

Normalization and SUV calibration tests were performed after successful installation of Gemini TF PET/CT system followed by SUV verification test. After SUV verification test all other tests were performed.

C.1. PET-CT co-registration: PET-CT co-registration was performed by using ^{22}Na tablet source on the PET/CT co-registration phantom. There are 6 tablet sources placed on the specific sites on the co-registration phantom. Serial CT and PET image are acquired and specific software is used to find out the error in co-registration in X, Y, and Z coordinate.

C.2. Energy Calibrations:

Procedure: Using a ^{22}Na point source, energy spectrum is generated for each crystal, peak is calculated individually and the peak of all the crystals is normalized to a common value with energy correction tables generated for individual crystal element. The system energy resolution is calculated by averaging overall crystals after correction at 511 keV. The default energy window is set at 440–665 keV in this scanner.

C.3. Timing Calibrations: This scanner is designed to work in time-of-flight mode and providing accurate timing information for each annihilation event is mandatory to work in this mode. Timing calibration is performed by using ^{22}Na point source.

C.4. Energy Resolution: Energy resolution is the ability of an imaging system to distinguish between two energy peaks closely associated to each other. Energy resolution of PET system is represented by the FWHM and FWTM of the energy spectrum.

C.5. Spatial Resolution: Spatial resolution of PET system varies across the scan field of view in axial and transaxial direction. So as per NEMA NU-2 2007 spatial resolution is calculated in axial and transaxial directions at six points. [2-3]

C.6. Sensitivity: The sensitivity of a PET scanner is the rate of detection of true coincidence events per unit of radioactivity concentration. Sensitivity value obtained for scanners should be free of confounding effects such as attenuation, scattering and count rate distortions in order to compare the scanners for sensitivity. [2-3]

C.7. Scatter fraction, count losses and random measurements: Scatters and random are phenomenon in PET imaging which introduces invalid events, hence affecting both image quality and quantitative accuracy of the system.

C.7.a. Scatter Fraction: The scatter fraction is defined as the ratio of scatter coincidences count to the total coincidence count when random event coincidences are negligible. Random coincidence is considered as being negligible at low count rates. PET system consisting of scintillation crystal with intrinsic radioactivity (like LSO, LYSO) has a substantially high intrinsic random coincidence which can be corrected by delayed imaging technique.[3, 11, 12]

C.7.b. Random: Random counts are the counts that emerge from two independent events and are then detected in the same coincidence window. There are manly two types of random events (intrinsic and extrinsic) that are detected in the LYSO crystal based detector. Intrinsic random events occur due to intrinsic radioactivity present in the detector and extrinsic random events occur due to increasing count rate. Since random introduces unwanted counts in the image hence it is corrected to achieve better image quality.

C.7.c. Count Rate performance: Count rate performance is the ability of a PET scanner to measure high radioactivity sources as well as low radioactivity sources accurately. Clinical studies are frequently performed with levels of radioactivity for which count losses due to system dead time are considerable, while the rate of random coincidences increases with the total single event count rate. So the measurement of count loss and random at various levels of activity is of utmost importance.

C.7.d. The Noise Equivalent Count Rate (NECR): NECR is one of the important parameter which has to be considered before performing any test that requires a high amount of radioisotope to be injected. The NECR of a PET scanner is the count rate performance of the scanner as a function of the radioactivity concentration. The peak NECR values and the corresponding radioactivity concentration are used to determine the optimal radioactivity to be administered to patients in a specific study. NECR is calculated by the NEMA Nu-2 2007 formula.[3]

C.8. Accuracy corrections for count losses and random: The data acquired to calculate scatter fraction was also used to measure the net error in count rate after correction for dead time loss and random. 65cm scatter phantom data was reconstructed and used to calculate accuracy for count loss and random by standard NEMA NU2-2007 parameters.

C.9. Image quality and accuracy of attenuation, and scatter correction: This test is performed by using NEMA image quality phantom and scatter phantom. Imaging of NEMA image quality phantom simulates whole body imaging with hot and cold lesions. NEMA NU-2 2007 formula was used to calculate image contrast, variability and accuracy of attenuation and scatter correction. NEMA Image Quality test was performed twice during our study period i.e. during acceptance testing and after 12 months.

D. Eighteen month observation: Our department works from morning 8:00am to 7:00 pm everyday to perform around 30 whole body PET/CT procedures every day on one PET/CT scanner. Hence newly installed Gemini TF PET system was observed for eighteen month to access the stability of system. The key parameters like photomultiplier tube (PMT) gain calibration error, energy resolution and timing resolution were obtained once in a week from daily quality control and analyzed. Daily QC parameters were compared with that of parameters obtained at the time of acceptance testing. Mean and standard deviation (SD) were also determined for the parameters obtained over the period of 18 month. The graph of weekly data obtained for eighteen months is plotted. Temperature in PET/CT system room was also monitored during the study. PET/CT procedure performed on the system during the observation period was also noted. NEMA Image quality test was repeated after 12 month of installation and data were compared with that of Acceptance test performed at the time of installation. Raw data of image quality tests were also reconstructed by using iteration reconstruction technique. The SUV value of hot bulbs and background was obtained and both the sets of SUV were compared for respective hot bulb and background.

Results:

Gemini TF 16 PET/CT was installed successfully and passed SUV verification test. Accuracy of PET/CT image registration was performed by using 512 X 512 matrix and the result was found to be well within the permissible limit.The system coincidence timing resolution was measured to be 542.3ps and energy resolution found to be 11.2%. The tangential, radial and axial resolutions near the center are 4.84 mm, 5.06mm and 4.73mm respectively and at 10 cm off center are 4.89mm 5.03mm and 5.19 mm respectively. The absolute sensitivity of this scanner measured with a 70-cm-long line source by using NEMA sensitivity Phantom is 7901 cps/MBq, whereas scatter fraction is 24.712% measured with a 70-cm-long line source placed in a 20-cm-diameter NEMA Scatter phantom. For the same line source cylinder, the peak NECR is measured to be 112.499 Kcps at an activity concentration of 0.015 MBq/ml. Peak coincidence count rate was found to be 263.975kcps at 0.01652 MBq/ml activity concentrations. 50% dead time loss in coincidence count occurs at 0.028 MBq/ml. Image quality test performed by NEMA Image Quality phantom with scatter phantom and result was within the specified limit. Comparison of NEMA Image Quality test performed at the time of acceptance and after 12 months of installation does not show much difference [Table 1]. The SUV comparison of NEMA image quality phantom for hot bulbs and background at the time of acceptance test and post 12 month tests shows similar result [Table 2]. Total number of PET CT performed on this system during this period was 8473 with the daily average of 28±4 studies daily. Eighteen month observation of the PET/CT scanner did not show much fluctuation in the observed daily quality control parameters and results are summarized in the table3. The total iteration required for PMT gain calibration over the period of 18 months is shown in graph [Figure 1A]. The average error observed in PMT gain calibration over the period of 18 months is shown in graph [Figure 1B]. The average energy resolution observed over the period of 18 months is shown in graph [Figure 2]. The average timing resolution observed over the period of 18 months along with the manufacturers passing criterion is shown in graph [Figure

3]. On all occasions the timing resolution remained within the pass limit, except on three occasions it passed with notice. The average percentage error in gain calibration found to be 0.238±0.026%. The average energy resolution was 11.664± 0.147%, the average timing resolution was 547.045± 1.772ps in comparison with acceptance testing energy resolution of 11.2% and timing resolution 542.3ps respectively. PET/CT system room temperature was also monitored during the period of our study but not stored properly. On three occasions temperature increased beyond 30° Celsius with maximum recorded temperature of 36° Celsius. The maximum temperature fluctuation in a day was around 5-6° Celsius.

Discussion:

PET/CT scanner has been established as an important diagnostic modality in oncology imaging for staging restaging and follow-up studies. The image resolution (to detect smallest lesion) and imaging speed (to finish the scan faster) are two important limiting factors of a PET scanner mainly determined by the characteristics of crystals in identifying the event emerging from inside the patient's body. [7] With the advent of Lutetium oxyorthosilicate (LSO) or cerium-doped lutetium yttrium orthosilicate (LYSO), Time of Flight (ToF) technology was first time utilized in clinical PET by Philips Medical System in their Gemini TF PET/CT scanner developed in the year 2005. These crystals have excellent timing resolution of approximately 49 nanoseconds which enabled their use in ToF imaging. [12-14]

LSO and LYSO based PET detectors contain natural radioactivity of lutetium which provides intrinsic random during the acquisition. [3, 15, 16] Because of presence of intrinsic activity in the detector even at very low count rates, contribution of random to the true counts cannot be achieved as less than 1% of true count which effects the NEMA test procedure, Thus performing NEMA NU2 2001 test in these PET scanners is not possible. Modifications have been suggested by Erdi YE, et al and Watson CC, et al to account for the intrinsic random by counting in delayed window. [15, 16] NEMA NU2 2007 has incorporated the change suggested by Watson CC, et al and delayed window counting was introduced to account for intrinsic random contribution in true counts. NEMA NU-2 2007 suggests the subtraction of delayed count from prompt count to correct for intrinsic random for the PET system with LSO or LYSO crystal.[3] Philips Gemini TF also uses LYSO crystal as scintillation detector which contains intrinsic radioactivity that contributes to intrinsic random counts during imaging. Use of LYSO crystal in the scanner allows it to perform Time of Flight imaging with excellent timing resolution. The less dead time, high stopping power and high photo yield of the LYSO crystal leads to high sensitivity and resolution. [5] Scatter is one of the components responsible for image degradation in PET imaging. The lower level energy discriminator setting is an important parameter to minimize scatter from the image.[17, 18] The use of Anger-logic detector with a uniform light spread coupled with LYSO crystal in the detector system of Gemini PET has improved the system energy and timing resolutions, which allows the lower threshold of the energy window to be set as high as 440 keV thereby enabling an excellent energy resolution (FWHM = 11%) of photo peak and leads to reduced scatter correction during image acquisition.[7, 8] Capability of improvement in image quality due to Time of Flight (TOF) imaging was not tested in the study but qualitatively it has been perceived as an obvious improvement in image quality. A very important parameter for a fusion imaging device is the co-registration of the gantry. A misalignment in the gantry can cause a significant difference in the image registration. In our system we found an excellent co-registration of PET and CT image with an error of less than 2mm.

To check the consistency of the system over eighteen months we compared the various parameters obtained at the time of acceptance testing with those obtained by daily quality control. We did not find much change in the parameters during the eighteen month period of our observation. In comparison with acceptance testing, the timing resolution, and energy resolution of this scanner was found to be very stable as shown in the result. The average error in gain calibration was found to be minimal. Daily quality control report over 18 months shows consistent electronic stability and overall system stability of this system despite huge workload.

Conclusion:

The Gemini TF whole-body scanner passed all initial NEMA NU-2 acceptance testing. This system passed all daily quality control parameter for 18 months of observation without any significant variation in daily QC testing. It suggests that the system is robust and capable of performing high volume operation.

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Figure 1

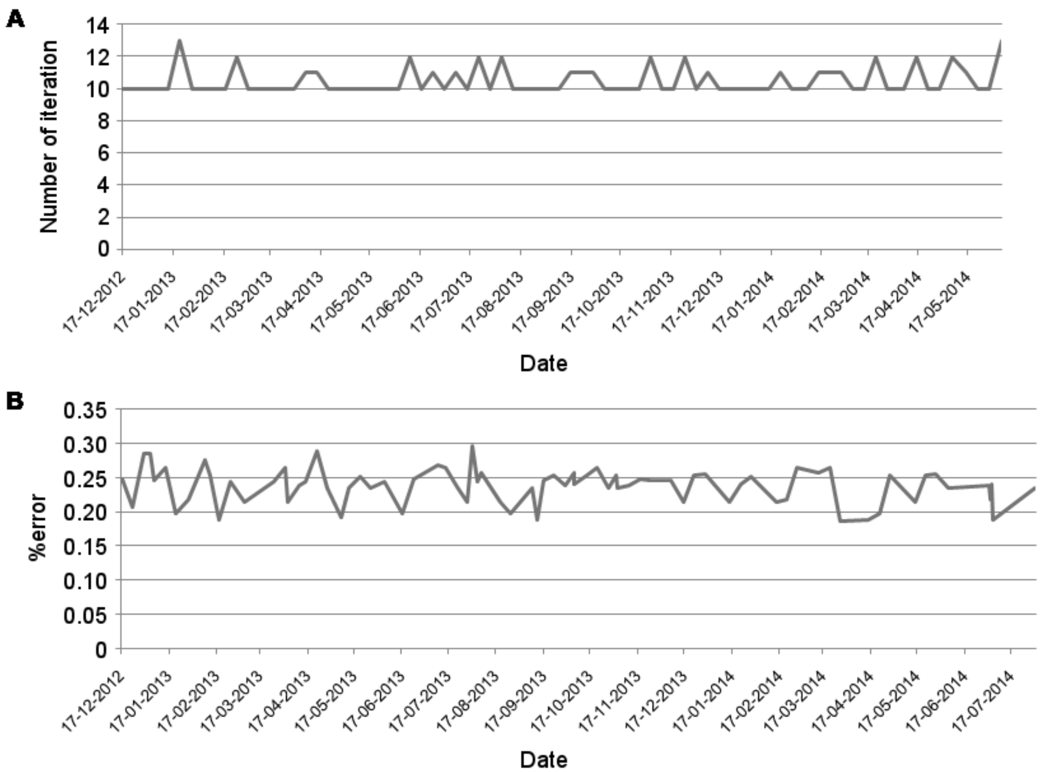

Figure 1: Graphical representation of variations in number of iterations required for PMT gain calibration during the observation period (A), Graphical representation of variations in Percentage average Error in PMT gain calibration during the observation period (B).

Figure 2

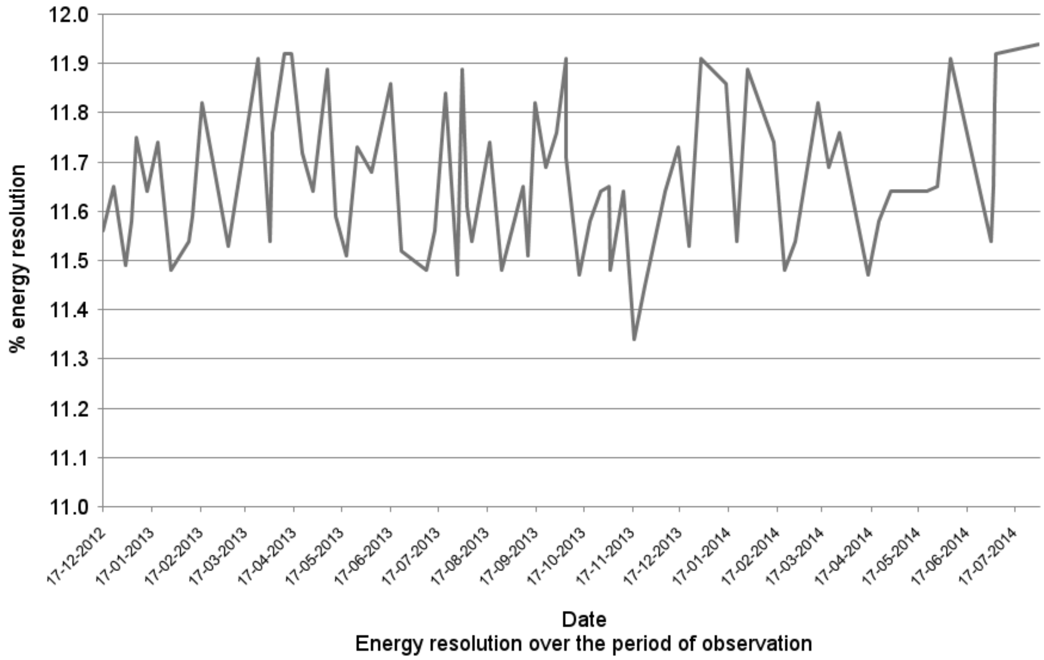

Figure 2: Graphical representation of variations in system energy resolution during the observation period

Figure 3

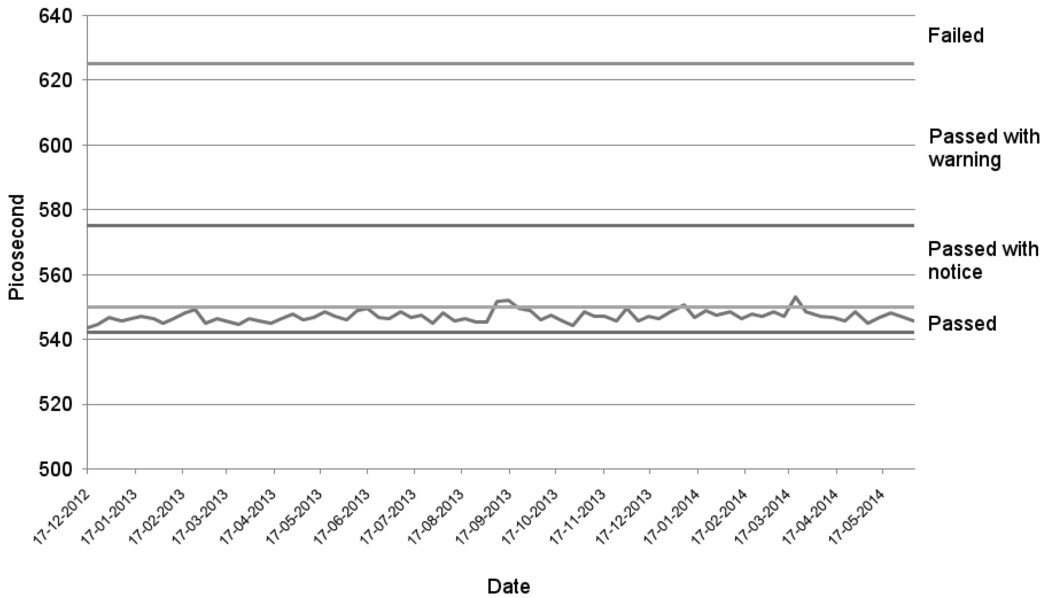

Figure 3: Graphical representation of variations in system timing resolution during the observation period (passing criteria is mentioned)

Tables

Table 1: Comparison of Image Quality with Scatter performed during acceptance test and after 12 month: (FBP Reconstruction)

Diameter		10 mm	13 mm	17 mm	22 mm	28 mm	37 mm
% Contrast recovery	During Acceptance test	34.70%	51.43%	60.83%	72.13%	73.88	77.65%
	After 12 month	36.30 %	50.62%	60.13%	70.69%	72.12	76.92%
	Difference of % contrast recovery between two studies	+1.6%	-0.81%	-0.60%	-1.44%	-1.76%	-0.73%
%Background variability	During Acceptance test	8.65%	7.89%	7.05%	6.15%	5.46%	5.04%
	After 12 month	8.96%	8.01%	6.85%	6.65%	5.77%	5.32%
	Difference of % background variability between two studies	+0.31%	+0.12	-0.20%	+0.50%	+0.31%	+0.28%

Table 2: Comparison between SUV of different lesions and background of Image quality phantom at the time of acceptance test and after 12 month of the acceptance test.

	SUV at the time of acceptance test			SUV after 12 month			%error in SUV_{max} estimation in second study in comparison with first study
SUV	MAX	MIN	AVERAGE	MAX	MIN	AVERAGE	
LESION1 (22mm)	4.95	2.1	3.04	4.7	1.98	2.97	5.05%
LESION2 (17mm)	4.65	1.98	2.84	4.53	1.93	2.75	2.58%
LESION3 (13mm)	3.91	1.63	2.2	3.73	1.58	2.12	4.60%
LESION4 (10mm)	2.35	0.96	1.44	2.33	1.08	1.50	0.85%
BACKGROUND	1.36	0.98	1.20	1.34	1.03	1.15	1.47%

Table 3: Daily quality control parameters for observation period of eighteen months.

	No. of Iterations required for PMT gain calibration	PMT gain calibration Error (%)	Average Energy Resolution (%)	Timing Resolution (Pico second)
Average	10.493	0.238	11.664	547.075
Standard Deviation	0.812	0.026	0.147	1.772