DOI: 10.1478/AAPP.932A3

AAPP | Atti della Accademia Peloritana dei Pericolanti
Classe di Scienze Fisiche, Matematiche e Naturali
ISSN 1825-1242

Vol. 93, No. 2, A3 (2015)

PERFORMANCE CHARACTERIZATION OF THE PET-CT TOMOGRAPH AT THE PET-CYCLOTRON-RADIOCHEMISTRY SITE OF MESSINA UNIVERSITY

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(communicated by Paolo V. Giaquinta)

ABSTRACT. A PET-cyclotron-radiochemistry plant was built at Messina University Hospital, whose diagnostics section was equipped with a PET-CT scanner composed by a time of flight PET and a 16-slice CT. The present note reports about the results of tomograph's acceptance tests, which had been planned and carried out in order to verify the correspondence of the specific scanner's performances declared by the firm and the fulfillment of Italian law's minimal criteria of acceptability. Acceptance tests gave positive results for all the physical parameters measured. The assessment of CT slice thickness, with regard to the thinner slices of 0.75 and 0.6 mm, required the employment of a manual procedure exploiting a phantom equipped with low inclination ramps. These results allowed us to assess a baseline of performance parameters to be taken as a reference for periodic constance tests.

1. Introduction

Positron Emission Tomography (PET) is a functional diagnostic modality that is gaining more and more diffusion in the recent years due to the superior quality of its imaging and the increasing number of specific radiopharmaceuticals. The diagnostic power, together with the capability to be exploited as a basis for external beam radiotherapy and internal radionuclide treatment planning, is further increased by the association with a morphologic imaging such as Computed Tomography (CT). The combined nuclear medicine and radiologic PET-CT examination is capable to give accurate quantitative information about morphology and function of the physio-pathologic processes for applications in oncology, neurosciences, cardiology and other disciplines.

Messina University has funded the construction of a PET - cyclotron - radiochemistry plant at the University Hospital "Gaetano Martino" in the framework of the research project entitled "A model of integrated molecular diagnostics and targeted non-pharmacologic therapy in breast tumours and neuro-oncology", funded by the National grant CIPE No. 45602 (PON 2007/2013) under the responsibility of one of the Authors (F.T.). The site was equipped by a self-shielded cyclotron (Siemens AG, Germany) accelerating 11-MeV H^- ions on liquid or gaseous targets, to obtain ^{18}F or ^{11}C positron emitting radionuclides to be labeled with different molecules in a radiochemistry laboratory equipped with four

TABLE 1. Main specifications of the Philips Gemini TF 16 PET-CT scanner.

PET SECTION		
Parameter	Value	Unit
Patient port	70	cm
Crystal material	LYSO	
Nr. of crystals	28336	
Crystal dimensions	4×4×22	mm
Nr. of PMTs	420	
Timing resolution	495	ps
CT SECTION		
Parameter	Value	Unit
Nr. of slices	16	
kV	90−120−140	kVp
mA	20−500	mA
Det. material	solid-state GOS	
Nr. of elements	16128	

hot cells and related syntesis modules. A quality control laboratory and an automatic fractionation system for the preparation of single doses complete the radiochemistry section of the plant. A state-of-the-art PET-CT tomograph (Philips, The Netherlands) was installed in the diagnostic section. It is composed by a time of flight PET tomograph and a 16-slice CT scanner, whose main specifications are reported in Table 1.

The present note reports about the results of PET-CT acceptance tests, which had been planned and carried out for the threefold aim of verifying the correspondence of the specific scanner's performances declared by the firm, the fulfillment of Italian law's minimal criteria of acceptability and the assessment of a baseline of performance physical observables to be taken as a reference for periodic constance tests.

2. Materials and methods

Acceptance tests of the Philips Gemini TF 16 PET-CT tomograph were carried out after having established a protocol describing the quality control procedures to be used. Such protocol is written in fulfillment of the legal issues regarding health protection of individuals against the dangers of ionizing radiation in medical exposures ("Dlgs 187/00" 2000). The technical basis of the protocol relies, besides of the Annexes of "Dlgs 187/00" (2000), on the reference guidelines and reports edited by CEI (1998, 2007), IEC (2005, 2013), NEMA (2012), IAEA (2009), AIFM-AIMN (2006), AIFM (2007), and on the Philips user manuals (Philips Medical Systems 2009, 2013b). The experimental procedures adopted agree with the ones described by Surti *et al.* (2007). The protocol defines the professional figures in charge of delineating and updating the quality assurance procedures, and those entitled to the execution of acceptance and costancy tests.

For which concerns the PET section of the PET-CT tomograph, the parameters verified during acceptance tests were: energy resolution, timing resolution, spatial resolution, sensitivity, scatter fraction, noise equivalent count rate (NECR), image quality (IQ), calibration

and validation of the standard uptake values (SUV). Measurements were carried out following the approaches suggested by NEMA (2012), practically implemented as reported in the Philips performance manual (Philips Medical Systems 2013b).

The NEMA phantom set was employed, which consisted of: NEMA PET scatter phantom, an HDPE cylindrical phantom divided in four sections, with a hole drilled 4.5 cm off-axis allowing the insertion of a capillary tube filled with radioactivity; NEMA IEC body phantom, a 9.7-l fillable thoracic section hosting six hollow spheres with diameters between 10 and 37 mm, allowing to reproduce hot and cold regions with respect to the surrounding background; NEMA PET sensitivity phantom, a capillary tube filled with radioactivity surrounded by five concentric aluminium tubes that can be extracted in order to vary the photon attenuation, a set of glass capillaries, 10 cm long with an inner diameter of 1 mm, that can be placed at different positions of a metal support in order to measure axial and transverse spatial resolution at 1 cm and 10 cm off axis; a 30 cm hollow cylindrical phantom fillable with radioactivity, for uniformity and SUV measurements. The measured values of each tested parameter were compared with the corresponding reference values declared by Philips, and tolerance limits for acceptance were set in accordance with IAEA (2009).

Concerning the CT section of the PET-CT tomograph, the parameters under acceptance test were: accuracy of the X-ray tube high voltage, linearity, noise, CT numbers of water and nylon, uniformity, slice thickness, spatial resolution, low contrast detectability, computed tomography dose index (CTDI), accuracy of the bed positioning and bed movement in helical CT acquisition. Such parameters include those considered in the minimal criteria of accetability of CT equipments defined in the Annexes of Italian regulation ("Dlgs 187/00" 2000).

Two multi-purpose phantoms were employed for the performance characterization of the CT section: the Philips CT phantom (Philips Medical Systems 2013a) and the Catphan 600 phantom (Goodenough 2014).

The Philips CT phantom contains a body and a head section. The body section is a 30 cm diameter nylon cylinder with water and teflon inserts, while the head section is a 20 cm diameter cylinder divided in three layers, containing several test objects: a physical layer equipped with 45° diagonal aluminium strips for CT performance characterization for slice thickness, a water layer and a multi-pin layer with several inserts of materials characterized by different electronic densities.

The Catphan 600 phantom is composed by five layers, containing several test objects for CT performance characterization: spheres and rods of different electronic densities, 23° ramps for slice thickness, inclined wires and beads for MTF evaluation, high- and low-contrast scales, water equivalent bulk material for uniformity tests. Also in this case, measurements were compared with corresponding references declared by Philips, taking into account the minimal criteria of acceptability from "Dlgs 187/00" (2000). Measurements were carried out following the recommendations of AIFM-AIMN (2006), AIFM (2007), and the Philips performance manual (Philips Medical Systems 2013b).

CT dose measurements were conducted by means of a 10 cm long pencil ionization camera connected with a digital electrometer together with two standard 15 cm long cylindrical PMMA phantoms: a head phantom with a diameter of 16 cm, and a body phantom with a diameter of 32 cm. The conventional methodology allowed us to measure $CTDI_W$ following the approach described by AIFM (2007).

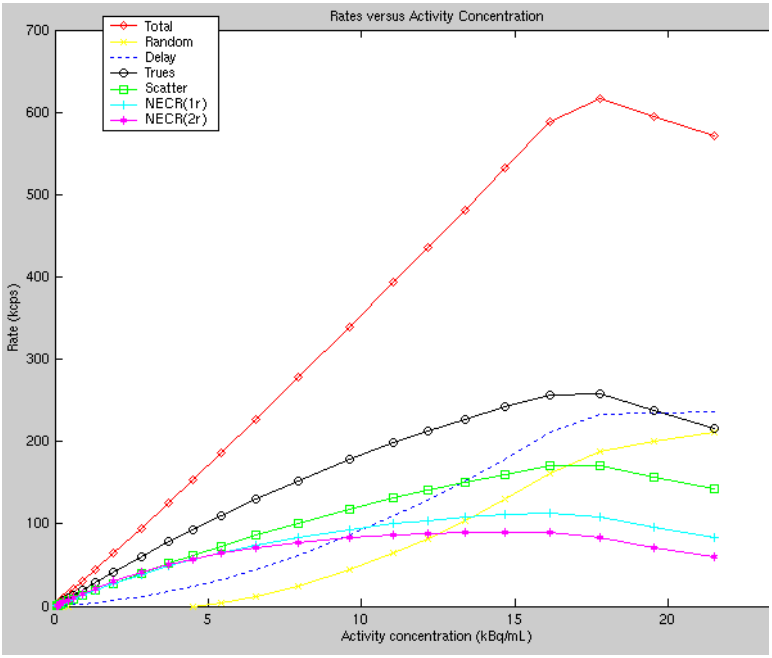

FIGURE 1. Count rate performance of the PET tomograph: Total counts, Trues, Scatter, Random, Delayed and NECR as a function of the activity concentration.

TABLE 2. Measurement results for NEMA PET acceptance tests.

Parameter	Measurement	Value	Reference
Energy resolution	at 511 keV	11.87%	$< 1.05 \cdot 11.70\%$
Timing resolution	TOF	511.81 ps	$< 1.05 \cdot 495$ ps
Spatial resolution at 1 cm	axial, FWHM	4.30 mm	$< 1.05 \cdot 4.7$ mm
Spatial resolution at 1 cm	transaxial, FWHM	4.69 mm	$< 1.05 \cdot 4.7$ mm
Spatial resolution at 10 cm	axial, FWHM	4.85 mm	$< 1.05 \cdot 5.2$ mm
Spatial resolution at 10 cm	transaxial, FWHM	4.99 mm	$< 1.05 \cdot 5.2$ mm
Sensitivity	average at 0 and 10 cm	10.79 cps/kBq	$> 0.95 \cdot 7.2$
Scatter fraction	at low activity	27.97%	$< 1.05 \cdot 30\%$
Peak NECR	at 16 kBq/ml	112.90 kcps	> 110 kcps
SUV		1.0	1.0 ± 0.1

3. Results and discussion

Tables 2-7 and Fig. 1 show the results of the measurements carried out during the acceptance tests of the Philips Gemini TF 16 PET-CT tomograph. For which concerns CT dose measurements, $CTDI_W$ values of 25.31 mGy and 16.43 mGy were obtained, for head and body phatoms, respectively, when scanning at 120 kV and 267 mA.

The acceptance tests gave positive results for all the physical parameters measured, and the reference values for subsequent constancy tests were determined. Particularly

TABLE 3. Measurement results for PET Image Quality acceptance tests.

Sphere diameter (mm)	10	13	17	22	28	37
Reference contrast %	> 20	> 40	> 50	> 55	> 50	> 50
Measured contrast %	33.83	52.93	63.66	73.19	75.31	79.30
Reference bkg. var. %	< 8	< 8	< 7	< 7	< 6	< 6
Measured bkg. var. %	6.79	6.15	5.47	5.05	4.66	4.04

TABLE 4. CT linearity test conducted on the Philips phantom at 120 kV, 4x3 collimation, 0.75 s rotation time and 200 mAs.

Material	Density (g/cm^3)	CT number (HU)	Reference and tolerance (HU)
Air	1.2×10^{-3}	-1001.25	-1000 ± 50
Polyethylene	0.91	-74.95	-80 ± 10
Water	1.00	-0.95	0 ± 4
Nylon	1.15	94.4	100 ± 10
Lexan	1.20	117.8	120 ± 10
Acrylic	1.20	140.5	140 ± 10
Teflon	2.16	1020.1	1065 ± 50

TABLE 5. CT noise, uniformity, CT numbers and low-contrast detectability tests conducted on the Philips phantom.

Parameter	Value (HU)	Reference and tolerance (HU)
Noise	4.1	4.1 ± 0.4
Uniformity	1.37	0.92 ± 2.00
Water CT nr.	1.17	0.0 ± 4.0
Nylon CT nr.	108.52	100 ± 10
Minimum diam. visible inserts	0.3 cm at 1%	< 0.35 cm

TABLE 6. CT spatial resolution tests conducted on the Philips phantom.

Phantom section	Acquisition protocol	MTF 50% (Reference)	MTF 10% (Reference)
Head	120 kV, 16×1.5, 0.75 s, Std, 200 mAs	2.85 (2.3−3.3)	5.45 (5.0−6.0)
Body	120 kV, 16×1.5, 0.75 s, Std, 240 mAs	3.50 (2.8−3.8)	6.45 (6.0−7.0)
Head	120 kV, 16×0.75, 0.75 s, Hi, 400 mAs	7.40 (6.8−8.2)	11.55 (10.5−12.5)
Head	120 kV, 16×0.75, 0.75 s, UH, 400 mAs	7.95 (6.5−10.6)	17.05 (15.0−18.6)

noteworthy are sensitivity and spatial resolution measured in PET, whose results were superior with respect to those reported by Surti *et al.* (2007). NECR and Image Quality gave similar results as those reported by Surti *et al.* (2007). The assessment of CT slice thickness, with regard to the thinner slices of 0.75 and 0.6 mm, required the employment of the Cathpan test object. Previous measurements on the proprietary phantom with the automatic acquisition and analysis protocol resulted in a systematic over-estimation of the slice thickness (+36% at 0.75 mm and +65% at 0.6 mm), significantly above the tolerance limits fixed by the minimal criteria of acceptability. As reported in literature (AIFM 2007),

TABLE 7. CT slice thickness tests conducted on the two different phantoms with 0.75 s rotation time acquisitions at 200 mAs.

Phantom	Acquisition protocol	Measurement (mm)	Reference and tolerance (mm)
Philips	120 kV, 16 × 1.5 (6 mm), Std	6.06	6 ±20%
Philips	120 kV, 16 × 1.5 (1.5 mm), Std	1.77	1.5 ±20.0%
Philips	120 kV, 4 × 3 (3 mm), Std	3.07	3 ±20%
Philips	120 kV, 4 × 1.5 (1.5 mm), UH	1.60	1.5 ±20.0%
Philips	120 kV, 4 × 4.5 (4.5 mm), Std	4.53	4.5 ±20.0%
Catphan	120 kV, 16 × 0.75 (0.75 mm), Hi	0.76	0.75 ±20.00%
Catphan	120 kV, 4 × 0.75 (0.75 mm), Hi	0.71	0.75 ±20.00%
Catphan	120 kV, 2 × 0.6 (0.6 mm), UH	0.67	0.6 ±20.0%

a test object as a low-inclination ramp, such as the one contained in the Catphan phantom, is to be preferred when thin slices have to be characterized. Furthermore, a significantly overestimated measurement of the slice thickness can not represent a valid reference value for constancy tests, since slight drifts in the real thickness would be masked in the measurement.

4. Conclusions

The results of the measurement protocol established allowed us to accept for the clinical usage the tomograph, and set the basis for the quality assurance program to be implemented during the lifetime of the machine.

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Communicated 2 December 2014; manuscript received 21 May 2015; published online 22 October 2015