PET performance of the GEMINI TF PET - MR: the world' s first whole body PET - MRI scanner

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Abstract— **The GEMINI TF PET-MRI (Philips Healthcare, Cleveland, OH) is a newly released whole body hybrid imaging system with a Philips Achieva 3T system and a Philips TF (TruFlight) PET. We report the standard NEMA NU2 measurements for the scanner. Compared to PET-CT, modifications to the PET were made to avoid mutual system interference and deliver uncompromising performance which is equivalent to the standalone systems. The PET gantry was redesigned to introduce magnetic shielding for the PMTs. Stringent electromagnetic noise requirements of the MR system necessitated the removal of PET gantry electronics to be housed in the PET-MR equipment room. All PET calibrations and measurements were done with the MRI ramped to 3T, shimmed and calibrated. Measurements were performed as described in NEMA standard manual. GEMINI TF PET-CT typical NEMA values were compared to PET-MR ($n \geq 4$ for PET-MR data). Spatial resolution and sensitivity were comparable to PET-CT results. Timing resolution and energy resolution of the PET-MR system (not NEMA standard measurements) were measured to be 520 ps and 12%, respectively. Image quality measurements performed with IEC phantom yielded results comparable to PET-CT. The NEMA results obtained with PET-MR are equivalent to typical GEMINI TF PET-CT results. System energy and timing resolution were comparable to PET-CT demonstrating the effect of magnetic shielding to maintain the PMTs in normal flux levels. In conclusion, we report the design of a whole-body hybrid PET-MRI system where PET performance is comparable to standalone GEMINI TF PET-CT system.**

Keywords- PET-MR, performance measurement

I. INTRODUCTION

The GEMINI TF PET-MRI (Philips Healthcare, Cleveland, OH) is a newly released whole body hybrid imaging system with a Philips Achieva 3T system and a Philips TF (TruFlight) PET. We report the standard NEMA NU2 measures for spatial resolution, sensitivity, count-rate capability and contrast recovery for the scanner. The NEMA NU 2 standard is a useful benchmark for characterizing performance of PET scanners as it facilitates comparison between different scanner models [1].

II. METHODS

A. *GEMINI TF PET - MRI Scanner*

The GEMINI TF PET-MRI is a sequential hybrid imaging system, similar to a PET-CT. In this design, a turntable between the MRI and PET facilitates patient motion between the two systems. Compared to PET-CT, modifications to the PET were made to avoid mutual system interference and deliver uncompromising performance which is equivalent to the standalone systems. The PET gantry was redesigned to introduce magnetic shielding for the PMTs which ensured their operation in 'normal' flux levels close to the Earth's magnetic field. The design was guided by the requirement that no shielding material was to be placed in the direct path of gamma rays. Furthermore, stringent electromagnetic noise requirements of the MR system necessitated the removal of PET gantry electronics to be housed in the PET-MR equipment room.

The GEMINI TF PET is a 3D scanner comprised of 28 modules arranged cylinder that is 90 cm in diameter by 18 cm axially. Each LYSO crystal element is 4 x 4 x 22 mm^3 in size. Data are acquired in list-mode with indices of the activated detectors recorded along with the differential time of arrival using a 460 keV lower-level discriminator. Reconstruction is typically performed to yield slices containing 144 x 144 pixels that are 4 x 4 x 4 mm^3 for body and 2 x 2 x 2 mm^3 for brain. The MR was used for attenuation correction of PET, using a specifically designed MRAC technique [2].

III. SCANNING

All PET calibrations and measurements were done with the MRI ramped to 3T, shimmed and calibrated.

A. *Sensitivity*

Sensitivity was measured using 8.8 MBq of ^{18}F-FDG in a 70 cm long line source placed inside five concentric aluminum sleeves. Coincidence rates were measured for 1 through 5 of the sleeves in place while the source was centered and at 10 cm from scanner axis. Count rates were obtained from list-mode files and interpolated to obtain the rate with zero thickness of aluminum under the assumption that all positrons would be annihilated in the absence of attenuating material.

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B. *Spatial resolution*

Spatial resolution was measured using approximately 1 mm ^{18}F-FDG point sources in glass tubing. Sources were measured at standard locations: 1 cm and 10 cm from center of the scanner. Axially, the point sources were placed at the center of the FOV and at one quarter of the extent of the axial FOV from the center (45 mm). Images were reconstructed using filtered backprojection not making use of TOF information.

C. *Hot sphere contrast recovery*

Hot-sphere contrast recovery (ratio of observed contrast to true contrast) and variability (standard deviation of sphere background) were measured using the IEC phantom with spheres using an initial concentration of 5.4 kBq/mL ^{18}F-FDG in the background and 4 times higher concentration in the 10, 13, 17 and 22 mm spheres. The larger 28 and 37 mm sphere were filled with water to assess cold-sphere contrast recovery (CSRC).

MR-based Attenuation correction (MRAC) of the PET image was implemented for the IEC phantom. The intent of the NEMA IQ method is to test PET reconstructed image quality while applying the default clinical imaging workflow, acquisition protocol and reconstruction technique. The NEMA NU2-2007 standard was written for standalone PET and hybrid PET-CT systems, where it is assumed that a method for AC is readily available on the system, and that the same method is used for clinical imaging and phantom imaging. This methodology is not strictly applicable to PET-MRI as the MRI does not provide a direct measurement of the amount of gamma photon attenuation. The MR sequence (called atMR for attenuation correction MR sequence) used for IEC phantom imaging was slightly modified from the patient imaging sequence. Small flip angle of 2° was used to suppress the excess signal from water, and reduce dielectric artifacts from the MR images. A 2-segment MRAC image segmentation technique was applied to the atMR images for generation of the attenuation map of the IEC phantom. This technique was essentially similar to the clinical MRAC technique but was modified to enable segmentation of the lung insert.

Images were reconstructed using a list-mode OSEM using 3 iterations with 33 subsets each, a blob basis function, TOF information and accounting for attenuation, scatter and random events in the system matrix.

D. *Noise equivalent count rate*

The standard 20 cm diameter x 70 cm long phantom with 555 MBq of ^{18}F-FDG in a 70 cm line source at 4.5 cm from the central axis of the cylinder was used for measurement of count rates. Data were acquired at several time points as activity decayed in the cylinder. The prompt and delayed coincidence window data were acquired at low counting rates and rebinned using single-slice rebinning. True events (*Ti*) at *i*th slice were calculated from the prompts sinogram profile within a 2 cm radius of the source, and non-true events (sum of scatters and randoms) were obtained within an object diameter of 24 cm (4 cm larger than the phantom diameter). Random events for the *i*th slice (*Ri*) were obtained from the delayed sinogram profile, also for an object of 24 cm. Noise-equivalent count rate performance vs. activity and scatter fraction were measured as

$$NECR = \frac{Trues^2}{Trues + Scatter + Randoms}$$

IV. RESULTS

Table 1 shows GEMINI TF PET-CT typical NEMA values compared to PET-MR (n≥4 for PET-MR data). Timing resolution and energy resolution of the PET-MR system (not NEMA standard measurements) were stable over time and measured to be 520 ps and 12%, respectively. Scatter fraction for larger cylinders with diameter 27 and 35 cm were 32% (38%) and 41% (46%), and NEC was measured as 45 kcps (46kcps) and 16 kcps (18 kcps), respectively with PET-CT values in parentheses [3].

Specification	**GEMINI TF PET-CT**		**GEMINI TF PET-MRI**	
Spatial res 1cm transverse (FWHM)	4.7 mm		4.7 ± 0.1 mm	
Spatial res 10cm radial (FWHM)	5.1 mm		5.1 ± 0.1 mm	
Spatial res 10cm tangential (FWHM)	5.1 mm		5.1 ± 0.1 mm	
Spatial res 1cm axial (FWHM)	4.7 mm		4.7 ± 0.2 mm	
Spatial res 10cm axial (FWHM)	5.2 mm		5.2 ± 0.4 mm	
Sensitivity 0cm/10cm (cps/MBq)	7000/7200		7000 ± 155/7200 ± 142	
Scatter Fraction -20cm	30%		26% ± 3%	
NECR Max (kcps) -20cm	110		90 ± 3	
NEC peak location (kBq/mL) -20cm	16		14.2 ± 0.6	
IEC 4:1 contrast	***Contrast***	***BV***	***Contrast***	***BV***
10 mm sphere (%)	33	5	30 ± 5	7 ± 0.5
13 mm sphere (%)	51	4	50 ± 5	6 ± 0.3
17 mm sphere (%)	63	4	66 ± 1	5 ± 0.7
22 mm sphere (%)	64	3	70 ± 2	5 ± 1
28 mm sphere (%)	77	3	72 ± 2	4 ± 1
37 mm sphere (%)	80	2	77 ± 3	3 ± 1

Table 1: NEMA performance comparison between GEMINI TF PET-MR and PET-CT systems.

Fig 1 shows typical NEMA count-rate performance of the PET-MR system. The total, true, random, scatter and NEC rates were plotted against an effective activity concentration which was calculated by dividing the total activity in the line source by the total volume of the cylindrical phantom

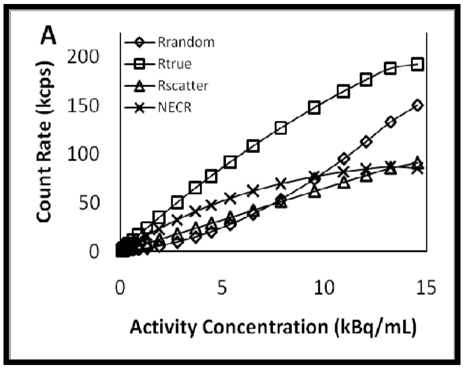

Fig 1: Count-rate performance, NEC

A central slice from an IEC phantom with 4:1 background to hot ratio is shown in Fig 2. Qualitatively and quantitatively, the images are equivalent to the images obtained from a GEMINI TF PET-CT scanner.

Representative patient images obtained from the system are shown in Fig 3. Details of initial clinical imaging experience with the GEMINI TF PET-MR are discussed elsewhere [4].

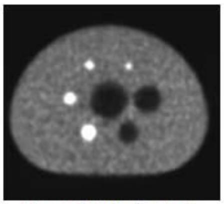

Figure 2: IEC phantom

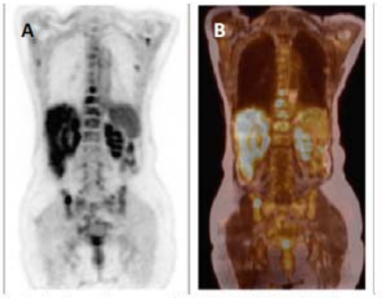

Fig 3: Patient images; (A) PET, (B) PET-MR fusion

V. DISCUSSION

The concept of PET-MR arose even before PET-CT was introduced, but it is a technical challenge to maintain PET PMT functionality in a high magnetic field. The design presented here introduces magnetic shielding for the PET gantry for hybrid PET-MR imaging. The NEMA results obtained with PET-MR are comparable to typical GEMINI TF PET-CT results. System energy and timing resolution were comparable to PET-CT demonstrating the effect of magnetic shielding to maintain the PMTs in normal flux levels. There was a slight decrease in peak NECR, which can be attributed to a different patient table used in the PET-MR system. A minor increase in IEC background variability was also ascribed to the same reason. Overall, the results demonstrated that both PET and MRI can function in close proximity without compromising PET imaging performance and quality.

Attenuation correction for clinical imaging represents the biggest challenge facing the field of PET-MRI. We implemented a 3-segment approach for generation MR-based attenuation maps. PET images obtained from the PET-MR system (Fig 3), reconstructed with default reconstruction method portrayed good image fidelity, qualitatively comparable to PET-CT. The superior soft tissue resolution and anatomy provided by MRI along with semi-quantitative spectroscopy and perfusion imaging can now be combined with high sensitivity functional PET imaging. It is conceived that advantages of hybrid PET-MRI would become evident in the near future.

In conclusion, we report the design of a whole-body hybrid PET-MRI system where PET performance is comparable to standalone Gemini TF PET-CT system.

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