A Novel Model for Monte Carlo Simulation of Performance Parameters of the Rodent Research PET (RRPET) Camera Based on NEMA NU-4 Standards

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Abstract— **Rodent Research PET (RRPET) is a newly designed small-animal PET integrated several novel methods to develop performance parameters of the system. A novel model has been defined to calculate some of performance parameters of the RRPET using Monte Carlo simulations by GATE. Simulations were done in 2 stages: evaluation phase and calculation of sensitivity and count rate parameters of the RRPET based on NEMA NU 4 – 2008 Standards which has recently published for performance measurements of small-animal PET systems. Evaluation phase shows a sensitivity of 10.7%, and maximum NECR of 800 kcps @ 1.5 mCi for a mouse-like phantom. Using NEMA NU-4 protocol, for the mouse phantom, average total absolute system sensitivity is 2.7%, while peak true count rate is 2,050 kcps @ 95 MBq, and peak Noise Equivalent Count Rate (NECR) is 1,520 kcps @ 82.5 MBq. Scatter Fraction (SF) is computed 4.7% for the mouse phantom based on NEMA NU-4. By presenting the accuracy of our new model, it can be used for further calculations of other performance parameters of the RRPET.**

Keywords— **RRPET, small animal PET, NEMA NU 4–2008, Monte Carlo.**

I. Introduction

In the last two decades, the use of small-animal models in the field of biomedical research for studying disease have accelerated, and after the first dedicated rodent PET by Hammersmith Hospital (London, UK) in collaboration with CTI PET Systems, Inc. (Knoxville, Tennessee), dedicated small-animal PET systems have continued playing their role as a strong imaging modality in investigating cellular and molecular processes associated with disease in live animals [1, 2]. Rodent Research PET (RRPET) is a newly designed small-animal scanner that has been commercialized as the world's first animal PET-CT (XPET) scanner. Main design goals of RRPET were lower cost, higher sensitivity, higher image resolution, and large axial field of view (AFOV). Applying Photomultiplier-Quadrant-Sharing (PQS), Slab-Sandwich-Slice (SSS) production technique for building the detector blocks more efficiently, in addition to using a high yield pileup event recover (HYPER) method has complied the main goals [3]-[7]. The RRPET consists of 6 detector rings, and each ring is comprised of 30 pentagonal block detectors [8] as shown in Fig. 1. System parameters of the RRPET and properties of detector blocks are summarized in Table 1.

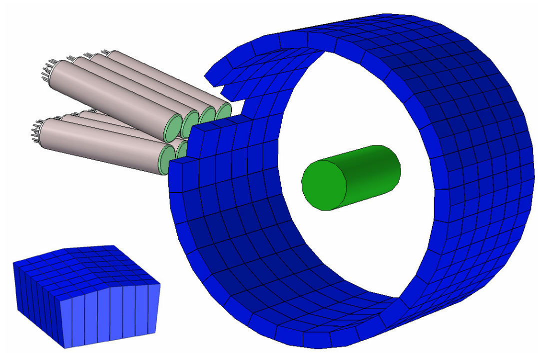

Fig. 1 The detector cylinder and several PMTs, in addition to an enlarged pentagonal block in the bottom-left corner. Green cylinder shows a mouse-like phantom [13]

Monte Carlo techniques have become one of the most popular tools in different areas of medical physics in general and medical imaging in particular in order to overcome difficulties of practical experiments or analytical solutions [9]. GATE (Geant4 Application for Tomographic Emission) [10] is a Monte Carlo simulator toolkit mainly developed for medical imaging particularly PET and SPECT. GATE results are reliable due to using libraries and well validated physics models of Geant4 [11].

Due to rapid expansion and development of small animal PET systems, a specific testing protocol is needed to make the comparison of different systems possible. NEMA NU 4 – 2008 Standards [12], which has been recently published, is dedicated to performance measurements of small animal PETs.

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While other studies on the RRPET, have been performed using a simplified model and not in a special protocol [13, 14], we used a novel accurate model to calculated sensitivity and count rate performance of the RRPET based on NEMA NU-4.

Table 1 System parameters of the RRPET and its detector blocks properties [8, 13]

System parameters of the RRPET	
Transverse field of view	100 mm
Detector ring diameter	165 mm
Axial field of view	116 mm
Septa	No septa between rings
Data collection	3D
Image planes	95
Properties of the detector blocks	
Scintillator	BGO
Crystal width (transaxial)	1.36 mm (edge), 2.32 mm
No. of crystals	8 x 8 = 64
Averaged crystal depth	9.4 mm

II. Method

A. Definition and Evaluation of RRPET in GATE

Because of the complicated geometry of the RRPET, in particular its pentagonal blocks, it is not assumed as a standard geometry in GATE. So Monte Carlo Simulations performed up to now have been done using simplified models in GATE [13, 14]. In such model, cubic block detectors have been used instead of pentagonal blocks. Furthermore, in previous studies for simulating time-dependent parameters, a 10-sided polygon model has been employed as a replacement of the real 30-sided polygon model. Whereas we used a more accurate model for detector blocks, and also a 30-sided polygon model for all simulations including the simulations of time-dependent parameters. Fig. 2 depicts the 30-sided polygon model we defined. Employing these models in GATE should lead to more precise and reliable results. However, for evaluating our new model, first we repeated some experiments of [13], whose authors had the real RRPET system, in their methods but with our own model.

In our simulations, the energy resolution for BGO detector block, the energy window, the time window, and finally the dead-time of each sector are set as 25%, 340 to 750 keV, 16 ns, and 60 ns, respectively [13].

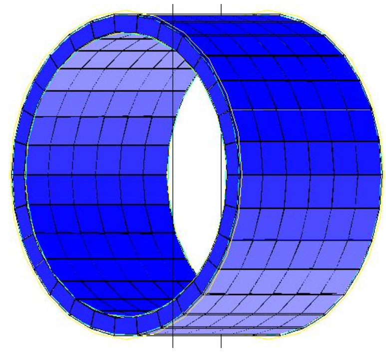

Fig. 2 The 30-sided polygon model used in our simulations

B. Sensitivity

We calculated the sensitivity in two ways: firstly at the center of field of view (FOV) with an ideal 0.04 mCi point source as done in [13], and secondly according to NEMA NU-4. For second approach, following the protocols of NEMA NU-4, a spherical Na-22 source (0.3 mm in diameter) embedded in an acrylic cube (10mm in all sides) was employed. The activity should be low enough to guarantee that the count losses are less than 1% and the random event rate is less than 5% of the true event rate. 200 kBq activity (A_{cal}) was chosen to satisfy these conditions. For the first step, the source was placed at the center of the scanner, both axially and transaxially for acquiring 10,000 true counts. Its corresponding time determines the acquisition time (T_{acq}) for next steps. Then the source was stepped axially to the both sides of the scanner identically to the thickness of the slices. In each step, data collected for the same acquisition time as the first step. After each acquisition, Single Slice Rebinnig (SSRB) algorithm [15] was applied on data and the corresponding slice was represented by a 2D sinogram. In every sinogram, the pixel with the largest value in each row (angle) was located, and all pixels greater than 1cm from this pixel was set to zero. No correction for scatter or random counts, and decay was applied. Finally, all pixels were summed to calculate the total counts in that slice. By dividing this value by T_{acq}, the counting rate (R_i) for that slice in counts per second was determined.

C. Count Rate Performance

We calculated coincidence count rates in two methods. First, according to [13], we used uniform distributions of different amounts of activity in a mouse-like phantom. The mouse-like phantom employed in this stage is a φ 30 mm x 70 mm cylinder. After that, we computed count rate parameters based on NEMA NU-4. The mouse phantom of NEMA NU-4 is a φ 25 mm x 70 mm. A cylindrical hole (3.2 mm diameter) is drilled parallel to the central axis at the radial distance of 10 mm whose central 60 mm is used for inserting activity uniformly distributed in water. F-18 is used as radionuclide in simulations with different initial activity for every acquisition. After applying SSRB and generating sinograms, in each sinogram, all pixels out of the 16 mm band wider than the phantom are set to zero. Then, each row is shifted so that the maximum pixel is aligned with the central pixel of the sinogram. A sum projection is produced such that a pixel in the sum projection is the sum of the pixels in each angular projection having the same radial offset as the pixel in the sum projection. Finally, by considering a 14 mm-band from the central pixel and interpolating, all counts above the connecting line of 2 borders of the band are assumed to be true counts, and the remaining counts below the line are considered to be the sum of random and scatter counts.

III. RESULTS

A. Sensitivity

Using a 0.04 mCi ideal point source at the centre, we computed the sensitivity equal to 10.7% which shows a very small difference with the practical value 10.2% reported in [13].

Then, according to NEMA NU-4, the sensitivity (in counts per second per Bq), and the absolute sensitivity (by taking the branching ratio of Na-22 into account) were calculated respectively as follow:

$$S_i = \left(\frac{R_i - R_{B,i}}{A_{cal}} \right), S_{A,i} = \frac{S_i}{0.906} \times 100$$

Sensitivity profile over axial position is sketched in Fig. 3. Other sensitivity parameters are reported in Table 2.

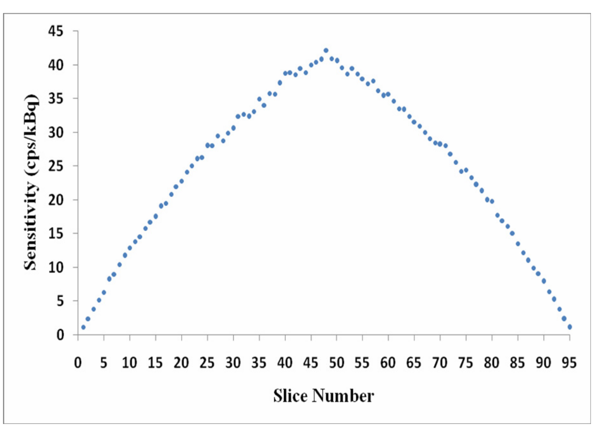

Fig. 3 Sensitivity profile over slices

Table 2 Average system parameters of the RRPET according to NEMA NU-4

Parameter	Value
Average system sensitivity for mouse (cps/kBq)	33
Average system sensitivity for rat (cps/kBq)	25
Average absolute system sensitivity for mouse	3.7%
Average absolute system sensitivity for rat	2.7%
Average total system sensitivity (cps/kBq)	25
Average total absolute system sensitivity	2.7%

B. Count Rate Performance

Total coincidence rate, true coincidence rate, random coincidence rate, and scatter coincidence rate using the φ 30 mm x 70 mm mouse-like phantom are shown in Fig. 4. Our results show a negligible difference with count rate curves of [13]. Noise Equivalent Count Rate (NECR) was calculated for every acquisition by the equation below:

$$NECR = \frac{(\text{True Count Rate})^2}{\text{Total Count Rate}}$$

NECR curve for the same mouse-like phantom is illustrated in Fig. 5 which shows that peak value of NECR is 800 kcps with a 1.5 mCi activity.

In order to obtain count rate parameters according to NEMA NU-4, we simulated 33 acquisitions from initial activity of 500 MBq down to 10 kBq. Each acquisition lasted so that adequate counts were acquired. Our results showed that peak true count rate is 2,050 kcps (achieved at 95 MBq equivalent to 2.765 MBq/mL), peak NECR is 1,520 kcps (achieved at average activity 82.5 MBq equivalent to 2.401 MBq/mL), and finally, the Scatter Fraction (SF) is 4.7% for mouse phantom. System true event rate, random+scatter event rate, total event rate, and NECR are illustrated in Fig. 6 for different values of average effective activity concentrations.

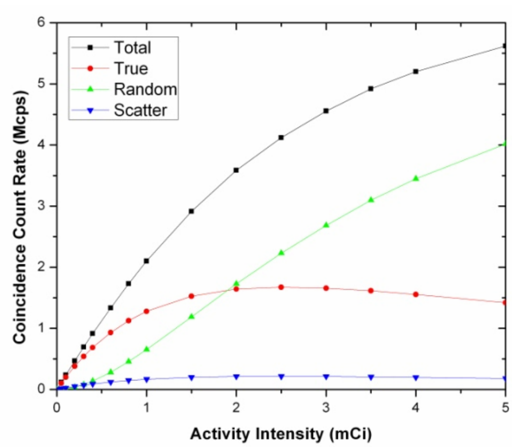

Fig. 4 Count rate curves of the mouse-like uniform phantom

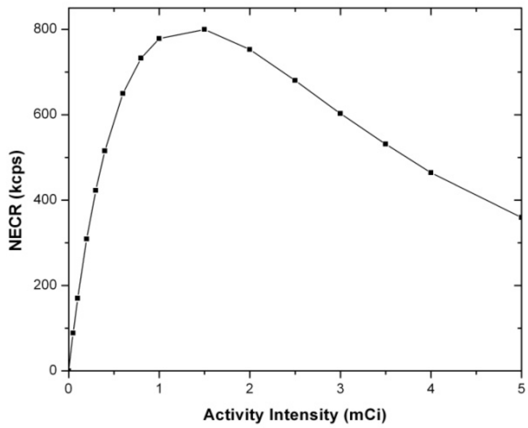

Fig. 5 NECR curve of the uniform mouse-like phantom

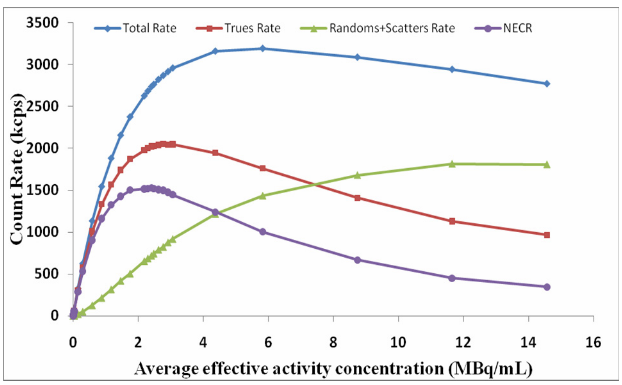

Fig. 6 Count rate curves over average effective activity concentration

IV. Conclusion and discussion

In this study, we designed a new model of the RRPET for more accurate Monte Carlo simulations using GATE. The accuracy of our model was evaluated by comparing our results with the results of [13]. Then, sensitivity and count rate performance parameters were calculated according to NEMA NU-4. Due to more realistic geometry of our model, our results in the field of count rate parameters are more reliable than previous studies. In addition, although the model tolerates a smooth overestimation because of special definition of the blocks, it can be employed for calculating other performance parameters of the RRPET accurately based on NEMA NU-4, and also for assessment of the impacts of different factors such as randoms, scatters, positron range, etc. on reconstructed images. We are currently performing mentioned possible studies that will be published in close future.

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