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Assessment of the Mosaic animal PET system response using list-mode data for validation of GATE Monte Carlo modelling

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Abstract

Monte Carlo modelling is widely used in nuclear medicine for system optimization and for image processing in order to obtain system data that cannot be measured experimentally. Any simulation model should be validated, especially in terms of spatial resolution, count rates, scatter fraction and sensitivity in the case of positron emission tomography (PET) systems. The aim of this study was to compare the performance of a Mosaic animal PET system model to the real system by using raw data in a list-mode format, in order to preserve all the precision and accuracy of the acquired data. GATE package was used to design a realistic model of the Mosaic system. Detectors, shielding, cap, air medium, phantoms, sources and electronic processing were simulated in GATE. Sensitivity obtained from experimental and simulated data were compared using the list-mode data for different energy windows. Measurements of count rates were performed for uniform cylindrical phantoms for both mouse and rat. Output data were recorded with the same spatial sampling as the experimental data. Point spread functions at different locations in the field of view were analysed in raw and reconstructed formats. Simulated and measured sensitivity differed by less than 5%. Simulated and measured single and prompt count rates agreed within 6% for activities up to 100 MBq for the two phantoms. A semi-empirical approach was used to simulate energy efficiency and losses of resolution after crystals interactions (detector blurring). Spatial resolution, assessed on simulated sinograms and on reconstructed data, agreed with real data. Comprehensive evaluation of the Monte Carlo modelling of a microPET system was performed using list-mode data and showed that the GATE model was appropriate to accurately reproduce the response of the system.

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Keywords: Animal PET; Monte Carlo simulation; List-mode acquisition; Performance evaluation

1. Introduction

The modelling of positron emission tomography (PET) systems by Monte Carlo methods are becoming more and more important in nuclear medicine like optimizing PET systems, investigations in image reconstruction. Such models can replace complicated experiments. Modelling of a PET system should be validated by comparing different performances like single and coincidences count rates, system sensitivity, scatter fraction (SF) and spatial resolution.

In this work, we presented a simulation study of the Mosaic animal PET system (Philips Medical Systems) by GATE, a Monte Carlo toolkit based on GEANT4 and dedicated to nuclear medicine.

For the purpose of validation of our model, experimental data were acquired in list-mode format, an acquisition tool suited for research work.

2. Materials and methods

2.1. The system model

Mosaic is an animal PET scanner using 14,456 $2 \times 2 \times 10\,mm^3$ gadolinium oxy-orthosilicate (GSO) crystals arranged in a ring and coupled to a continuous, slotted

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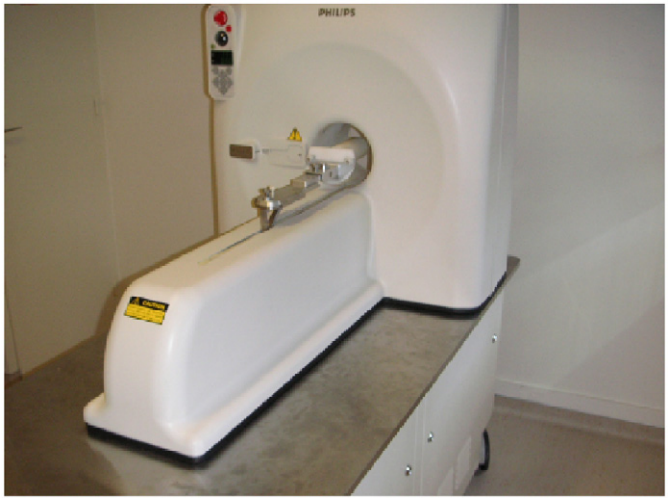

Fig. 1. Mosaic animal PET system.

light-guide 12 mm thick, and an array of 288, 19 mm diameter PMTs for signal readout (Fig. 1). The system is based on Anger-logic detector with 22% energy resolution [1].

The scanner covers transverse and axial field-of-views of 128 and 119 mm respectively.

Acquisition of data was obtained by using two approaches: sinogram format as used for most exams and list-mode format. The last format is dedicated to research investigations due to the large space required for each set of data. List-mode gives precise information about detected events and simple access to data management.

2.2. Monte Carlo simulation

All data were simulated with GATE, taking into account all processes from the decay of the source to the detection of annihilation photons [2].

GATE simulates generation, tracking and annihilation of positrons. The range of the positrons and the γ–γ acolinearity are simulated. Photoelectric effect, Compton and Rayleigh interactions of the photons in phantom, medium, shielding and detectors are taken into account. The position of each event is obtained with an energy-weighted centroid of the different energy deposit locations by interactions of photon in crystals.

Based on raw and corrected energy spectra measurements, a Gaussian energy resolution of 30% and a low energy threshold simulate the rejection of events due to the variations of energy deposition across the field of view and the processing at the constant fraction discriminator (CFD) level. Then, a Gaussian energy resolution of 22% is applied to raw energy deposits to take account of the energy correction.

Gaussian blurring on crystal position was added to compensate for scintillation processes and light collection. We introduced a 6 ns coincidence window to collect coincidences events and a 100 ns delayed window to collect random events. A 200 ns non-paralysable dead time for both prompt and delayed events was used to simulate lost events by the data processing unit. Upper and low energy thresholds were applied before storing all singles and coincidence data of each event (Fig. 2).

3. Protocols of acquisitions

All measurements were adapted from the NEMA standards NU2-2001 used for clinical PET [3]. The protocols needed to be adapted to small animal systems [4]. We have previously validated a protocol for SF [5]. Parameters for energy efficiency curve were derived from spectral analysis of point and cylindrical phantoms filled with ^{18}F.

3.1. System sensitivity

Measurements and simulations were performed with a ^{18}F point source with a volume of 1 mm^3 and 0.2 MBq activity. This source was placed in a glass capillary with an inner diameter of 1 mm and a wall thickness of 0.2 mm and was positioned in the centre field of view of the scanner. Sensitivity was defined as the ratio of true coincidences events to the number of positron-emitting decays from the source during the acquisition time. Acquisition was performed for lower energy thresholds of 150, 250, 350,

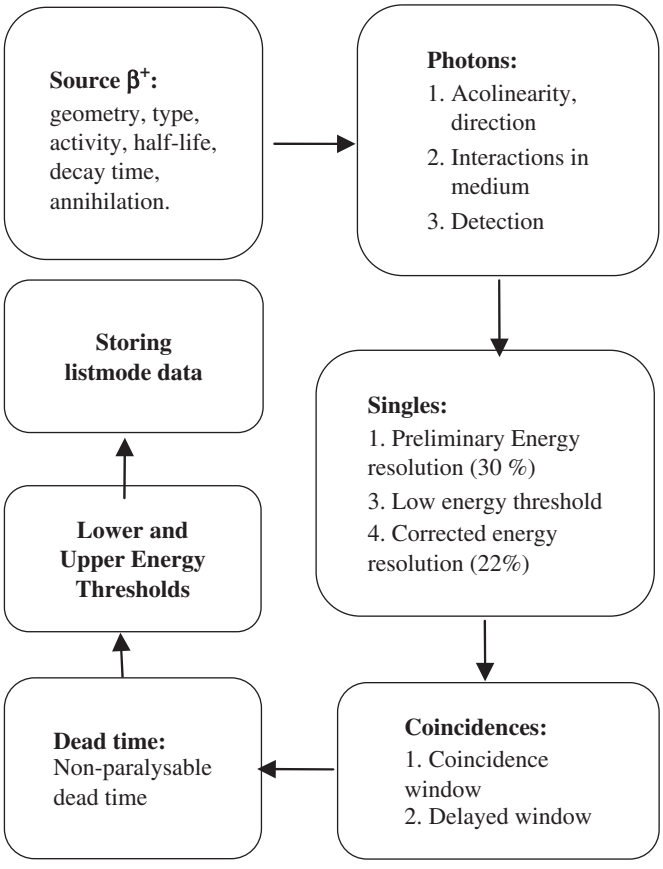

Fig. 2. GATE simulation of the Mosaic system.

410 keV and a fixed upper energy threshold of 665 keV. The true coincidence events were obtained by subtracting random events from prompt events.

3.2. Spatial resolution

The spatial resolution was measured using the same ^{18}F point source at various positions in the field of view. All measurements were carried out in list-mode format with energy window set to 410 and 665 keV for lower and upper thresholds. Events were recorded as pairs and their spherical coordinates (X, Y, Z) were sampled as raw histograms for R_X, R_Y and R_Z coordinates (Figs. 3 and 4).

$$R_X = \frac{X1 + X2}{2} \quad (1)$$

$$R_Y = \frac{Y1 + Y2}{2} \quad (2)$$

$$R_Z = \frac{Z1 + Z2}{2}. \quad (3)$$

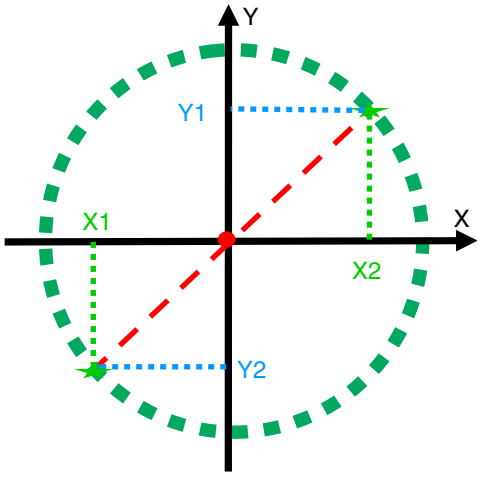

Fig. 3. List-mode spatial resolution on X and Y-axes.

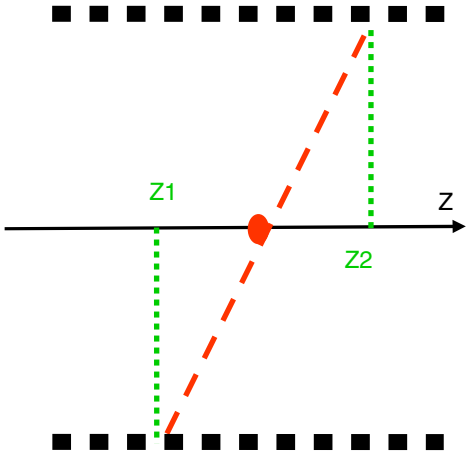

Fig. 4. List-mode spatial resolution on Z-axis.

To calculate reconstructed spatial resolution, list-mode data files were rebinned using single slice rebinning (SSRB) into 3D sinograms and reconstructed using the conventional analytical reconstruction algorithm filtered back projection. Spatial resolution specified as full-width half-maximum (FWHM) of the point source response was calculated according NU2-2001 standards using the same ^{18}F point placed in the centre of the field of view.

3.3. Count-rate performance

Acquisitions were performed on the Mosaic system with two uniform cylindrical phantoms simulating a mouse (3 cm in diameter, 7 cm length) and a rat (7 cm diameter, 15 cm length).

The phantoms were filled with ^{18}F solution with initial activity of 180 MBq for both phantoms. Measured and simulated data was acquired for 410–665 keV energy window.

Acquired true (T) and scatter (S) count rates were calculated from the measured prompt (P) and random (R) count rates by

$$T = (P - R)(1 - SF) \quad (4)$$

$$S = (P - R)(SF). \quad (5)$$

The random coincidences events were estimated on the real and simulated Mosaic animal PET system with a delayed coincidence window.

4. Results

4.1. System sensitivity

Table 1 shows comparison between simulated and measured sensitivity of the Mosaic system as a function of different energy windows.

We observed a good agreement between simulations and measurements with a maximum error inferior to 3%.

4.2. Spatial resolution

4.2.1. Intrinsic spatial resolution

Fig. 5 shows R_X, R_Y and R_Z components of simulated and measured intrinsic spatial resolution for three axial

Table 1
Measured and simulated sensitivities of the Mosaic scanner for different energy windows

Energy window (keV)	Measured sensitivity (kcps/MBq)	Simulated sensitivity (kcps/MBq)	Error (%)
410–665	12.3	12.5	1.6
350–665	12.6	12.9	2.4
250–665	15.6	15.8	1.3
150–665	16.7	17.1	2.4

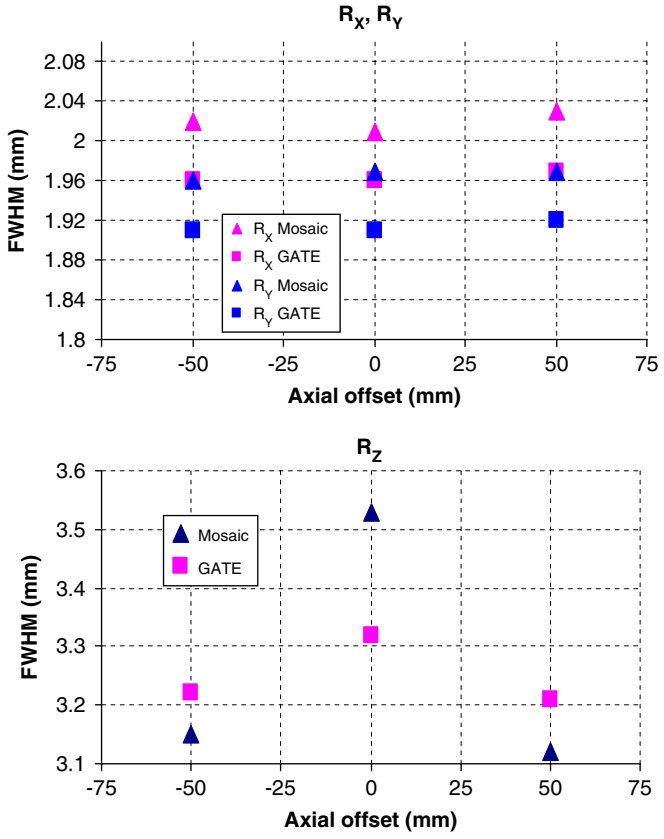

Fig 5. Simulated and measured intrinsic spatial resolutions at different axial offsets for transverse (R_X, R_Y) and axial (R_Z) parameters.

Table 2
Simulated and measured image resolution using FBP reconstruction

Spatial resolution FWHM (mm)	Mosaic	GATE	Error (%)
Radial	2.36	2.35	0.4
Tangential	2.50	2.38	4.8
Axial	2.80	2.72	2.8

offsets. With Gaussian blurring fitting, simulations and measurements agreed well, with less than 6% error. Transverse intrinsic resolutions were independent of the position of the source along Z-axis. On the other hand, axial intrinsic resolution decreased when the axial distance from the centre increased, due to error introduced by the obliquity of the LOR more pronounced at the centre of the field of view.

4.2.2. *Spatial resolution in image*

Radial, tangential and axial image spatial resolutions calculated according NEMA procedure (Table 2) confirmed that the modelling was appropriate.

4.3. *Count-rate performance*

Measured and simulated single and prompt count rates agreed well for all activities up to 100 MBq for the two

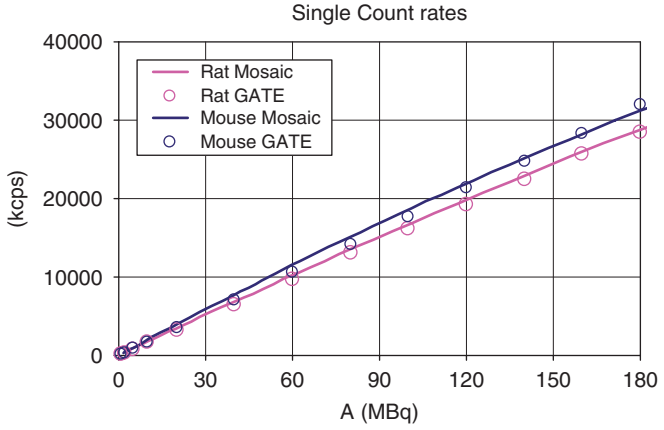

Fig 6. Simulated and measured single count rates for rat and mouse phantoms.

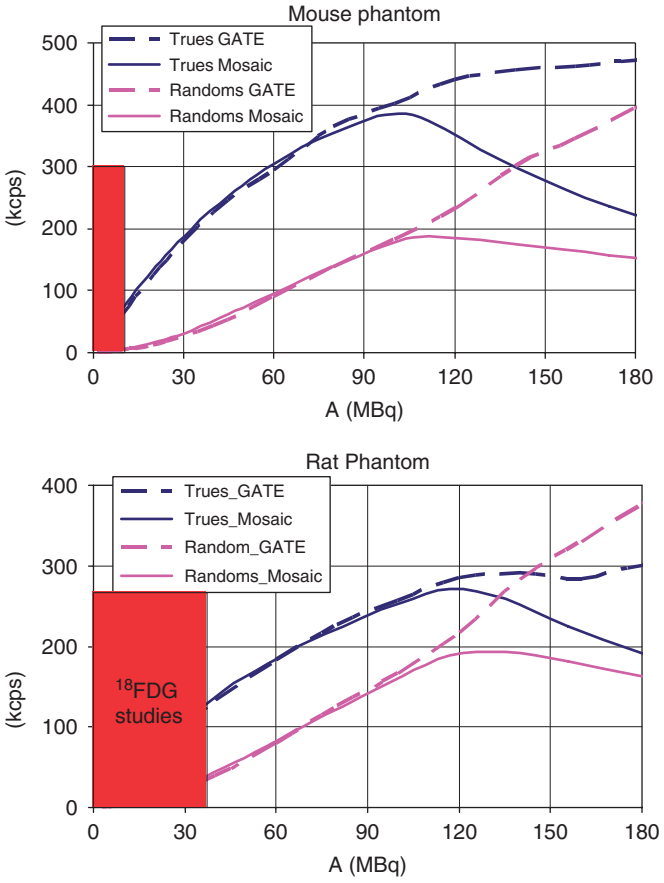

Fig 7. Simulated and measured coincidence count rate for rat and mouse phantoms. (Typical ^{18}F activities injected to mouse or rat are superimposed in pink)

homogeneous phantoms (Figs. 6 and 7) with 6% error. The activity limit of the model is higher than typical activity levels administered for ^{18}F rodent studies. For higher activities, the error increases due to the saturation of processors dedicated to the calculation of the energy and the position of each coincidence event that has not yet been simulated.

5. Discussion and conclusion

This paper presents a comparison between simulation and experimental data obtained on the Mosaic system using list-mode acquisition. Handling list-mode data was an important issue to derive the detector blurring on raw histograms. The approach has been validated on reconstructed point spread functions. Simulations agreed well with measured data obtained on the animal PET system and then will be used for a future work on image reconstruction.

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