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Nuclear Instruments and Methods in Physics Research A 569 (2006) 368–372

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

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Comparative evaluation of two commercial PET scanners, ECAT EXACT HR+ and Biograph 2, using GATE

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Available online 22 September 2006

Abstract

Geant4 application for tomographic emission (GATE) is a generic Monte Carlo simulation platform based on a general-purpose code GEANT4 and designed to simulate positron emission tomography (PET) and single photon emission tomography systems. Monte Carlo simulations are used in nuclear medicine to model imaging systems and develop and assess tomographic reconstruction algorithms and correction methods for improved image quantification. The purpose of this study is to validate two GATE models of the commercial available PET scanner HR+ and the PET/CT Biograph 2. The geometry of the system components has been described in GATE, including detector ring, crystal blocks, PMTs etc. The energy and spatial resolution of the scanners as given by the manufacturers have been taken into account. The GATE simulated results are compared directly to experimental data obtained using a number of NEMA NU-2-2001 performance protocols, including spatial resolution, sensitivity and scatter fraction. All the respective phantoms are precisely modeled. Furthermore, an approximate dead-time model both at the level of single and coincidence events was developed so that the simulated count rate curve can satisfactorily match the experimental count rate performance curve for each scanner In addition a software tool was developed to build the sinograms from the simulated data and import them into the software for tomographic image reconstruction where the reconstruction algorithm of FBP3DRP was applied. An agreement of less than 0.8 mm was obtained between the spatial resolution of the simulated system and the experimental results. Also the simulated scatter fraction for the NEMA NU 2-2001 scatter phantom matched the experimental results to within 3% of measured values. Finally the ratio of the simulated sensitivities with sources radially offset 0 and 10 cm from the central axis of each of the two scanners reaches an agreement of less than 1% between the simulated and experimental values. This simulation code will be used in a second phase in order to study scatter phenomena and motion artifacts. The simulation results will be used to optimize image reconstruction algorithms, with emphasis on dynamic PET studies.

Keywords: GATE; PET; HR+; Biograph; Monte Carlo simulations; Validation

1. Introduction

Monte Carlo simulations are used in nuclear medicine to model positron emission tomography (PET) or single photon emission tomography (SPECT) imaging systems in order to develop and assess tomographic reconstruction algorithms and correction methods for improved image quantification [1]. For these purposes several simulation codes have been used in the past. Geant4 application for tomographic emission (GATE) is a generic Monte Carlo simulation platform based on a general-purpose code

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0168-9002/$ - see front matter © 2006 Published by Elsevier B.V.
doi:10.1016/j.nima.2006.08.110

GEANT4 [2] and designed to answer the specific needs of PET/SPECT applications [3,4]. GATE includes specific modules necessary to perform realistic simulations, including modules managing time and time-dependent processes (detector and source movements, radioactive decay, and dynamic acquisitions), complex source distributions and easy description of scanner geometry. The ability to synchronize all time-dependent components allows a coherent description of the acquisition process and is one of the most innovative features of this package. GATE is an open source software and its development and validation is carried out by members of the OpenGATE collaboration.

The purpose of this study is to validate a Monte Carlo model for the simulation of the commercial available SIEMENS PET scanners of ECAT EXACT HR+ and the PET/CT Biograph 2 using GATE simulation package (version 2.2.0). Both scanners were chosen because of their wide area of applications throughout the last years. Their comparative evaluation on a simulation level is going to contribute to our better understanding of the influence of each one of their basic operational parameters on the efficiency and sensitivity of these systems. Furthermore, the comparative presentation of both the simulation and experimental data can trigger a thorough analysis in order to optimize the simulation parameter values at GATE and achieve tolerable and satisfying agreement between simulation and experimental output. This simulation code will be used in a second phase in order to study scatter phenomena and motion artifacts. The simulation results will be used to optimize image reconstruction algorithms, with emphasis on dynamic PET studies.

2. Materials and methods

2.1. Description of geometry

The scanner's physical and technical specifications were obtained from Siemens medical and CTI innovations data sheets. Direct measurements at the place of the installation were performed as well.

The ECAT EXACT HR+ PET scanner (Fig. 1) is located at Hammersmith Imanet Hospital at London. It consists of 4 block rings of 72 detector blocks each. Each block is constructed of an 8×8 BGO crystal array. The dimensions of each crystal element are $4.05\,\mathrm{mm} \times 4.39\,\mathrm{mm} \times 30\,\mathrm{mm}$. The detector ring diameter is 82.4 cm while the axial FOV is 155 mm [5].

On the other hand Biograph 2 (Fig. 2) is located at the Hospital of Ygeia in Athens. It consists of 3 block rings of 48 detector blocks each. Each block is made of an 8×8 LSO crystal array. The dimensions of each crystal element are $6.45\,\mathrm{mm} \times 6.45\,\mathrm{mm} \times 25\,\mathrm{mm}$. The detector ring diameter is 82.5 cm while the axial FOV is 180 mm.

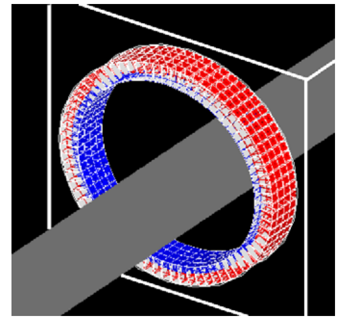

Fig. 1. ECAT EXACT HR+ geometry model using ECAT system in GATE.

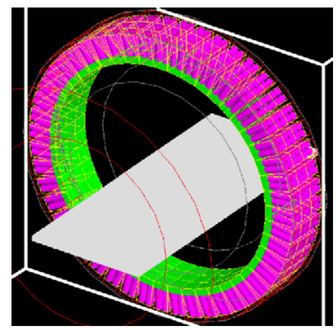

Fig. 2. Biograph 2 geometry model using cylindrical PET system in GATE.

2.2. Description of physics components

GATE is a simulation platform that has been designed to use the underlying physics components of Geant4 [6]. We selected to incorporate into our GATE simulation the low-energy models for the Compton, Rayleigh and photo-electric photon interactions. Specifically the following energy and range cuts were implemented into both of our models: delta ray, 10 keV; X-ray, 10 keV; and electron range, 2 mm.

2.3. Signal processor chain

One of the most interesting features of GATE is its ability to simulate the conversion of photon interactions into digital counts in an attempt to model the detector and electronic responses of a real scanner. [7] For this purpose a chain of signal processing functions is implemented into GATE which is called digitizer.

One of the digitizer modules we have used is Crystal-Blurring, which assumes an energy resolution for each crystal of the block randomly drawn from a uniform distribution for each scanner [5]. In the case of the ECAT EXACT HR+ scanner this distribution varies from 20% to 30% at 511 keV, while in the case of the Biograph 2 it varies from 16% to 26% at 511 keV. A global sensitivity factor for each crystal is also applied. In the case of the ECAT EXACT HR+ we found that a QE of 88% better matches the sensitivity experimental results, while in the case of the Biograph 5 a value of 92% proved to be the most appropriate.

Furthermore we applied a paralyzable approximate dead-time model in order to simulate the dead time both at the singles and the coincidences level of the signal processor chain of the scanner. In the case of the ECAT EXACT HR+ we applied a dead time of 5000 ns at the singles (block geometry level) and 500 ns at the coincidences level, while in the case of Biograph 2 the values that best fitted the respective count rate experimental results were 900 ns (block level), 300 ns (module level) at the singles and 300 ns at the coincidences. We should stress here that the manufacturers of both scanners did not provide us with any specific information concerning the dead time values of their scanners. As a result we estimated those values by choosing the ones that produced count rates and sensitivity that matched the measured values as close as possible.

In accordance with the specifications of the manufacturers we applied a 2τ coincidence time window of 12 ns for ECAT EXACT HR+ and of 6 ns for the Biograph 2. Coincidences are allowed between each of the 72 blocks and the opposing 31 blocks in the case of ECAT EXACT HR+ and between each of the 48 blocks and the opposing 24 blocks in the case of Biograph 5.

3. Results

The National Electrical Manufacturers Association (NEMA) performance protocols describe a series of explicitly defined experiments that have a significant recognition at the field of performance measurements for both PET and SPECT systems [8,9]. Therefore we had designed our simulation experiments according to these protocols. We have used ROOT data analysis framework [10] as an output data format. The simulated values produced for each scanner about the performance parameters of spatial resolution, sensitivity and scatter fraction were directly compared with the respective experimental values [11].

3.1. Spatial resolution

The spatial resolution of a system is a parameter that indicates its ability to distinguish between two points of radioactivity in an image and is measured in the transverse slice in two directions, radially and tangentially, and in the axial direction.

In accordance with the NEMA NU-2 2001 specifications we simulated an 1 mm diameter sphere which was uniformly filled with ^{18}F and placed at six different positions in the active FOV. Two axial positions are selected—namely, the center of the axial FOV and a position one-fourth of the axial FOV from the center. For both axial locations, the source is simulated at three positions, (a) $x = 0$ and $y = 1$ cm (1 cm vertically from the center of FOV), (b) $x = 0$ and $y = 10$ cm, and (c) $x = 10$ and $y = 0$ cm [8,9].

The images for the quantification of the spatial resolution were reconstructed using the software for tomographic image reconstruction (STIR) FBP3DRP code [12].

Table 1 contains values for the radial and tangential resolutions averaged over both axial positions, and for the axial resolution for each radial position considered (1 and 10 cm) for both scanners.

3.2. Sensitivity

The sensitivity performance parameter of a scanner represents its ability to detect annihilation radiation. In the NU 2-2001 standard, the absolute sensitivity of a scanner, which is expressed as the rate of detected coincidence events in counts per second (cps) for a given source strength, expressed in MBq is measured [8,9].

The NEMA NU 2-2001 sensitivity phantom is a 70-cm-long plastic tube that is uniformly filled with a known amount of radioactivity (18 F), sufficiently low that count losses and randoms are negligible. More specifically, random event rate should be less than 5% and the singles event count losses less than 1% of the true rate. This tubing is encased in five concentric aluminum tubes placed around the line source. The length of the aluminum tubes are also 70 cm and can be placed one inside the other.

Table 2 presents a comparison of the simulated and measured absolute sensitivities for the ECAT EXACT HR+ and Biograph 2 scanner when the sensitivity phantom is placed at the center and 10 cm from the center of FOV.

3.3. Scatter fraction

According to NEM NU 2-2001 standard, scatter fraction is defined to be the ratio of scattered events to total events, which are measured at a sufficiently low counting rate that random coincidences, deadtime effects and pileup are

Table 1
Spatial resolution for two different radial positions (1 and 10 cm from the center of FOV), calculated in accordance with the NEMA NU2-2001 protocol

	HR+		Biograph 2	
Experimental results				
Radial position (cm)	1	10	1	10
Orientation				
Radial resolution (mm)	4.82	5.65	6.12	7.02
Tangential resolution (mm)	4.39	4.64	5.89	6.31
Axial resolution (mm)	5.1	5.33	6.25	6.65
Simulated results				
Radial position (cm)	1	10	1	10
Orientation				
Radial resolution	4.17	4.62	5.43	6.54
Tangential resolution (mm)	3.83	3.98	5.24	5.71
Axial resolution (mm)	4.42	4.55	5.56	5.93

Table 2
Comparison between simulated and experimental values of absolute sensitivity (cps/MBq) for both scanners

	HR +	Biograph 2
Experimental results		
Transaxial offset position (cm)		
0	6650 cps/MBq	6722 cps/MBq
10	7180 cps/MBq	7237 cps/MBq
Ratio (0 cm/10 cm)	0.926	0.929
Simulated results		
Transaxial offset position (cm)		
0	6705 cps/MBq	6785 cps/MBq
10	7226 cps/MBq	7282 cps/MBq
Ratio (0 cm/10 cm)	0.928	0.932

Table 3
Comparison of the intrinsic scatter fraction simulated and experimental values for both scanners and for two energy windows

	HR +	Biograph 2
Experimental results		
Energy window (keV)		
300–650	46.9%	45.3%
425–650	N/A	34.1
Simulated results		
Energy window (keV)		
300–650	45.4%	44.1%
425–650	N/A	33.4%

negligible. Total events therefore, are the sum of unscattered events (trues) and scattered events [8].

According to NEMA NU 2-2001 standard, the scatter fraction phantom comprises a 20.3 cm diameter solid polyethylene cylinder with an overall length of 70 cm. A 70 cm-long line source is uniformly filled with ^{18}F and is threaded through a hole in the cylinder at a radius of 4.5 cm and parallel to the central axis [8,9].

Table 3 presents a comparison of the simulated and experimental values of the intrinsic scatter fraction of both scanners at two energy windows: (a) 300–650 keV and (b) 425–650 keV. We have experimental measurements only for the first energy window in case of the HR + and only for the second in case of the Biograph 2. In order to make a comparative evaluation of the scatter fraction parameter we simulated the NEMA scatter fraction experiments using both energy windows for both scanners.

4. Discussion and conclusion

The spatial resolution values, obtained using the simulated GATE model, are within 9% of the experimental values. Furthermore we observe that the results of the simulation are consistently indicating improved spatial resolution in comparison to the respective experimental measurements. These discrepancies are observed due to the absence of modeling within GATE the light shielding both within and between the detector blocks, the inherent limitations of the resolution of the photomultiplier tube's (PMT) and the light scatter within the crystals [6]. The underestimation of the simulated resolution can be accounted for and modelled by introducing an analytical Gaussian blurring function with a specific FWHM [6].

The analysis of the comparison between the simulated and experimental sensitivity values of both scanners demonstrates that the simulated measurements are less than 2% higher than the measured sensitivity.

The same factors as previously (in the case of spatial resolution) can also account for the discrepancies observed between simulated and measured sensitivity values. The implementation of the global quantum efficiency reduced the differences significantly, but the assumption of a uniform global factor does not reproduce the reality. The application of a varied QE factor might provide better agreement.

Finally the differences between the sensitivity of the HR + and Biograph 2 are nearly the same with the discrepancies observed between experimental and simulated data.

The comparative evaluation between simulated and experimental scatter fraction values shows a discrepancy of less than 3% for both scanners. The main factor that contributes to that difference is the approximation of the two geometry models used for the GATE simulation.

In order to compare the scatter fraction performance of the two scanners we decided to conduct simulations for both energy windows for each scanner. We concluded that in all cases Biograph 2 demonstrates a 2–3% better performance in terms of scatter fraction.

The conclusion of this study is that GATE has the ability to simulate accurately both the ECAT EXACT HR + and Biograph 2 PET systems. The discrepancies between experimental and simulated data were tolerable. In addition the relative differences between the experimental measurements of the two scanners remained in the case of the simulation results as well.

The above results indicate that the two GATE models described in this study were validated and can now be used for the optimization of emission acquisition protocols and validation of newly developed data correction and reconstruction algorithms. The use of voxelised phantoms and patient data will be the next step in order to include corrections of scatter and patient motion in reconstruction algorithms, thus improving quantification in clinical PET studies.

Acknowledgments

The authors would like to thank all the GATE users and developer community for their valuable suggestions and insight they have provided us during this validation study.

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