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Section A

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Validation of a GATE model for the simulation of the Siemens biograph^{TM} 6 PET scanner

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Abstract

The recently developed Geant4 Application for Tomographic Emission (GATE) toolkit is a Monte Carlo simulation platform developed for PET and SPECT simulations and is freely distributed by the OpenGATE collaboration. GATE provides the ability of modelling time-dependent phenomena, such as geometry element movements and source decay kinetics, allowing the simulation of time curves under realistic acquisition conditions. The purpose of this paper was to validate a GATE model for the simulation of the Siemens PET Biograph^{TM} 6 scanner. This three-dimensional GATE model simulated 24336 LSO (Lutetium Oxyorthosilicate) detectors grouped into 144 blocks in accordance with the vendor's specifications. GATE results were compared with experimental data, obtained in accordance with the NEMA NU 2-2001 performance measurement protocol. The scatter phantom used by this protocol was also modelled within GATE, allowing us to simulate scatter fraction and count rate performance measurements.

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Keywords: Validation; GATE; PET; Monte Carlo simulations; Biograph 6; NEMA NU 2-2001

1. Introduction

The main objective of the present study was to validate a Geant4 Application for Tomographic Emission (GATE) [1] model for the simulation of the Siemens Biograph 6 PET scanner. This was performed by comparing simulated results with experimental results for the scatter fraction and count rates performance parameters. An accurate dead inconsistent time model on detected single events level was developed. The comparison carried out was based on the NEMA NU 2-2001 performance protocol for a nominal activity concentration of 1 kBq/cm^3. Similar studies on different systems, either clinical or small-animal dedicated, have recently been published [1–6].

2. Materials and methods

2.1. Model description

2.1.1. Scanner geometry

GATE combines the advantages of the Geant4 simulation toolkit [2], like powerful visualization tools and the construction of simple shapes, such as boxes, spheres and cylinders in an explicit and user-friendly way, to generate complex geometric structures.

In accordance with the Siemens Biograph 6 PET scanner geometry, its digital geometry model comprises 48 detector

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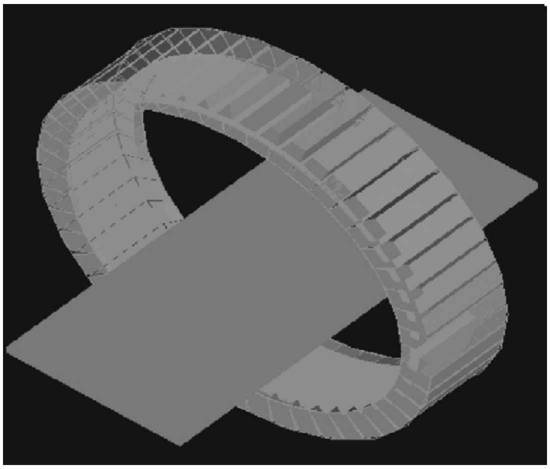

Fig. 1. GATE geometry model of the Siemens Biograph 6 PET scanner. Crystal modules, light guide, lead shields, on either side of the detector gantry, and couch are depicted.

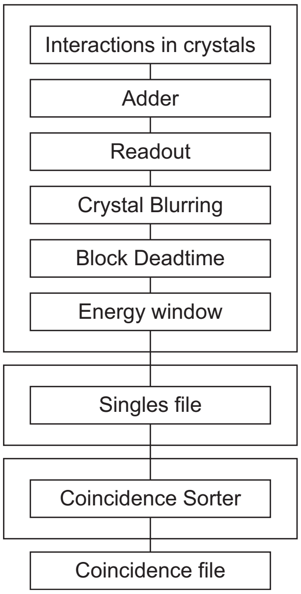

Fig. 2. Schematic diagram of the digitizer chain.

modules, arranged in three block rings. Each one of these modules consists of three blocks in the axial direction. Each block is made of 13 × 13 LSO (Lutetium Oxyorthosilicate) crystals (169 crystals per block). The whole scanner consists of 24,336 crystals arranged in 39 detection rings, each one with 624 crystals and 83 cm in diameter. The surface area and the thickness of the individual crystals are 4 × 4 mm^2 and 20 mm, respectively. The scanner has an axial field of view (FOV) of 16.2 cm and transverse FOV of 58.5 cm. In addition, the lead shielding rings (2.54 cm in thickness) on either side of the detection gantry as well as the scanning bed were included in the model. A light guide used to couple the crystal blocks with the cylindrical photomultipliers tubes (PMTs) was also included in the model as a photon scattering medium. The digital model of the scanner is shown in Fig 1.

2.1.2. Physics processes

The standard and low-energy Geant4 packages are used by GATE to simulate electromagnetic processes [1]. GATE also inherits the Geant4 capability to set thresholds for the production of secondary electrons, X-rays and δ-rays [1]. In this study, the standard energy package was used to model the photoelectric and Compton interactions and the low-energy one for the simulation of the Rayleigh interactions. The energy and range cuts for photons and electrons were the following [2]: electron range = 30 cm, δ-ray = 1 GeV and X-ray = 1 GeV.

2.1.3. Signal processing (or digitizer chain)

GATE also has the ability to simulate the behaviour of the scanner's detectors and the signal processing chain. This is achieved by a series of signal processors, which is referred to as the digitizer. The latter processes the photon interactions and produces single events from which the coincidence events are formed. Each signal processor of the digitizer mimics a separate portion of a real scanner's signal processing chain [3]. The digitizer modules used in our model are shown schematically in Fig. 2. Firstly, the *Adder* module sums the energy deposited by he particles' interactions within an individual crystal to yield a pulse. Next, the *Readout* module regroups pulses per block of crystals to create a pulse. Then, a *Crystal Blurring* module assigns a different energy resolution for each crystal in the detector block between a minimum (12%) and a maximum (18%) value referenced at 511 keV and applies a detection efficiency factor (0.9) to the *Redout* pulses [4]. Next, a paralysable Deadtime module is inserted in order to apply a deadtime on the single events level. Then, at the same level an *Energy Window* of between 425 and 650 keV is applied via the *Thresholder* and *Upholder* modules, both incorporated within the *Energy Window*. The modules described above result in the creation of a ROOT [5] *Singles File*, which contains the detected single events and, for each single event [6], the energy deposited and the coordinates of detection within the modelled scanner geometry. The *Coincidence Sorter* module searches, into the singles list, for pairs of coincident singles registered within the coincidence time window of 4.5 ns.

In the singles list, the event ID number (which uniquely identifies the annihilation event from which each single is coming from) and the number of Compton interactions that have occurred during the tracking of each photon are also stored [4]. The event ID number and the number of the Compton interactions are used in the classification of random and scattered coincidences, respectively [4].

2.2. Validation study

The National Electrical Manufacturers Association (NEMA) performance measurements protocol NU 2-2001 is widely accepted as the standard methodology for the assessment of individual PET system's performance. This

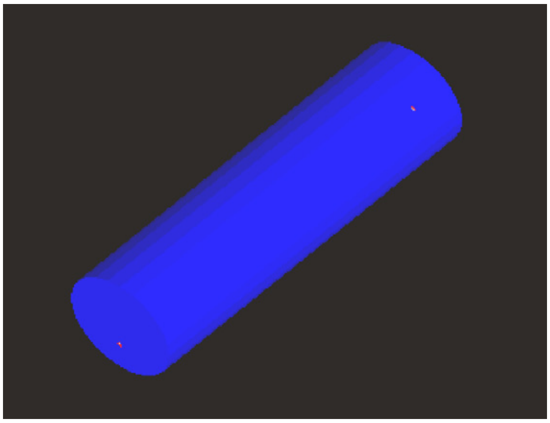

Fig. 3. View of the NEMA NU2-2001 scatter fraction phantom used in the scatter fraction and count rate performance measurements.

protocol includes revised measurements for spatial resolution, intrinsic scatter fraction, sensitivity, counting rate performance and accuracy of count loss and random corrections [7,8]. Only the scatter fraction and the count rates for a nominal activity concentration of 1 kBq/ml were examined for the evaluation of our deadtime model. The NEMA scatter phantom used for the measurements (scatter fraction and count rates) comprises a 20.3-cm-diameter solid polyethylene cylinder with an overall length of 70 cm and a 70-cm-long line source placed 4.5 cm radial offset from the centre of the cylinder [7,8]. The digital model of the scatter phantom is shown in Fig. 3.

2.2.1. *Coincidence count rates, scatter fraction, noise equivalent count rates*

The scatter fraction and count rate performance (both dead-time losses and randoms) measurements were simulated by filling the 70-cm-long line source uniformly with a solution of water and ^{18}F. The phantom was placed at the centre of the axial and transaxial fields of view and was rotated such that the line source is at the lowest position (i.e., nearest to the patient bed) [7,8].

Using the simulated count rates the SF was calculated as

$$\mathrm{SF} = \frac{S}{S+T}, \qquad (1)$$

where S and T are the scattered and true coincidences respectively, as described in Section 2.1.3 [7]. In addition, the Noise Equivalent Count (NEC) rates were calculated from the simulated count rates using the following expression (2):

$$\mathrm{NEC} = \frac{T^2}{T+S+kR}, \qquad (2)$$

where R is the number of random coincidences. The value of $k = 1$ was used during the direct measurements of NEC rates to denote a noiseless random correction [7,8]. Finally, as specified in the NEMA NU 2-2001 protocol, a fixed diameter of 24 cm (4 cm larger than the phantom diameter) was used for the calculations of the simulated count rates.

Table 1
Comparison of experimental and simulated count rates for 1 kBq/ml activity concentration and 900 ns (Simulated 1) and 700 ns (Simulated 2) dead time values

Results	True coincidence rate (CPS)	Random coincidence rate (CPS)	Scatter coincidence rate (CPS)	Total coincidence rate (CPS)
Experimental	13,846	638	6943	21,427
Simulated 1	11,949	609	5407	17,965
Simulated 2	12,224	635	5529	18,388

Table 2
Comparison of experimental and simulated noise equivalent count rates and scatter fraction for 1 kBq/ml activity concentration and 900 ns (Simulated 1) and 700 ns (Simulated 2) dead time values

Results	Noise Equivalent Count (NEC) rate (CPS)	Scatter fraction (%)
Experimental	8947	33,444
Simulated 1	7947	31,154
Simulated 2	8126	31,144

3. Results and discussion

Tables 1 and 2 contain experimental and simulated count rates and scatter fraction at specific activity concentration value of 1 kBq/ml for the NEMA NU 2-2001 scatter phantom. Simulated 1 and 2 results were taken after applying 900 and 700 ns deadtime values only on singles, respectively.

Considering low counting rates (1 kBq/ml), as specified by the NEMA NU 2-2001 protocol, simulated scatter fractions of 31.154% and 31.144% (see Table 2) were found for 900 and 700 ns deadtime values, respectively, against 33.444% for the measured one.

By decreasing the value of deadtime, scatter fraction values decreased as well, while the simulated count rate results (true, random, scatter and noise equivalent count rates) approached the experimental data.

4. Conclusions

The validation study of our Siemens Biograph 6 PET scanner model using GATE, a newly developed Monte Carlo simulation package, demonstrated good agreement between simulated and experimental results for scatter fraction and count rate performance measurements at 1 kBq/ml activity concentration.

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