

Scatter Fraction and Noise Equivalent Count Rate performance of the Siemens Biograph™ 6 Positron Emission Tomography (PET) scanner: Comparison of a GATE Monte Carlo simulation model with the NEMA NU 2-2001 protocol experimental data

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Abstract

GATE (Geant4 Application for Tomographic Emission) is a Monte Carlo simulation platform, based on the Geant4 Monte Carlo code, suitably developed for Nuclear Medicine applications, e.g. for Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT) system and dosimetry simulations. GATE is distributed by the OpenGATE collaboration and 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™ 6 scanner. This three-dimensional GATE model simulated 24336 LSO (Lutetium Oxyorthosilicate) detectors

grouped into 144 blocks in accordance with the vendor's specifications. The scatter phantom, used by the NEMA NU 2-2001 performance evaluation protocol, was also modelled within GATE framework, allowing us to simulate scatter fraction and count rate performance measurements. GATE simulation results were compared with experimental data, obtained in accordance with the NEMA NU 2-2001 protocol. Deviation of less than 3% was obtained for the scatter fraction and less than 9% for the noise equivalent count rate.

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1. Introduction

Monte Carlo simulation techniques are becoming an efficient research tool in the field of radiation physics and related medical imaging applications, such as design of new detector configurations, investigation of conditions for image quality optimization etc. GATE (Geant4 Application for Tomographic Emission) is a Monte Carlo simulation platform based on the Geant4 Monte Carlo code [1,2]. This platform is suitably developed for Nuclear Medicine applications, e.g. for Positron Emission Tomography (PET) and Single Photon Emission Computed Tomography (SPECT) system simulation and system design as well as for internal dosimetry simulations. GATE is distributed by the *OpenGATE collaboration* and 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 objective of the present study was to develop and validate a GATE (Geant4 Application for Tomographic Emission) [1] model for the simulation of the Siemens Biograph 6 Positron Emission Tomography (PET) scanner.

PET is widely accepted as a powerful imaging modality for functional imaging and treatment monitoring within the field of Nuclear Medicine. In the present work simulation results were compared with experimental results for the scatter fraction and count rates performance parameters. An accurate dead-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/cc. Similar studies on different systems, either clinical or small animal dedicated, have recently been published in the literature [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 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 24336 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 $4 \times 4 \text{ mm}^2$ 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 photomultiplier tubes (PMTs) was also included in the model as a photon scattering medium. The digital model of the scanner is shown in Fig 1.

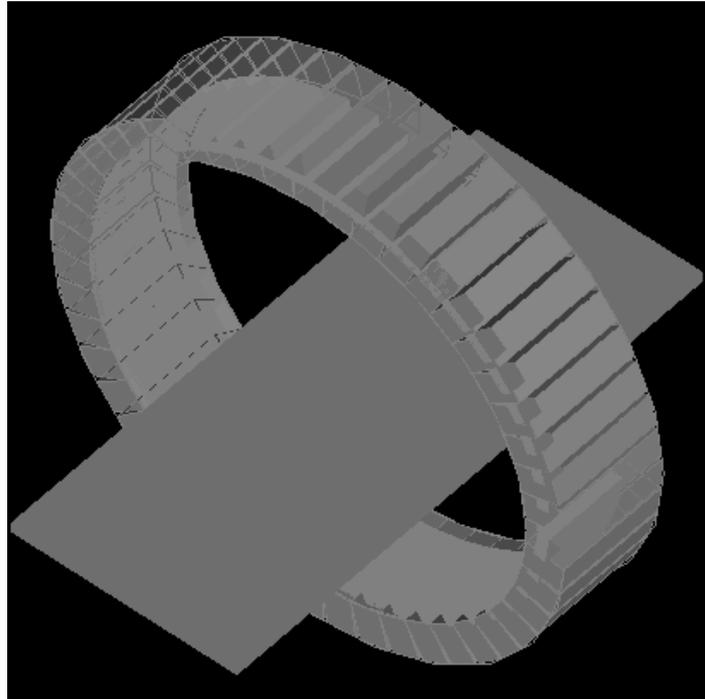


Fig. 1. GATE geometry model of the Siemens Biograph 6 PET scanner. Crystal modules, light guide, lead shields, on either side of the detector gantry, and -couch are depicted.

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 delta-rays [1]. In the present 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 the 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 *Readout* pulses [4]. Next, a paralyzable *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 keV 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].

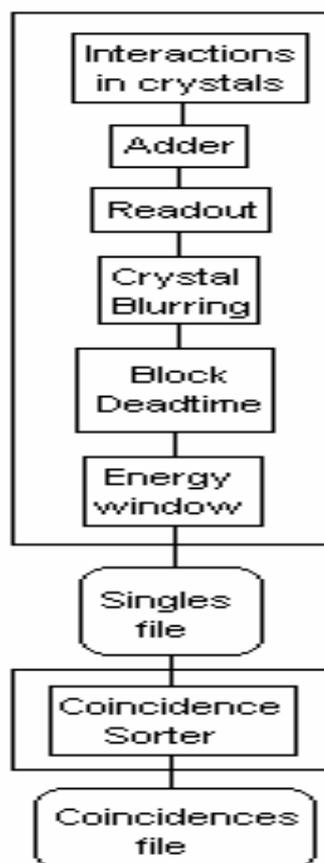


Fig. 1. Schematic diagram of the Digitizer chain.

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 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 scatter fraction was calculated as

$$SF = \frac{S}{S + T} \quad (1)$$

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):

$$NEC = \frac{T^2}{T + S + kR} \quad (2)$$

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 24cm (4 cm larger than the phantom diameter) was used for the calculations of the simulated count rates.

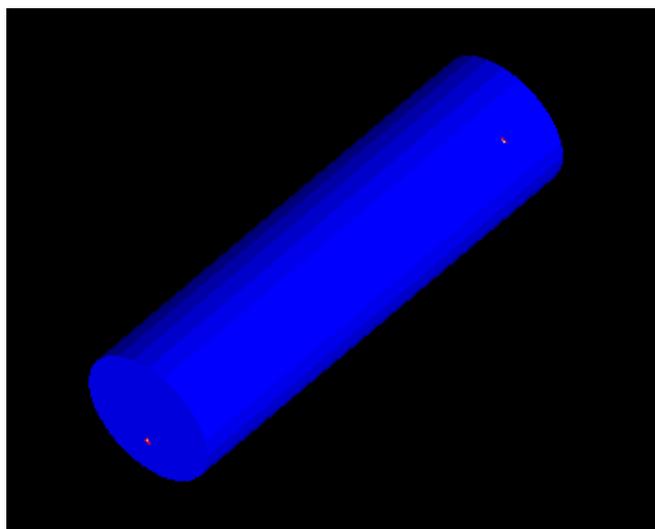


Fig.1: View of the NEMA NU2-2001 scatter fraction phantom used in the scatter fraction and count rate performance measurements.

3. Results and Discussion

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

Results	True Coincidence Rate (cps)	Random Coincidence Rate (cps)	Scatter coincidence Rate (cps)	Total coincidence Rate (cps)
Experimental	13846	638	6943	21427
Simulated 1	11949	609	5407	17965
Simulated 2	12224	635	5529	18388

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.

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 ns and 700 ns dead time values respectively against 33.444 % for the measured one.

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

Results	Noise Equivalent Count (NEC) Rate (cps)	Scatter Fraction (%)
Experimental	8947	33.444
Simulated 1	7947	31.154
Simulated 2	8126	31.144

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.

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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References

- [1] S. Jan et al., Phys. Med. Biol. 49 (2004) 4543–4561.
- [2] S. Agostinelli et al., Nucl. Instr. Meth. A, 506 (2003) 250–303.
- [3] C.R. Schmidtlein C.R. et al., Med. Phys. 33 (2006) 198-208.
- [4] OpenGATE Collaboration : <http://www-lphe.epfl.ch/GATE>.
- [5] R. Brun and F. Rademakers., Nucl. Instr. Meth. A, 389 (1997) 81–86.
- [6] F. Lamare et al., Phys. Med. Biol. 51 (2006) 943-962.
- [7] National Electrical Manufactures Association, NEMA standards publication NU 2-2001, Performance measurements of positron emission tomographs, Washington, DC, 2001.
- [8] M.E. Daube-Witherspoon et al., J. Nucl. Med. 43 (2002) 1398-1409.