Original article

Monte Carlo simulation of the basic features of the GE Millennium MG single photon emission computed tomography gamma camera

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A B S T R A C T

Objective: To describe and validate the simulation of the basic features of GE Millennium MG gamma camera using the GATE Monte Carlo platform.

Material and methods: Crystal size and thickness, parallel-hole collimation and a realistic energy acquisition window were simulated in the GATE platform. GATE results were compared to experimental data in the following imaging conditions: a point source of \textsuperscript{99m}Tc at different positions during static imaging. The accuracy between two different energy windows was assessed using the Mann–Whitney–Wilcoxon test. Comparisons were made regarding the measurement of sensitivity and spatial resolution, static and tomographic. Simulated and experimental static resolutions for tomographic data were compared with the Kruskal–Wallis test to assess simulation accuracy for this parameter.

Results: There was good agreement between simulated and experimental data. The number of decays expected when compared with the number of decays registered, showed small deviation (<0.007%). The sensitivity comparisons between static acquisitions for different distances from source to collimator (1, 5, 10, 20, 30 cm) with energy windows of 126–154 keV and 130–158 keV showed differences of 4.4%, 5.5%, 4.2%, 5.5%, 4.5% and 5.4%, 6.3%, 6.3%, 5.8% and 5.3%, respectively. For the tomographic acquisitions, the mean differences were 7.5% and 9.8% for the energy window 126–154 keV and 130–158 keV. Comparison of simulated and experimental static resolutions for tomographic data showed no statistically significant differences with 95% confidence interval.

Conclusions: Adequate simulation of the system basic features using GATE Monte Carlo simulation platform was achieved and validated.

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Simulación de Monte Carlo de los rasgos básicos de la cámara gamma SPECT GE Millennium MG

R E S U M E N

Objetivo: Describir y validar la simulación de características básicas de la cámara gamma GE Millennium MG utilizando la plataforma GATE Monte Carlo.

Material y métodos: El tamaño y espesor del cristal, la colimación de agujeros paralelos y una ventana de adquisición de energía realizada se simularon en la plataforma GATE. Los resultados GATE se compararon con los datos experimentales en las siguientes condiciones de formación de imágenes: fuente puntual \textsuperscript{99m}Tc en diferentes posiciones durante la adquisición de imágenes estáticas y tomográficas utilizando 2 diferentes ventanas de energía. La precisión entre los eventos esperados y detectados por simulación se realizó utilizando la prueba de Mann–Whitney–Wilcoxon. Las comparaciones se hicieron con respecto a las medidas de los parámetros sensibilidad y resolución espacial, estáticas y tomográficas. Las resoluciones espaciales simulada y experimental de los datos tomográficos se compararon con la prueba de Kruskal–Wallis.

Resultados: Hubo buena concordancia entre los datos simulados y experimentales. El número de decaimientos esperado, en comparación con los registrados, ha revelado una pequeña desviación (<0.007%). Las comparaciones de sensibilidad entre las adquisiciones estáticas, para diferentes distancias desde la fuente al colimador (1, 5, 10, 20, 30 cm) con ventanas de energía de 126–154 keV y 130–158 keV, mostraron diferencias de 4.4, 5.5, 4.2, 5.5, 4.5 y 5.4, 6.3, 6.3, 5.8 y 5.3, respectivamente. Las comparaciones entre sensibilidad tomográfica fueron 7.5 y 9.8% para la ventana de energía 126–154 keV y 130–158 keV. La comparación de resoluciones espaciales simuladas y experimentales para los datos tomográficos no ha mostrado diferencias estadísticamente significativas con un intervalo de confianza del 95%.

Conclusions: Se ha conseguido efectuar y validar una simulación Monte Carlo con la plataforma GATE de características básicas de funcionamiento de una cámara gamma GE Millennium MG.

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Introduction

Nuclear medicine uses radiolabeled molecules to target metabolic functions in vivo, known as radiopharmaceuticals. After administering the radiopharmaceutical to a patient, a radiation detector system such as a gamma camera can be placed externally to the body in order to detect gamma photon emissions resulting from radioactive decay. The chemical specificity of these molecules for some biological processes gives nuclear medicine its high specificity and sensitivity and in vivo functional characteristics.

Monte Carlo methods are recognized as being particularly useful for the simulation of new detectors for nuclear medicine applications. They have been applied to the study of detector efficiency in the design and optimization of imaging systems and in the development and evaluation of image correction strategies.

Currently, the set of Monte Carlo codes available can be divided into two main groups: the first one encompasses the so-called generic codes. These are essentially developed for the needs of high energy physics experiments and include EGS, MCNP, Integrated Tiger Series, PENEOPE2 and GEANT. The second group includes specific application codes, conceived for the specific needs of medical applications including nuclear medicine, such as SIMSPECT, SIMSET, McMATH9 and GATE. These Monte Carlo codes are characterized by their relative ease of utilization when compared to the more complex and complete generic Monte Carlo codes of the first group. During the last years, the Geant4 Application for Tomographic Emission (GATE) platform has been gaining increasing acceptance for the simulation of nuclear medicine devices and imaging processes. The GATE platform has specific coding mechanisms (known as scripting), which consist of specific software routines used to define hardware models (e.g. the nuclear medicine acquisition system). This ease of use allows creating models of detectors and options of data output formats which are compatible with proprietary solutions from manufacturers. GATE allows modeling the process of radioactive decay within objects resulting from the decay of a radionuclide and the physical interactions that result of these decays within an object. Different distributions of radioactive sources and time modeling during experimental acquisitions can also be done. These features of GATE introduced unprecedented flexibility for Monte Carlo simulation for nuclear medicine applications.

GATE has been used to validate different gamma camera systems, namely the Axis and Solstice systems from Philips, the Millennium VG Hawkeye and the DST-XII from General Electric. These studies have demonstrated that GATE can be used to accurately simulate different gamma camera systems, in different acquisition modes, using different acquisition conditions. The authors of these studies have considered that GATE allows obtaining precise results which closely follow experimental data. This paper describes and validates the use of GATE to model the basic imaging features of a Millennium MG gamma camera from General Electric. According to our knowledge, this gamma camera has never before been modeled using Monte Carlo computer codes.

Material and methods

Modeling the basic characteristics of the Millennium MG gamma camera

The GATE platform was installed and run in a 32-bit based PC server system with 4 GB of RAM and two processors with 3.4 GHz. The Linux Fedora Core 6 system, the gcc 4.1.1 compiler, and the Geant4 code were necessary to run GATE, CLHEP libraries, and the ROOT analysis software. After implementation of this simulation platform we have created a template of the Millennium MG gamma camera system using information supplied by General Electric. The simulated results produced by this model, in simple imaging situations, were then validated against experimental data. The Millennium MG gamma camera experimental data were obtained with the support of the department of molecular medicine of Hospitals Particulares de Portugal (MM – HPP), SA in Porto – Portugal.

Basic characteristics of the Millennium MG gamma camera

The Millennium MG gamma camera (GE Healthcare) is a dual detector nuclear medicine system that allows the detectors to be positioned with angles of 101.5°, 180.0° or 90.0° between them. Each one of the detectors is composed by a collimator, a scintillation crystal, a light guide, an array of photomultiplier tubes (PMTs) and the associated electronics. All these components, except the collimator, are attached to a shielded compartment. A collimator is an array of holes built into a lead or tungsten matrix. These holes can have different shapes, diameters and depths, depending on the type of collimator chosen, but they are always used to select the photons which will contribute for creating an image of the patient. The use of a so-called Low Energy High Resolution (LEHR) collimator, which possesses parallel holes, is extremely frequent in gamma cameras.

The features of the collimators used in the modeled gamma camera system reproduce the information provided by General Electric and present in the gamma camera operation guides. The lead collimator has rectangular (536 mm × 380 mm × 41 mm) geometry with 60,000 hexagonal holes of 1.8 mm of diameter and septa of 0.18 mm of thickness. The Millennium MG gamma camera is usually connected to an image processing workstation known as Xeleris™, which uses data processing software developed by General Electric.

The Millennium MG gamma camera is equipped with a thallium-activated sodium iodine (NaI(Tl)) crystal with thickness of 8.5 mm, density of 3.7 g/cm³, and dimensions of 536 mm × 380 mm. The detection of scintillation events, occurring through the arrival of photons emitted by an object in face of the detectors, that have crossed the collimator and interacted with the crystal, is assured by a hexagonal matrix of 48 PMTs with a diameter of 7.7 mm each. The intrinsic and extrinsic characteristics of the gamma camera detectors, such as the system’s energy resolution (9.7%), its intrinsic spatial resolution (3.9 mm), its extrinsic spatial resolution when equipped with the LEHR collimator (8.3 mm at 10 cm in air without dispersion, given by the manufacturer only for a static acquisition) and its sensitivity (61 cps/MBq at 10 cm in air without dispersion) were reported by General Electric, at the time of installation of this gamma camera on the MM – HPP.

Modeling the gamma camera’s basic geometry

In GATE, the geometrical structures of basic models must be defined within a generic virtual environment support volume known as world, where every simulated object must exist. The center of this world is also used to define the Cartesian axis (X,Y,Z) to which all object positions will be referred to (Fig. 1A).

The simulation starts by reproducing the geometrical characteristics of the detection system (i.e. each of the detectors, that include collimator, crystal and back compartment). Each detector was simulated as a parallelepiped (dimensions in three space directions: \(X = 199.5\,\text{mm}, \, Y = 536\,\text{mm} \) and \(Z = 380\,\text{mm}\) (Fig. 1A)).

A model of the LEHR collimator described above was then attached to one of each parallelepiped on one surface. The precise modeling of the LEHR collimator was done using the manufacturer’s technical specifications, relative to the diameter of the holes and the thickness of the septa.
Modeling the LEHR collimator geometrical characteristics

The LEHR collimator that we have developed consists of approximately 60,000 hexagonal holes. In order to reach a regular arrangement (Fig. 1B) of 60,000 hexagonal structures in a \(536 \times 380\) mm matrix and 41 mm of thickness, we were forced to perform some previous calculations in order to be able to obtain a realistic model of the gamma camera system. In GATE, one must provide the distance from the hole center to one of the faces of the hexagon, to be able to define it as an object. Considering that distance as \(r\) and taking into account a regular hexagon with length side \(s\), its inscribed and circumscribed circles will have a radius \(r\) and \(R\) respectively, as represented in Fig. 2A.

For a regular hexagon such as the one in Fig. 2A, we know the following:

\[
r = \frac{\sqrt{3}}{2} s; \quad R = s; \quad A = \frac{3}{2} \sqrt{3} s^2
\]

where \(A\) is the hexagon area.\(^{18}\)

Fig. 2C shows the distribution of the collimator holes within the plane of the collimator.

To determine the distance between the centers of the collimator holes \((Z_1\) and \(Z_2\) in Fig. 2C) we have used the following calculations. Since a regular hexagon has \(R = s\), and a circumscribed circle passes through the vertexes of the hexagon, then the triangle defined in Fig. 2B is equilateral and all the three angles are equal to 60°. Whereas the collimator septa have all the same thickness, this means that all the holes are centered along the directions \(Y\), \(Z\) and the direction on bisectrix of the angle \(\alpha\) defined (Fig. 2B).

Since the amplitude of \(\alpha\) is 60°, \(Z_1 = 1.98 \times \cos(30) \approx 1.7147\) mm and \(Z_2 = 2Z_1 = 2 \times 1.98 \times \cos(30) \approx 3.4295\) mm.

For the total numbers of holes which were to be included in the simulation of this collimator, we considered that each hole is an hexagon with internal diameter equal to the effective diameter of the hole (1.8 mm) plus the thickness of the septa (0.18 mm), and the distance between the centers of the hexagons was \(r = 0.99\) mm (Fig. 2C). If we consider a regular hexagon with side \(s'\), its circumscribed circle with radius \(R'\) and its effective area \(A'\), and taken into account the previous equations for the hexagon geometric properties, the following calculations were achieved:

\[
r' = \frac{1.8}{2} + \frac{0.18}{2} = 0.99\text{ mm}; \quad s' = \frac{2}{\sqrt{3}} r' \approx 1.1432\text{ mm};
\]

\[
R' = \frac{2}{\sqrt{3}} r' \approx 1.1432\text{ mm}; \quad A' = 2\sqrt{3} r'^2 \approx 3.3952\text{ mm}^2
\]

Along the \(Y\) axis, we therefore obtain a total number of approximately 270 holes.

However, along the \(Z\) axis, two different situations coexist. In the odd rows (first and third rows in Fig. 2C) the separation between odd and even hexagon centers was \(Z_2\) and \(Z_1\), respectively. Along this axis, we would have an approximate total number of holes of 221, according to the calculation:

\[
\frac{380}{1.98 \cos(30)} \approx 221
\]

The exact number of holes in the collimator can be determined by:

\[
\frac{536 \times 380}{1.98 \times 1.98 \cos(30)} = 59,991
\]

which is very close to the estimated total number of holes (~60,000) in the collimator.\(^{17}\)

Once these calculations are performed, we have used the repeat command of GATE in order to replicate these structures. To do this we have used: a cubic array repeater to shape the odd rows, and a linear repeater to shape the even rows (Fig. 3).

The features used to simulate the NaI(Tl) crystal of the gamma camera were a geometric box, with the dimensions 8.5 mm \(\times\) 536 mm \(\times\) 380 mm in the axis \(X\), \(Y\) and \(Z\). The material used to simulate the crystal was precisely NaI(Tl). This

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**Fig. 1.** Two simulated detectors in the interior of the world volume. (A) The dark gray represents the collimator, the black represents the crystal and the light gray represents the back compartment. (B) Collimator surface zoomed.

**Fig. 2.** (A) Geometric representation of hexagonal collimator hole, with radius \(r\) and \(R\) of the inscribed and circumscribed circles, and \(s\) the length side of the hexagon. (B) Angle definition in a hexagon for the calculation of collimator hole characteristics. (C) Disposition of the hexagons (i.e. holes) in the LEHR collimator used in the Millennium MG gamma camera system.\(^{17}\)
material was simulated as a mixture with 3.7 g/cm³ density and the composition of the elements with different weight fractions: 0.152 (sodium), 0.838 (iodine) and 0.010 (thallium).

The properties of the light guide and the PMTs were not supplied by the manufacturer. Therefore, we rely on the work of DeVries et al. and we considered a single glass layer (named back compartment) with 2.5 g/cm³ density, in our case the dimensions of this layer (X,Y,Z) were 150 mm × 536 mm × 380 mm, based on the real dimensions of the PMTs matrix of this gamma camera.

**Modeling the radioactive source**

The radioisotope used in the simulations was Technetium-99m ($^{99m}$Tc), which is the most common radioisotope used in nuclear medicine and used in similar simulation studies. The radioactive source of $^{99m}$Tc used in the simulations was defined as a “Point Source” (PS) monoenergetic gamma emitter of 140 keV, with an isotropic angular distribution emission of gamma photons.

**Basics of the physical processes simulation**

The interaction of the emitted photons with the gamma camera volumes (i.e. collimator, crystal, back compartment) was simulated using the GATE low energy package. This package comprises the Photoelectric, the Compton and the Rayleigh effects suffered by photons while crossing media of different densities.

Taking into account the information supplied by General Electric, we have considered that the gamma camera energy resolution at 140 keV would be 9.7% and its intrinsic spatial resolution 3.9 mm. We have considered that photons could be detected in two different energy windows: 126–154 keV (i.e. 20% energy window set symmetrically over the $^{99m}$Tc photopeak) which is frequently used in routine nuclear medicine procedures, and 130–158 keV (i.e. 20% asymmetric high energy window over the $^{99m}$Tc photopeak with 3% offset), which is used in cases where clinicians want to increase image contrast at the cost of some sensitivity loss.

**Comparison of simulated and experimental data**

The validation of the Monte Carlo model of the gamma camera data acquisition process was done using experimental data acquired at the nuclear medicine department of MM – HPP. In order to do this we have followed the approach taken by several other groups, which compared Monte Carlo simulations with experimental data acquired in similar conditions. Both planar and tomographic (i.e. Single Photon Emission Computed Tomography – SPECT) studies were performed.

Simulated and experimental data were transferred to a nuclear medicine software workstation – XelerisTM (GE Healthcare), and the tomographic data were reconstructed using the software package GeneralSPECT. This package implements filtered backprojection algorithm and used Hanning post-reconstruction filter. After this, all the simulated and experimental studies were analyzed using the same procedure. Comparison procedures were divided into two different sets: sensitivity tests, aiming to compare simulated and experimental data acquisition statistics; and image spatial resolution tests, aiming to compare it in the simulated and experimental data; both in planar and tomographic images. Both tests were performed using the two energy windows already defined and for different distances between the radioactive source and the detector. The acquisitions at different distances were used to evaluate if the Monte Carlo model could also account for sensitivity and spatial resolution resulting from these differences.

For sensitivity studies we used a $^{99m}$Tc PS with 1.74 MBq, based on a previous study. The static studies were acquired/simulated with a 128 × 128 pixel matrix, during 120 s and at different distances source to collimator (1, 5, 10, 20 and 30 cm). Point source sensitivity values were calculated in counts per second per MBq (cps/MBq), by dividing the total number of photons counts per second by the activity of the PS. This was done both for simulated and experimental data. The tomographic studies of a $^{99m}$Tc PS with 39.15 MBq were acquired/simulated at 20 cm from source to collimator, with a 128 × 128 pixel matrix, during 5 seconds per projections, so each tomographic acquisition had 160 s, in total of 32 projections per detector.

All simulations were repeated five times, in order to obtain the standard deviation (SD) concerning the average value and the percentage relative error. Besides that, all the acquired/simulated data were used with both energy windows aforementioned.

The accuracy of the Monte Carlo system developed to simulate the gamma camera was evaluated by comparing simulated and experimental, static and tomographic studies. In terms of the number of events theoretically expected taking into account the radioactive source activity and those simulated, statistical analysis was done using the Mann-Whitney–Wilcoxon test. The simulated and experimental sensitivities were compared using the number of cps/MBq, obtained for these studies in all conditions and furthermore was determined, for each study at different distances and for different energy windows, the percentage relative error. The evaluation of the system spatial resolution, in static and tomographic images, consisted in obtaining horizontal and vertical activity profiles (HP and VP) over the point source images. These profiles were then used to fit Gaussian functions. The full width at half maximum (FWHM) resulting from each of these fits was deemed to be representative of the system’s spatial resolution. The percentage relative error was used to compare the spatial resolution in static images and the Kruskal–Wallis test was used to test whether there were statistical significant differences between the system spatial resolution values obtained for the simulated and experimental data of tomographic acquisitions.

**Results**

**Number of events theoretically expected vs number of events registered in statics and tomographic images**

Table 1 shows the number of events theoretically expected and those registered by the simulation model, for the static and tomographic imaging of the $^{99m}$Tc PS tested, using two energy windows and different distances from the source to the collimator.

The inferential statistical analysis performed using the Mann–Whitney–Wilcoxon test demonstrates that the number of events registered by the simulation model is not statistically significant different from the number of events expected. This is the case for both energy windows (126–154 keV and 130–158 keV), in static images ($p=0.065$ and $p=0.057$, respectively) and tomographic images ($p=0.067$ and $p=0.024$, respectively). The agreement between these values was used as a first indication that the implemented simulation produced adequate results.
Table 1  
Counting rate expected and registered, at different energy windows and distances from the PS\(^{a}\) to the collimator.

<table>
<thead>
<tr>
<th>Source to collimator distance (cm)</th>
<th>1</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Static images</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of decays expected</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EW(^{a}) 126–154 keV and 130–158 keV</td>
<td>2.08680E + 08 (\pm 14.446) (^{c})</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of counts registered</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EW(^{a}) 126–154 keV</td>
<td>2.08690E + 08</td>
<td>2.08680E + 08</td>
<td>2.08683E + 08</td>
<td>2.08685E + 08</td>
<td>2.08675E + 08</td>
</tr>
<tr>
<td>Number of counts registered</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EW(^{a}) 130–158 keV</td>
<td>2.08691E + 08</td>
<td>2.08687E + 08</td>
<td>2.08697E + 08</td>
<td>2.08695E + 08</td>
<td>2.08667E + 08</td>
</tr>
<tr>
<td><strong>Tomographic images</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of decays expected</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EW(^{a}) 126–154 keV and 130–158 keV</td>
<td>1.95730E + 08 (\pm 13.990) (^{d})</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of counts registered</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EW(^{a}) 126–154 keV</td>
<td>1.95728E + 08</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Number of counts registered</td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>EW(^{a}) 130–158 keV</td>
<td>1.95727E + 08</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^{a}\) Point source.  
\(^{b}\) Energy window.  
\(^{c}\) For PS in static images, the number of decays expected was calculated by \(1.739.000(Bq) \times 120\) s. The error \(\pm 14.446\) was associated with the mean of the \(\sqrt{n}\) decays expected.  
\(^{d}\) For PS in tomographic images, the number of decays was calculated by \(39.150.000(Bq) \times 5\) s. The error \(\pm 13.990\) was associated with the mean of the \(\sqrt{n}\) decays expected.

Sensitivity measurements for static and tomographic images

The sensitivity calculations of simulated and experimental measurements for static images are compared in Table 2, at five different distances between the \(^{99m}\)Tc PS (1.74 MBq) and the detector, and for the two different energy windows tested.

The sensitivity comparisons between static acquisitions, for different distances from the source to the collimator with energy windows of 126–154 keV and 130–158 keV, showed percentage relative error below 5.5% and 6.3%, respectively.

The system sensitivity values obtained for simulated and experimental measurements, in the case of tomographic images, are compared in Table 2, for a \(^{99m}\)Tc PS (39.15 MBq) placed 20 cm away from the collimator, and for the two energy windows.

For the tomographic acquisitions the percentage relative error was 7.5% and 9.8% for the energy window of 126–154 keV and 130–158 keV.

Spatial resolution measurements for static and tomographic images

The simulated and experimental image activity profiles obtained for static images, which were used for the calculation of image spatial resolution, can be seen in Fig. 4 (the example for 1 cm and 30 cm). The corresponding values of spatial resolution are shown and compared to the value given by the gamma camera manufacturer in Table 3.

Fig. 5 shows the tomographic slices of the experimental acquisitions after image reconstruction. In the different slices shown in Fig. 5, profiles were drawn through the center of the image. Table 4 presents the spatial resolution (i.e. FWHM) measurements obtained from orthogonal activity profiles (HP and VP), in the simulated and experimental data for the three tomographic slices and the two energy windows considered.

According to Table 5, the results of using the Kruskal–Wallis test, in these data, showed no statistically significant differences, except for the simulated HP with EW 126–154 keV (\(p\) value \(< 0.05\)).

Discussion

This paper aimed to describe the Monte Carlo simulation of the basic data acquisition characteristics of a gamma camera system that has not been simulated before, and we have managed to produce realistic simulations using GATE Monte Carlo platform.

The number of events theoretically expected (i.e. total disintegration calculated from the activity), both in static and tomographic images, showed a relative error inferior to 0.007% in relation to the number of events that actually were registered by the simulation.

Table 2  
Comparisons regarding the experimental and simulated point source sensitivity values, obtained for planar and tomographic images, at different distances and energy windows.

<table>
<thead>
<tr>
<th>Images</th>
<th>Distances (cm)</th>
<th>EW(^{a}) 126–154 keV</th>
<th>Percentage relative error(^{d})</th>
<th>EW(^{a}) 130–158 keV</th>
<th>Percentage relative error(^{d})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Cps/MBq ± SD)</td>
<td>(Cps/MBq ± SD)</td>
<td>(%)</td>
<td>(Cps/MBq ± SD)</td>
<td>(Cps/MBq ± SD)</td>
</tr>
<tr>
<td>Planar</td>
<td>1</td>
<td>95 ± 0.5</td>
<td>91 ± 0.1</td>
<td>4.4</td>
<td>92 ± 0.6</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>99 ± 0.1</td>
<td>94 ± 0.1</td>
<td>5.5</td>
<td>96 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>99 ± 0.9</td>
<td>95 ± 0.1</td>
<td>4.2</td>
<td>96 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>98 ± 0.5</td>
<td>93 ± 0.3</td>
<td>5.5</td>
<td>96 ± 0.0</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>97 ± 0.2</td>
<td>93 ± 0.4</td>
<td>4.5</td>
<td>94 ± 0.4</td>
</tr>
<tr>
<td>Tomographic</td>
<td>20</td>
<td>98 ± 0.5</td>
<td>91 ± 1.1</td>
<td>7.5</td>
<td>96 ± 1.6</td>
</tr>
</tbody>
</table>

\(^{a}\) Energy window.  
\(^{b}\) Counts per second.  
\(^{c}\) Standard deviation.  
\(^{d}\) Percentage relative error \([\text{experimental-simulated}/\text{experimental}] \times 100\) between the experimental and simulation data.
These results showed that the simulation model implemented can predict accurately the number of theoretically events expected. For the results obtained we can also deduce that the modeled system accurately reproduces the sensitivity of experimental measurements within a percentage relative error inferior to 6.3%. Furthermore, these results are in agreement with what is described in the literature.  

When comparing the sensitivity of static and tomographic images, determined in simulated versus experimental studies, we have identified that the sensitivity measurements from simulation data yield higher values. These differences may be related to the fact that the implemented gamma camera model did not take into account small areas (dead spaces) between PMTs. Effectively, our model agglutinated PMTs and electronics in a back compartment with a uniform density. This means that the model assumes an area for photon detection which is bigger than that on the real gamma camera. The experimental loss of counts can also be due to the decay correction while gamma camera is acquiring. This is most important in tomography acquisition because total time is larger and the gamma camera need also time to change each angular view. In addition to this, there is also a small, but measurable, error introduced by the real PS radioactivity measurement (usually around 10% and

**Table 3**

Spatial resolution measurements obtained with simulated and experimental planar acquisitions.

<table>
<thead>
<tr>
<th>EW (keV)</th>
<th>Distance (cm)</th>
<th>HP simulation (mm ± SD)</th>
<th>HP experimental (mm ± SD)</th>
<th>Percentage relative error (%)</th>
<th>VP simulation (mm ± SD)</th>
<th>VP experimental (mm ± SD)</th>
<th>Percentage relative error (%)</th>
<th>Manufacturer</th>
</tr>
</thead>
<tbody>
<tr>
<td>126–154</td>
<td>1</td>
<td>8.3 ± 0.03</td>
<td>8.1 ± 0.01</td>
<td>2.5</td>
<td>8.3 ± 0.08</td>
<td>8.5 ± 0.17</td>
<td>2.2</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>9.0 ± 0.03</td>
<td>8.8 ± 0.09</td>
<td>1.6</td>
<td>9.0 ± 0.01</td>
<td>8.3 ± 0.11</td>
<td>3.3</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>9.4 ± 0.02</td>
<td>9.5 ± 0.14</td>
<td>1.2</td>
<td>9.6 ± 0.09</td>
<td>9.6 ± 0.06</td>
<td>0.2</td>
<td>8.3</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>12.2 ± 0.03</td>
<td>12.7 ± 0.29</td>
<td>3.5</td>
<td>12.9 ± 0.06</td>
<td>13.3 ± 0.14</td>
<td>3.3</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>16.3 ± 0.13</td>
<td>17.0 ± 0.20</td>
<td>3.6</td>
<td>16.6 ± 0.04</td>
<td>17.3 ± 0.47</td>
<td>4.0</td>
<td>–</td>
</tr>
<tr>
<td>130–158</td>
<td>1</td>
<td>8.4 ± 0.03</td>
<td>8.2 ± 0.05</td>
<td>2.3</td>
<td>8.4 ± 0.03</td>
<td>8.0 ± 0.23</td>
<td>5.2</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>9.0 ± 0.01</td>
<td>8.6 ± 0.01</td>
<td>4.6</td>
<td>9.0 ± 0.04</td>
<td>8.5 ± 0.26</td>
<td>5.4</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>9.7 ± 0.03</td>
<td>9.1 ± 0.15</td>
<td>4.2</td>
<td>9.7 ± 0.04</td>
<td>9.2 ± 0.27</td>
<td>5.7</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>20</td>
<td>12.4 ± 0.03</td>
<td>13.1 ± 0.05</td>
<td>5.5</td>
<td>12.7 ± 0.03</td>
<td>13.3 ± 0.23</td>
<td>4.8</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>30</td>
<td>16.3 ± 0.09</td>
<td>17.1 ± 0.07</td>
<td>4.3</td>
<td>16.2 ± 0.03</td>
<td>17.1 ± 0.02</td>
<td>5.3</td>
<td>–</td>
</tr>
</tbody>
</table>

*a Energy window.

*b Full width at half maximum.

*c Horizontal profile.

*d Standard deviation.

*e Percentage relative error [(experimental-simulated)/experimental] \times 100 between the experimental and simulation data.

*f Vertical profile.
due to the uncertainty of the activity measurement device used\textsuperscript{[23]} which is not present in simulated data.

According to the results provided, the point source sensitivity in simulated and experimental studies with the 126–154 keV energy window is slightly higher than those obtained with the 130–158 keV energy window. One explanation for this may be the fact that a higher energy window eliminates some of the scattered photons included in the image, therefore reducing the total number of photons detected with respect to the other energy window tested. In fact, this is a strategy used by clinicians to reduce the amount of scattered photons contributing to an image (and by this, increasing the contrast through a higher signal to noise ratio). We were unable to compare the sensitivity values obtained by simulation with those provided by the manufacturer. This was because the manufacturer obtained this value using a planar source (instead of a point source) and a different (narrower, 15\%) energy window (129.5–150.5 keV). This narrower window, contrary to the ones selected for this study, is not commonly found in the clinical setting. The comparison between spatial resolution simulated and experimentally measured, showed for both energy windows, percentage relative error below 6\% for static images, except for the VP at 5 cm distance between the source to collimator, for which the value was 8\%. When comparing the values of spatial resolution for a PS 10 cm away from the collimator, we have found differences below 1\%, between the simulated and experimental studies acquired. However, when comparing the simulated and experimental data in these conditions, with the values given by General Electric, we have found differences of 13.3\% and 14.5\%, respectively. A possible explanation for these differences could be related to the specific settings and acquisition conditions used by the manufacturer to obtain the values of the gamma camera spatial resolution. In the case of tomographic data, the percentage relative error was below 5.5\%. These results are in agreement with other studies of simulation validation of Nuclear Medicine equipment.\textsuperscript{[11]}

**Conclusions**

Computer modeling is a powerful tool to assess the performance of nuclear medicine imaging devices. As we have reported in this paper, even relatively simple models can accurately predict the basic performance of very complex systems like a gamma camera. The results obtained by simulation are in very good agreement with data obtained in real experiments. This allowed us to validate this GATE based Monte Carlo model of the basic performance of this General Electric gamma camera, with respect to important operational parameters such as the sensitivity and spatial resolution. This was done for a LEHR collimator, the most commonly used in the clinical setting, both in static and tomographic images and acquiring with two different energy windows.

It becomes obvious from our results that this model deserves to be improved, especially through the inclusion of PMTs geometry, location and physical properties. Additionally, system electronics and data processing should be included in the model, in order to get effects as acquisition dead time adequately modeled. Since GATE allows managing time during an experiment, studies comparing simulated and experimental data using time dependent

---

**Table 4**

<table>
<thead>
<tr>
<th>Energy Window (keV)</th>
<th>Tomographic slices</th>
<th>HP\textsuperscript{a} Simulation (mm) ± SD\textsuperscript{d}</th>
<th>HP Experimental (mm) ± SD</th>
<th>VP\textsuperscript{b} Simulation (mm) ± SD</th>
<th>VP Experimental (mm) ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>126–154</td>
<td>Transaxial</td>
<td>19.0 ± 0.01</td>
<td>19.9 ± 0.02</td>
<td>18.9 ± 0.00</td>
<td>20.0 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>Sagittal</td>
<td>18.9 ± 0.01</td>
<td>19.9 ± 0.06</td>
<td>18.9 ± 0.07</td>
<td>19.9 ± 0.03</td>
</tr>
<tr>
<td></td>
<td>Coronal</td>
<td>19.0 ± 0.05</td>
<td>19.9 ± 0.11</td>
<td>18.9 ± 0.07</td>
<td>19.9 ± 0.03</td>
</tr>
<tr>
<td>130–158</td>
<td>Transaxial</td>
<td>19.0 ± 0.00</td>
<td>19.9 ± 0.00</td>
<td>19.1 ± 0.01</td>
<td>20.0 ± 0.02</td>
</tr>
<tr>
<td></td>
<td>Sagittal</td>
<td>18.9 ± 0.03</td>
<td>19.9 ± 0.09</td>
<td>19.1 ± 0.06</td>
<td>20.1 ± 0.15</td>
</tr>
<tr>
<td></td>
<td>Coronal</td>
<td>19.0 ± 0.01</td>
<td>19.9 ± 0.02</td>
<td>19.1 ± 0.04</td>
<td>20.0 ± 0.05</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Energy window.  
\textsuperscript{b} Full width at half maximum.  
\textsuperscript{c} Horizontal profile.  
\textsuperscript{d} Standard deviation.  
\textsuperscript{e} Vertical profile.

**Table 5**

<table>
<thead>
<tr>
<th>Profiles</th>
<th>EW\textsuperscript{a} 126–154 keV</th>
<th>EW 130–158 keV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulated slices</td>
<td>HP\textsuperscript{b} 0.013</td>
<td>0.368</td>
</tr>
<tr>
<td></td>
<td>VP\textsuperscript{c} 0.217</td>
<td>0.368</td>
</tr>
<tr>
<td>Experimental slices</td>
<td>HP\textsuperscript{b} 0.509</td>
<td>0.679</td>
</tr>
<tr>
<td></td>
<td>VP\textsuperscript{c} 0.073</td>
<td>0.638</td>
</tr>
</tbody>
</table>

\textsuperscript{a} Energy window.  
\textsuperscript{b} Horizontal profile.  
\textsuperscript{c} Vertical profile.
information (e.g. ECG GATED SPECT studies) could also be performed in order to help optimizing clinical imaging protocols.

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Conflicts of interest

The authors have no conflicts of interest to declare.

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References