Capabilities of the Monte Carlo Simulation Codes for Modeling of a Small Animal SPECT Camera

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Abstract

Purpose This study aims to compare Monte Carlo-based codes' characteristics in the determination of the basic parameters of a high-resolution single photon emission computed tomography (HiReSPECT) scanner.

Methods The geometry of this dual-head gamma camera equipped with a pixelated CsI(Na) scintillator and lead hexagonal hole collimator were accurately described in the GEANT4 Application for the Tomographic Emission (GATE), Monte Carlo N-particle extended (MCNP-X), and simulation of imaging nuclear detectors (SIMIND) codes. We implemented simulation procedures similar to the experimental test for calculation of the energy spectra, spatial resolution, and sensitivity of HiReSPECT by using ^{99m}Tc sources.

Results The energy resolutions simulated by SIMIND, MCNP-X, and GATE were 17.53, 19.24, and 18.26%, respectively, while it was calculated at 19.15% in experimental test. The average spatial resolutions of the HiReSPECT camera at 2.5 cm from the collimator surface simulated by SIMIND, MCNP-X, and GATE were 3.18, 2.9, and 2.62 mm, respectively, while this parameter was reported at 2.82 mm in the experiment test. The sensitivities simulated by SIMIND, MCNP-X, and GATE were 1.44, 1.27, and 1.38 cps/μCi, respectively, on the collimator surface.

Conclusions Comparison between simulation and experimental results showed that among these MC codes, GATE enabled to accurately model realistic SPECT system and electromagnetic physical processes, but it required more time and hardware facilities to run simulations. SIMIND was the most flexible and user-friendly code to simulate a SPECT camera, but it had limitations in defining the non-conventional imaging device. The most important characteristics like time and speed of simulation, preciseness of results, and user-friendliness should be considered during simulations.

Keywords HiReSPECT · Gama camera · GATE · SIMIND · MCNP

Introduction

Monte Carlo simulations (MCS) have greatly contributed to the development of nuclear medicine imaging in both single photon emission computed tomography (SPECT) and positron emission tomography (PET). They are extensively applied in the design and optimization of new medical imaging instruments [1]. They are also used to optimize data acquisition protocols, develop and evaluate tomographic image

reconstruction algorithms, and assess correction methods for improved image quantification [2–5]. So, accurate evaluation of gamma camera performance can be made by using Monte Carlo simulation techniques. Available Monte Carlo simulation codes in nuclear imaging are divided into two categories: general purpose codes (EGS4, GEANT, Monte Carlo N-particle (MCNP)), developed for high-energy physics or dosimetry, and dedicated codes (simulation of imaging nuclear detectors (SIMIND), SimSET, SimSPECT, PETSIM). Choosing each of these MC toolkits depends on various factors such as the abilities of the user and the computer system type and configuration [6]. In this paper, we evaluated and compared the ability of three independent Monte Carlo codes (GEANT4 Application for the Tomographic Emission (GATE), Monte Carlo N-particle extended (MCNP-X), and SIMIND) to simulate a small-animal SPECT system. The results of this study can help researchers to make better selection to consider the abilities and facilities of the codes. Also, the

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use of independent codes provide a valuable test of the Monte Carlo predictions.

Materials and Methods

In this study, we used high-resolution SPECT (HiReSPECT) which was designed and developed to provide high resolution for small-animal molecular imaging [7–9]. This dual-head gamma camera consists of pixelated CsI(Na) scintillator, a low-energy high-resolution (LEHR) parallel-hole collimator and two Hamamatsu H8500 position-sensitive photomultiplier tubes (PSPMT) in each head. The geometric characteristics of the pixelated crystal and hexagonal-hole collimator are presented in Table 1.

Monte Carlo Simulations

MCNP

MCNP-X is a general-purpose Monte Carlo N-Particle extended code developed at the Los Alamos National Laboratory and designed to track 34 different types of particles (nucleons and ions) over a broad range of energies. Firstly, the solid geometry (cells and surfaces) must be defined, and then the material and tally card implemented in the input file in the MCNP-X code. Cells are defined by intersections, unions, and complements of the regions and contained user-defined materials. Each cell is bound by a surface or multiple surfaces [10]. Figure 1 shows the geometry of HiReSPECT scanner and tracks of source particles simulated by MCNP-X.

The tally cards are used to specify what type of information (current across a surface, flux at a point, energy deposition averaged over a cell) the user wants to gain from the Monte Carlo calculation. Pulse-height tally (F8 tally) calculates the energy distribution of pulses created in a detector using gamma radiation and the scintillation light [11]. Figure 2 shows the energy spectra simulated by using the MCNP-X code. As seen in Fig. 2, the MCNP output pulse height spectrum shows sharp spectra.

Table 1 The geometric characteristics of detector and hexagonal collimator

Crystal		Collimator	
Crystal size	100 × 50 mm ²	Material	Lead
Crystal element size	1 × 1 × 5 mm ³	Thickness	34 mm
Crystal element pitch	1.2 mm	Hole size	1.2 mm
Active area per detector head	96 × 45.6 mm ²	Septa width	0.2 mm

MCNP-X code does not simulate physical effects leading to the broadening of the spectrum, while data has a Gaussian distribution shape for the energy lines in the experimental spectra. So, the MCNP uses a fitting technique that consisted of using a “FT8 GEB” card. GEB is a special treatment for tallies to better simulate a physical radiation detector in which energy peaks exhibit Gaussian energy broadening [12]. The tallied energy is broadened by sampling from the Gaussian which is done by Eq. (1):

$$f(E) = c e^{-\left(\frac{2\sqrt{\ln 2}(E-E_0)}{\text{FWHM}}\right)^2} \quad (1)$$

where E is the broadened energy; E_0 is the unbroadened energy of the tally; and c is normalization constant.

$$\text{FWHM} = a + b\sqrt{E} + cE^2 \quad (2)$$

where a , b , and c are fitting parameters [13]. Figures 3 and 4 show the images of a ^{99m}Tc (140 keV) point source on the homogenous and pixelated CsI(Na) detector surfaces simulated by the MCNP-X code when Gaussian energy broadening was applied. A point source images will spread into a distribution in gamma camera; the distribution is called the point spread function (PSF). Thickness of crystal, photoelectric absorption, and Compton scattering interactions affect PSF. PSF can be expressed mathematically as a one- or two-dimensional distributions.

SIMIND

SIMIND was developed in FORTRAN-90 and can be described by any standard clinical SPECT camera. It can model parallel-hole, pinhole, fan-beam, converging, diverging, and slant-hole collimators. SIMIND accurately simulate all interaction of photons in collimators by using analytic formulation. The SIMIND program consists of two programs named CHANGE and SIMIND. The CHANGE program enables the user to easily define the desired imaging system. It contains a series of menus that prompt the user to input parameter. The SIMIND program reads the input files created by the CHANGE program. It performs the actual simulation [14, 15].

GATE

GATE was written in C++ and incorporates the GEANT4 libraries describing the physics processes (photoelectric effect, Compton scatter, and Rayleigh scattering) by using the low-energy electromagnetic package. This simulation toolkit provides flexibility and simplicity in defining an input for simulating a complex geometry of both SPECT and PET cameras. The most important property of GATE is the ability to simulate time-dependent phenomena such as source decay, dynamic acquisitions, and movement components of the gamma

Fig. 1 **a** The HiReSPECT camera. **b** The geometry of HiReSPECT and tracks of source particles simulated by MCNP-X code

camera [16–18]. Figure 5 illustrates a 3D model of the HiReSPECT system simulated in the GATE environment.

In general, the output generated by GATE is stored as projection, ASCII, and ROOT file formats. The binary data (ROOT file) is read by the accompanying ROOT macro, written in C++ [19]. ROOT is a framework for data processing and visualizing large amount of data, developed at CERN.

Basic System Performances

The Monte Carlo codes, GATE v7.2, MCNP-X version 2.4.0, and SIMIND version 6.0 were employed in this paper. In order to trust the Monte Carlo simulation data, the simulation model must be validated. The validation of the small animal SPECT camera was based on the comparison of basic parameters measured experimentally [7] with the corresponding simulation data, energy spectra, spatial resolution (full width at half maximum (FWHM)), and sensitivity. All experimental and simulated data was acquired using 20% energy window (126–154 keV) centered in the photopeak to reduce the noise

Fig. 2 MCNP output pulse height spectrum without considering Gaussian distribution

effects. The energy resolution and spatial resolution were set about 20% at 140 keV and 1.2 mm, respectively, in simulations. The activity of 2 mCi (74 MBq) for ^{99m}Tc sources and 37.5 s in each projection were considered in GATE simulations. For each simulation, 570×10^6 events were tracked. A total number of 64 projections were simulated. A 5×10^9 photons/projection was considered in MCNP-X and SIMIND input files. The energy spectra created by SIMIND contained a spectrum of 512 channels.

Energy Resolution

The energy resolution was measured with a flood-field phantom with dimensions of $110 \times 60 \times 5 \text{ mm}^3$ filled with ^{99m}Tc solution. The same experimental procedure was considered for the simulations. We used ROOT analysis for the determination of the energy spectra in GATE simulation.

Spatial Resolution

The system spatial resolution was measured by using a thin capillary (1.1 mm inner diameter and 5 cm length) filled with Tc-99m. The line source was placed at different distances from the detector along short and long directions in the useful field of view (UFOV). Spatial resolution was calculated as FWHM of the line spread function (LSF).

System Sensitivity

The system sensitivity, defined as counts per second per activity (μCi), was experimentally measured and calculated by using GATE, MCNP-X, and SIMIND for a cylindrical phantom with an inner diameter of 32, and 5 mm thickness was filled with Tc-99m, centered on FOV, and located at different

Fig. 3 Intrinsic resolution with a ^{99m}Tc (140 keV) point source for the homogenous CsI(Na) detector. **a** Energy distribution of point source. **b** Intensity of source as Gaussian curve

distances from the collimator. A planar acquisition of this source was performed over 300 s and registered the total number of counts in the photopeak window (126–154 keV).

Results

The energy spectra obtained by the simulation of a CsI(Na) detector using SIMIND, MCNP-X, and GATE codes are shown in Fig. 6. Figure 6b illustrates the MCNP pulse height spectrum after applying the Gaussian spreading. Also, the contribution of scatter components simulated by GATE is seen in Fig. 6c. The energy resolution of the gamma camera was

determined by the measurement of the FWHM of the photopeak in the energy spectrum. The simulated energy resolutions acquired by SIMIND, MCNP-X, and GATE were 17.53, 19.24, and 18.26%, respectively, while it was calculated at 19.15% in experimental test [7].

Figure 7 shows the simulated LSF for the SPECT camera using Matlab via MCNP-X, SIMIND, and GATE outputs at 2.5 cm distance from the collimator surface with a 140-keV energy line source in the air. The spatial resolution was calculated as FWHM of the LSF. Figure 8 depicts the experimental and simulated FWHM as a function of distance from the collimator surface in (a) the vertical and (b) horizontal directions. As expected for parallel-hole collimator, the spatial resolution

Fig. 4 Intrinsic resolution with a ^{99m}Tc (140 keV) point source for the pixelated CsI(Na) detector. **a** Energy distribution of point source. **b** Intensity of source as Gaussian curve

Fig. 5 A 3D model of the simulated HiReSPECT system in the GATE code

had a linear trend with distance. The average spatial resolutions of the HiReSPECT camera at 2.5 cm from the collimator surface simulated by SIMIND, MCNP-X, and GATE were 3.18, 2.9, and 2.62 mm, respectively, while this parameter was reported at 2.82 mm in the experiment test [7]. The simulated sensitivities of the HiReSPECT as a function of

distance are shown in Fig. 9. The experimental and simulated sensitivities on the collimator surface are listed in Table 2. The sensitivity simulated by SIMIND was 6.6 and 13.38% more than GATE and MCNP simulations. While difference between SIMIND-simulated sensitivity and experimental data was 9.5%.

Discussion

GATE is a recent simulation toolkit, enabling the accurate modeling of a large variety of configurations in both SPECT and PET scanners. Slight difference observed between GATE simulation and experimental data in this study might be due to the imperfect modeling of the PSPMT non-uniform response. As the HiReSPECT is a dual-head camera, we presented both detector heads in the GATE simulation so that backscattering from one head onto the other can be modeled, which is important for the sensitivity, spectra, and scatter profiles and for resolution analysis, while MCNP and SIMIND codes do not

Fig. 6 The simulated energy spectrum using **a** SIMIND, **b** MCNP, and **c** GATE codes

Fig. 7 Line spread function (LSF) of the SPECT camera simulated by **a** SIMIND, **b** MCNP-X, and **c** GATE at 2.5 cm distance from the collimator surface

have this capability. It allows the users to describe time-dependent phenomena such as detector movements. MCNP has limited ability to simulate the optical photons so it is difficult to calculate the broadened energy spectrum. As seen in Fig. 2, the MCNP output pulse height spectrum showed sharp spectra when we did not consider the effects of broadening the photopeak and neither the response functions of the detector. Some of the effects that broaden the photopeak are inherent to

the electronic circuit of the system. It is necessary to consider these physical effects in the simulation for obtaining experimental adjustment parameters of the energy resolution of detector and apply the function provided by the MCNP-X code that fits a Gaussian to the spectrum [13]. Other drawback of MCNP is simulation of SPECT rotation because MCNP cannot simulate dynamic models. Although the SIMIND-dedicated code can model different collimators based on

Fig. 8 The simulated and experimental spatial resolutions of the HiRESPECT camera with respect to source-to-collimator distance in the **a** vertical and **b** horizontal directions

Fig. 9 The simulated sensitivities of SPECT camera as a function of distance from collimator surface

analytic formulations of the geometric response for collimators, it has limited flexibility for simulating non-conventional imaging device. Unlike GATE and MCNP-X, SIMIND cannot simulate pixelated configuration of a pixelated detector hence a homogenous detector is simulated. The dead area between crystals in pixelated detector can affect the performance of the imaging system. The pixelated detector had a lower sensitivity per area with respect to the homogenous detector due to the dead area between crystals. A gamma-ray photoabsorption within a pixelated crystal creates scintillation photons that are confined to a crystal and focused onto a small spot on the photodetector array. Because fewer photodetector elements are involved in positioning, this could improve the spatial resolution compared with continuous detector sharing light among several photodetectors. However, the pixelated detector has worse energy resolution compared with homogeneous detector because of reduced light transmission and subsequent collection by the photon transducers [20–22]. So, SIMIND results were different from that of GATE and MCNP simulations. Also, slight differences observed between GATE and MCNP simulation results are because of slight differences in the way that photons are detected in GATE and MCNP. Compared with GATE and MCNP, time of SIMIND simulation is short. In fact, one of the major motivations behind the development of dedicated MC codes is to build a user-friendly interface that requires minimal level of programming skills. This simplicity of use may be the reason behind the popularity of these codes in nuclear medicine imaging simulation studies.

Table 2 The experimental and simulated sensitivities of the HiReSPECT scanner

	GATE	MCNP-X	SIMIND	Experimental
Sensitivity (cps/μCi)	1.35	1.27	1.44	1.31 (head 1); 1.32 (head 2)
Spent time (min)	1576.8	1167.6	379.2	5

PC configuration, 8 CPU; 3.2 GHz

Conclusion

In this study, the HiReSPECT camera was evaluated with three Monte Carlo-based codes, namely MCNP-X, GATE, and SIMIND. A comparison between simulation and experiment including sensitivity, spatial, and energy resolutions showed that among these MC codes, GATE enabled to accurately model a realistic SPECT configuration. The major drawback of GATE is the computation time, especially when using complicated geometries. However, a solution to speed up simulations could be use in variance reduction techniques and computer clusters. Compared with GATE, MCNP-X showed more simplicities and easier handling, but MCNP had more complexity than SIMIND. Although the SIMIND-dedicated code is usually convenient to use and well suited to the simulations of SPECT camera, it cannot accurately simulate complex geometry of pixelated detector. So, we suggest a researcher who is going to perform simulation and validation using a SPECT camera to utilize the SIMIND as the primitive and easy estimator at first step and include GATE for developing the procedure in more detail afterward.

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Compliance with Ethical Standards

Conflicts of Interest Alireza Sadremomtaz and Zeinab Telikani declare that they have no conflict of interest.

Ethical Approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed Consent The institutional review board of our institute approved this retrospective study, and the requirement to obtain informed consent was waived.

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