

Monte Carlo simulations in emission tomography and GATE: An overview

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Abstract

Monte Carlo simulations are nowadays an essential tool in emission tomography (Single-Photon Emission Computed Tomography—SPECT and Positron Emission Tomography—PET), for assisting system design and optimizing imaging and processing protocols. Several Monte Carlo simulation software are currently available for modeling SPECT and PET configurations.

This paper presents an overview of current trends concerning Monte Carlo simulations in SPECT and PET. The evolution of the place of Monte Carlo simulations in SPECT and PET since 1995 is studied, together with the evolution of the codes used for Monte Carlo simulations. New features present in current codes are described, and new applications of Monte Carlo simulations in SPECT and PET are reviewed. Finally, upcoming developments in the field of Monte Carlo simulations in SPECT or PET are discussed. In this paper, a particular emphasis is given to the GATE code, as it is the most recent and publicly available code for Monte Carlo simulations appropriate for both SPECT and PET applications.

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1. Introduction

Monte Carlo simulations are nowadays an essential tool in nuclear medicine imaging, both in single-photon emission computed tomography (SPECT) and in positron emission tomography (PET). Two recent papers have thoroughly reviewed the principles and the use of Monte Carlo simulations in SPECT and PET, as well as the different codes available to perform such simulations [1,2]. This paper will thus focus not on Monte Carlo simulations in SPECT and PET in general, but rather on what has changed in the realm of Monte Carlo simulations recently in the past 5 years (2000–2004) with respect to the 5 years before (1995–2000), and on the current trends regarding the use of this approach.

To assess the evolution of Monte Carlo simulations in SPECT and PET in the past 10 years (since 1995), we considered publications cited in MedLine using “Monte Carlo” and “tomography” as key words for search. This search aimed at finding all medically oriented papers making use of Monte Carlo simulations in SPECT and PET. We emphasize that this bibliographic study was strongly biased towards medical applications since, for instance, only the “IEEE Transactions in Medical Imaging” journal was included, while “IEEE Transactions in Nuclear Science” was not. However, it was our intend to examine the practical role of Monte Carlo simulations in the medical community.

The paper is organized as follows. First, the general evolution of the use of Monte Carlo simulations in SPECT and PET is reported in Section 2. Then, the frequency of the use of the different codes available for Monte Carlo simulations is examined in Section 3. Section 4 presents new features recently added in Monte Carlo simulations while Section 5 presents new applications of Monte Carlo

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simulations in SPECT and PET. Finally, Section 6 discusses possible upcoming developments in that field. GATE, which is the most recent SPECT and PET simulator and is publicly available, is given a special attention along this paper.

2. Evolution of the use of SPECT and PET Monte Carlo simulations since 1995

The Medline search yielded 666 entries. Only those corresponding to studies using Monte Carlo simulations to produce SPECT and PET images were selected, resulting in 130 articles between 1995 and the date of the search (July 2005).

Since 1995, the number of full papers referenced in MedLine reporting the use of Monte Carlo simulations for modeling SPECT and PET studies keeps increasing slowly (Fig. 1). Forty-nine full papers have been published between 1995 and 1999, while 69 have been published between 2000 and 2004 (41% increase). As expected, more and more articles concern PET rather than SPECT. Between 1995 and 1999, 14% of the 49 published articles dealt with PET, while between 2000 and 2004, 35% of the articles dealt with PET (150% increase). Five papers concerned small animal imaging between 2000 and 2004, while none of the full papers published between 1995 and 1999 dealt with small animal imaging. These values support the fact that the applications of Monte Carlo simulations closely follow the general trends observed in nuclear medical imaging.

Also, there was an 18% increase in the number of labs producing papers involving SPECT and PET Monte Carlo simulations (28 labs between 1995 and 1999 against 33 labs between 2000 and 2004).

3. Evolution of the codes used for Monte Carlo simulations in SPECT and PET since 1995

Between 1995 and 1999, 14 codes were used for Monte Carlo simulations in SPECT and PET, among which 10 were “home-made”, i.e., not used by another group than the group who developed the code, and 4 were publicly

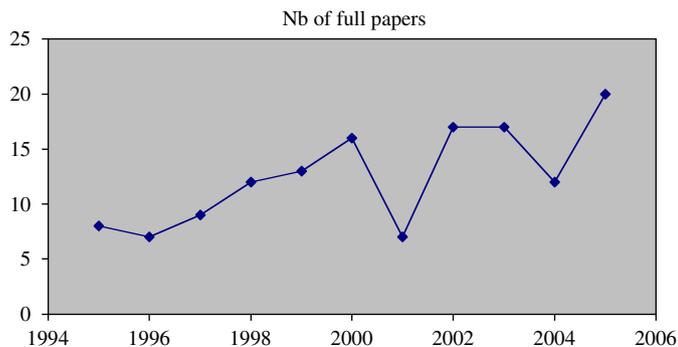


Fig. 1. Number of full-papers cited in Medline and making use of Monte Carlo simulations for producing SPECT or PET images.

released or available from authors (EGS4 [3], MCNP [4], SimSET [5], and SIMIND [6]). Between 2000 and 2004, 15 codes were used among which 8 were home-made and 7 were publicly released or available from authors (EGS4, MCNP, SimSET, SIMIND, GEANT [7], Penelope [8] and GATE [9]). The total number of codes used for Monte Carlo simulations in SPECT and PET is thus stable. This suggests that there is no such thing as a standard code for Monte Carlo simulations in SPECT and PET that most people would agree on and use. Two codes have yet been used predominantly since 1995: SimSET (20 articles) and SIMIND (24 articles). SimSET was developed at the University of Washington in Seattle [10]. It is publicly available and can model PET and SPECT acquisitions. Since 1995, its use has been reported in articles by 10 different labs, among which 6 in the United States. SIMIND was developed in Lund, Sweden and is available on request from authors [6]. It models SPECT acquisitions only, and has been used by 8 different labs among which 4 in Sweden. Since 2000, three additional codes have been used for SPECT and PET simulations: GEANT (versions 3 and 4), Penelope, and GATE. The use of GEANT and Penelope reveals the interest in using “generic” Monte Carlo codes for SPECT and PET simulations, i.e., codes which have not been originally designed for SPECT and PET simulations, but for a broad range of applications. This observation, together with the fact that users were ready to trust a code provided by others (as exemplified by the relatively wide use of SimSET and SIMIND) were actually two motivations for the development of GATE, based on GEANT4 [9]. The development of GATE by the OpenGATE collaboration (<http://www.opengatecollaboration.org>) in 2001 was initially started to overcome the limits of the existing codes at that time. More specifically, GATE was intended to provide a code: (1) based on a standard code to ensure reliability and long-term support; (2) which would make PET and SPECT simulations possible; (3) flexible enough to accommodate modeling of almost any type of PET and SPECT scanners, including prototypes; (4) with original functionalities relevant for SPECT and PET simulations, especially modeling of time-dependent processes; (5) user-friendly enough not to restrict its use to a small community already knowledgeable in Monte Carlo simulations. Even now, none of the codes except GATE meets all these conditions.

It is too early to say whether GATE, which has been publicly released in May 2004, will become the code most frequently used for SPECT and PET simulations. In the 2004 IEEE Medical Imaging Conference proceedings however, among the 61 proceedings involving Monte Carlo simulations in SPECT or PET, 11 used GATE, 9 used GEANT4, 8 used SimSET, 4 used SIMIND, while all the other codes were used in less than 3 proceedings. 15 papers reported the use of home-made codes. Also, on August 2005, more than 400 individuals had subscribed to the GATE users mailing list, confirming the interest potential

users show in a public domain tool for SPECT and PET Monte Carlo simulations.

4. New features in Monte Carlo simulators

Current Monte Carlo simulators present some appealing functionalities that were lacking in previous codes. The most recent advances concern the modeling of time-dependent processes, the increase of the throughput of simulations, and the modeling of original detector designs. These recent advances will now be explained and illustrated.

4.1. Modeling time-dependent processes

A major and recent advance in Monte Carlo simulations is the current possibility to model time-dependent phenomena. This makes it possible to realistically model dynamic biodistributions of the tracers, physiological motions such as respiratory and cardiac motions, displacement of the scanner (rotation of the camera heads in SPECT for instance), time-of-flight (TOF) PET, radioactive decay, and dead time effects. Any Monte Carlo simulation code can do at least part of that by just repeating simulations while changing the input data concerning the description of the object (to mimic changes in the biodistribution or motions), or concerning the description of the detector (to mimic change in the detector position with respect to the object). However, at least three codes have been specifically designed so that time-dependent phenomena can be more easily handled. PET-SORTEO [11,12] can model the evolution of activity concentration in time within different regions as defined by the user. However, it cannot easily model respiratory or cardiac motion. SimSET has been recently extended to keep track of TOF [13]. This makes it suitable for modeling TOF PET. However, SimSET cannot easily handle simulations of time–activity curves in different physiological regions, nor detector motion. To the best of our knowledge, the only code which can model any time-dependent effect is GATE. In GATE, time is explicitly used when defining the configuration to be simulated and is always kept track of during the simulation. As a result, GATE can model detector motion (e.g., [14]), time–activity curves in different physiological regions, radioactive decay [15], TOF PET [16], and physiological motions.

4.2. Increasing the throughput of the simulations

A major drawback of Monte Carlo simulations is the computation time required to get a realistic data set, especially when simulating realistic configurations involving voxelized descriptions of activity and attenuation distributions. Efforts to reduce computation time have been recently reported, using different strategies.

Use of acceleration methods: One option is to use accelerations techniques, such as importance sampling

[17]. Such techniques are for instance available in SimSET, and it has been shown that their use reduce the computational time by a factor between 2 and up to more than 10 [18], without jeopardizing the accuracy of the simulated data. The main issue related to the use of such techniques is that they strongly alter the statistical properties of simulated data [18]. The only way to get realistic data from a statistical point of view therefore consists in simulating almost noise-free data, using a very high statistics, and then adding noise following an appropriate model (e.g., Poisson noise for SPECT data). The method of delta scattering has also been recently used to speed-up Monte Carlo simulations in SPECT, by avoiding the calculation of intersections between photon paths and boundaries between different media [19]. The acceleration factors associated with the use of this method in SPECT and PET simulations have not been reported yet.

Combining Monte Carlo and non-Monte Carlo modeling: Another option to speed up Monte Carlo simulations in SPECT and PET is to model particle transportation using a combination of Monte Carlo and non-Monte Carlo modeling. This approach is worthwhile for modeling effects that are, from a macroscopic point of view, well suited to an analytical or tabulated description. A typical example is the analytical modeling of the collimator response function in SPECT: photon propagation is modeled using the Monte Carlo approach in the object, and once the photon escapes from the object, an analytical model is used to determine the position of impact of the photon in the crystal of the camera, given the parameters of the collimator. This approach, which has been implemented in SimSET, is well suited when the collimator response mostly depends on its geometrical characteristics, and when the scatter and septal components of the collimator response can be neglected. This is true only for low-energy isotopes, such as Tc-99m, when considering photons in the conventional 20% energy window. However, such a model is not appropriate for isotopes presenting high-energy emission, such as In-111 [20]. For high energy isotopes, Monte Carlo transportation of photons in the collimator can still be avoided by using pre-calculated angular response functions [21]. Whatever the non-Monte Carlo modeling method of the collimator response function is, simulation time is reduced by a factor between a hundred and several thousands. Similarly, scatter can also be modeled approximately without performing full Monte Carlo transportation in specific configurations (e.g., modeling of downscatter in Ref. [22]). All these approaches have the potential to speed up Monte Carlo simulations, at the expense of a loss of generality as they are based on models with a limited range of applications. The most satisfactory approach might therefore be to have them included as options in simulators, while still having the possibility of running fully Monte Carlo simulations.

Parallelizing the code: A third track that has been recently explored to speed up simulations is that consisting in adapting the code to make it appropriate for parallel

execution. Several successful attempts have been made along this line. For instance, a specific scheme has been described for parallel execution of SimSET using a client–server system for distributed computation [23]. Since the servers do not have to be identical machines, a client-side scheduler was implemented to partition the total decay events by taking into account the inherent computer speeds and recent average workloads. The only modification that had to be made to the original SimSET code was to ensure that the total number of decay events specified by the user was maintained in the distributed simulation. The increase of speed was typically equal to the number of “maximum-service” processors corresponding to the total number of processors available, where the “maximum-service” processor corresponds to the fastest processor with a zero workload.

SIMIND has also been successfully implemented on an IBMSP2 distributed memory parallel computer [24]. In that example, parallelization was based on equally partitioning photons among the processors. The message passing interface library was used for interprocessor communication. The scalable parallel random number generator (SPRNG) was used to generate uncorrelated random number streams. A linear increase in computing speed with the number of processors was demonstrated for up to 32 processors.

Although no option for parallel execution is proposed yet in the public release of GATE (version 2.2), the feasibility of the execution of GATE on a cluster of computers has already been demonstrated [25]. The approach is platform independent, and automatically generates macros and a cluster submit file, without requiring any interaction from the user. The feasibility of the deployment of GATE on a grid architecture has also been demonstrated [26]. It is expected that future GATE releases will include the material needed for the parallel execution of GATE.

4.3. Modeling original detector designs

As new detectors are being developed at an increasing speed, Monte Carlo simulations play an increasing role in predicting performance as a function of the detector design. Such studies are feasible if the code is flexible enough to model various types of detector geometry or components. To model a broad range of detector geometry, there are currently two options: either use a generic simulator, such as GEANT4, EGS4 or Penelope, or use GATE, which is currently the code able to accommodate the largest number of detector geometry. For instance, the spherical shape of the Hi-Rez PET tomograph could not be accurately modeled using SimSET, but only using GATE (or a generic code) [27]. GATE is the code used the most for studying prototypes, including—to quote a few—a CsI(Tl) gamma camera dedicated to small-animal imaging [28], the PhotoDetection Systems prototype PET scanner [29], the OPET system [30], a high-resolution

SPECT system dedicated to small animal imaging [31], a dual layer phoswich detector for small animal PET [32]. The flexibility of GATE is further illustrated by the number of commercial tomographs that have been modeled using GATE, both in SPECT (e.g., AXIS, IRIX, DST-Xli and Millenium VG Hawkeye), in PET (e.g., ECAT Exact HR+, Advance, Allegro, ECAT HRRT, Hi-Rez) and in small animal imaging (e.g., MicroPET P4, microPET Focus 220, ClearPET), to quote only some for which results have already been reported (all corresponding references on <http://www.opengatecollaboration.org>). Despite its recent availability, GATE has thus already been proven to be highly flexible. This is a new trend compared to older codes which are much less flexible.

5. New applications for Monte Carlo simulations

5.1. Evolution of the applications in time

To study the different applications of the simulations, we excluded the review papers (2 papers only) and assigned the remaining papers to one among 4 categories: (1) design and/or assessment of reconstruction or correction methods, (2) study of the imaging system response (including optimization of the detector design), (3) use of the simulation in the very imaging process (e.g., for scatter correction or for calculating the system matrix), and (4) data production for evaluation purpose (e.g., for assessing detectability).

Between 1995 and 1999, the most two widespread applications were assessment of correction or reconstruction methods (47%) and study of the imaging system response (51%). Only one article (2%) reported the use of Monte Carlo simulations for producing datasets to be used for detectability studies. Between 2000 and 2004, Monte Carlo simulations were still used a lot for assessment of correction or reconstruction methods (42%) and for study of the imaging system response (33%), but new applications appeared. Simulations were used in the very imaging process, either for corrections or for calculating the system matrix used for reconstruction (8%). They were also used more for producing data needed for evaluation studies (8%). In addition, more articles were dedicated to the description of simulation codes or of the way they could be efficiently implemented (9%). This suggests that the range of potential applications for Monte Carlo simulations currently broadens. To illustrate this trend, two very recent applications are presented below.

5.2. Using Monte Carlo simulations to calculate the system matrix

Tomographic reconstruction consists in solving the inverse problem:

$$p = \mathbf{R}f$$

where p represents the sinograms or the projections, f is the object to be reconstructed and \mathbf{R} is the system matrix. Each element \mathbf{R}_{ij} represents the probability that a photon (or positron) emitted in voxel j of the object be detected in projection bin i . For a long time, the system matrix was calculated using analytical modeling as a function of the detection geometry. Recently, several groups have proposed to calculate the system matrix using Monte Carlo simulations. There are two reasons why this can be advantageous. First, for non-conventional system geometries, \mathbf{R} may be difficult to derive analytically. This is especially the case for small animal imaging device, for which the analytical calculation of \mathbf{R} might be a real challenge (e.g., Refs. [33,34]). Second, it might be desirable to estimate \mathbf{R} using Monte Carlo simulations in fully 3D reconstruction, to precisely model 3D scatter which is hard to predict from a theoretical point of view. For these two situations, \mathbf{R} can be estimated using Monte Carlo simulations and can account either for the detector geometry only (e.g., Refs. [33,34]), or for the detector geometry and the object attenuating properties derived, for instance, from a CT scan of the patient (e.g., Ref. [35]). Although Monte Carlo calculation of the system matrix is very computationally intensive, results are quite promising and emphasize the need for more efficient simulations to make such applications clinically feasible.

5.3. Using Monte Carlo simulations for feeding database

Another recent application is the use of Monte Carlo simulations to produce datasets appropriate for validation studies. In SPECT and PET, there is a lack of databases including realistic data well suited for the evaluation of reconstruction or correction methods, of segmentation or registration algorithms, or of any processing algorithms. Few well-known anthropomorphic phantoms are used, such as the Zubal phantom [36], the MCAT phantom [37], or the NCAT phantom [38], but many evaluation studies would gain from considering large samples of cases, mimicking a large variety of configurations, and for which the actual activity distribution is precisely known (unlike with real patient scans). Monte Carlo simulations are an ideal tool to build appropriate database for evaluation purpose. Two recent attempts in that direction have just been reported [12,39]. Although it is too early to assess the impact of these initiatives, building databases using Monte Carlo simulations might become more and more frequent. This would especially be useful as Monte Carlo simulators remain technical tools, not easy to master well, and which request important computational resources. Some labs can therefore not afford to run their own simulations, while they would yet benefit from Monte Carlo simulated data if available. Similar to real case databases, databases of simulated configurations might become important, not only for evaluation purpose but also for educational purpose. In this latter application, as the exact activity distribution used for the simulation is known, as well as the

exact characteristics of the propagation medium and of the detector, the link between reconstructed images and actual activity distribution can be thoroughly studied and understood, as well as the quantification biases.

6. Upcoming developments in Monte Carlo simulations

6.1. Bridging the gap between imaging and dosimetry

In Nuclear Medicine, Monte Carlo calculations are currently used not only in the context of SPECT and PET imaging, but also in the context of dosimetry, to assess dose deposit following internal or external radiation. Most often, different codes are used for these two fields, although some codes have been used for both, like EGS4. The reason for using different codes is that the particles of interest are different (mostly photons for imaging and electrons for irradiation), and that the scaling at which computations have to be made is also different (mm for imaging, rather micrometers for dosimetry). Nevertheless, these two fields tend to become closer. Indeed, imaging is used more and more often for dosimetric purpose. A typical example is the study of the biodistribution of a radiotracer using imaging to predict the dose distribution of a therapeutic agent. For instance, dosimetry of Zevalin labeled with Yttrium 90 can be performed using SPECT imaging of Zevalin labeled with Indium111 [40]. A desirable evolution of Monte Carlo simulations would be to bridge the gap between these two uses of Monte Carlo simulations, so that a dose map could be directly obtained from the activity distribution as input for PET and SPECT Monte Carlo simulations. This would make it possible to directly compare the actual dose map corresponding to the biodistribution of the tracer used for producing the SPECT or PET data with that estimated from the reconstructed PET or SPECT images. Using a single simulation framework would make it possible to use a common coordinate system, a common object description, and consistent sampling, thus reducing issues occurring when using different simulation frameworks. Efforts in that direction are under way, for instance in GATE [41].

6.2. Modeling hybrid machines including a CT

With the advent of SPECT/CT and PET/CT machines, one can question the relevance of simulating the CT components of such machines. Simulators for CT scans do exist, but are often not based on Monte Carlo simulations, because of the very high flux of photons needed to get CT images. Monte Carlo simulations of CT data have been reported however for dedicated applications (e.g., Ref. [42]). The availability of simulated CT data together with simulated PET or SPECT data would be especially useful for studying corrections of PET or SPECT data based on the CT data (e.g., attenuation, scatter or partial volume effect correction) and for studying the effect of motions which affect CT and PET or SPECT data differently.

6.3. Designing realistic phantoms

The value of Monte Carlo simulated data depends on the realism of the input data. Currently, Monte Carlo simulations are mostly used for simulating relatively simple phantoms. For instance, most of the time, even when considering anthropomorphic phantoms [36,37], patient respiratory and cardiac motions are ignored, and so is the change of the physiological biodistribution of the tracer during the scan. However, even when interested in static scans only in which the heart is not of interest, respiratory and cardiac motions should not be ignored as they introduce kinetic blurring affecting detection and quantification in neighboring regions [43]. A more systematic use of realistic input data for Monte Carlo simulations would make simulations even more relevant.

Another example illustrating this idea is the use of NEC curves for studying the performance of a PET tomograph when changing detector components or acquisition parameters. The NEC curves are often calculated for standard activity distributions in the field of view, while it would be more relevant to assess the NEC curves for various types of patients (e.g., thin, obese, short, tall), to determine how well NEC curves measured using NEMA phantoms predict NEC curves for real patients.

Although quite realistic anthropomorphic phantoms are already available, both for human and for small animal studies, the impact of Monte Carlo simulations in SPECT and PET would be increased by the development of a wider variety of numerical realistic anthropomorphic phantoms. These should include humans with a wide variety of body habitus and motions, and small animal models with breathing and cardiac motions. The accuracy, especially in terms of spatial and time sampling, with which the activity distribution and the propagation media have to be defined to get images similar to clinical images still have to be determined. In the future, Monte Carlo simulators will have to enable the use of such complicated numerical phantoms in reasonable time to meet the always-increasing need of researchers.

7. Conclusion

The field of Monte Carlo simulations in SPECT and PET is expanding, as this approach offers invaluable possibilities to better understand the power and the limits of SPECT and PET imaging, and to pinpoint the critical aspects of the imaging process which currently limit the capabilities of these modalities. The latest developments in Monte Carlo simulations, together with the increased power of computers now make Monte Carlo simulations an accessible tool, which can generate realistic complex data in reasonable time for various applications. Monte Carlo simulations might be even more present in nuclear medical imaging in the future, maybe in the very imaging process, or at least as a continual guide

to properly interpret qualitatively and quantitatively real patient images.

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