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Development and Validation of a Monte Carlo Simulation Tool for Multi-Pinhole SPECT

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Abstract

Purpose—In this work, we developed and validated a Monte Carlo simulation (MCS) tool for investigation and evaluation of multi-pinhole (MPH) SPECT imaging.

Procedures—This tool was based on a combination of the SimSET and MCNP codes. Photon attenuation and scatter in the object, as well as penetration and scatter through the collimator detector, are modeled in this tool. It allows accurate and efficient simulation of MPH SPECT with focused pinhole apertures and user-specified photon energy, aperture material, and imaging geometry. The MCS method was validated by comparing the point response function (PRF), detection efficiency (DE), and image profiles obtained from point sources and phantom experiments. A prototype single-pinhole collimator and focused four- and five-pinhole collimators fitted on a small animal imager were used for the experimental validations. We have also compared computational speed among various simulation tools for MPH SPECT, including SimSET-MCNP, MCNP, SimSET-GATE, and GATE for simulating projections of a hot sphere phantom.

Results—We found good agreement between the MCS and experimental results for PRF, DE, and image profiles, indicating the validity of the simulation method. The relative computational speeds for SimSET-MCNP, MCNP, SimSET-GATE, and GATE are 1: 2.73: 3.54: 7.34, respectively, for 120-view simulations. We also demonstrated the application of this MCS tool in small animal imaging by generating a set of low-noise MPH projection data of a 3D digital mouse whole body phantom.

Conclusions—The new method is useful for studying MPH collimator designs, data acquisition protocols, image reconstructions, and compensation techniques. It also has great potential to be applied for modeling the collimator-detector response with penetration and scatter effects for MPH in the quantitative reconstruction method.

Keywords

Monte Carlo simulation; SPECT; Multi-pinhole; SimSET; MCNP

Introduction

Molecular imaging is an essential tool for biomedical research using small animals in various disease models. These applications usually require imaging modalities with ultra high spatial resolution and detection efficiency due to the size of the animals [1, 2]. Pinhole SPECT has been recognized as an important molecular imaging modality for its ability to provide excellent spatial resolution [3]. It also offers better tradeoff between spatial resolution and detection efficiency compared to the conventional parallel-hole SPECT for imaging small objects [4, 5]. However, its detection efficiency is still about 10^2 to 10^3 times lower than that of a PET system [6]. The inherent low detection efficiency of pinhole SPECT significantly impedes its application in dynamic studies.

To improve detection efficiency, the use of multi-pinhole (MPH) collimators for SPECT imaging, originally for cardiac applications, has been proposed as early as 1970s [7–9]. MPH SPECT can improve the efficiency by a factor up to the number of pinholes used. Because of this advantage, MPH has been employed in small animal SPECT imaging [10–13]. The improved detection efficiency can also be traded for other desirable performance measures, such as lower injected activity, shortened acquisition time, or better spatial resolution, when different parameters are adopted in the system design. Therefore, it is very important to carefully investigate the relationship between different design parameters and the associated imaging characteristics of a MPH collimator, such as magnification factor, pinhole pattern and multiplexing (projection overlap), in order to optimize system performance for various imaging tasks.

Monte Carlo simulation (MCS) provides a powerful means to determine design parameters for optimization studies. It provides an accurate and efficient way for studying and designing a MPH SPECT system prior to expensive manufacturing and physical testing of prototypes. A number of MCS tools have been developed for emission tomography that offer different tradeoffs between simulation accuracy and computation time [14]. These tools have been frequently used in the development and evaluation of many imaging systems and image reconstruction algorithms [15, 16].

The Simulation System for Emission Tomography (SimSET) [17, 18] is among those dedicated MCS codes specifically designed for the use with voxelized phantoms for the simulation of SPECT or PET. It is equipped with variance reduction techniques specifically tailored for nuclear medicine that can greatly increase the simulation efficiency. However, the collimator-detector system in SimSET is modeled by an approximate analytical model [19–21] that neglects effects such as photon penetration and scatter components in the collimator. This significantly reduces the accuracy, especially for medium- to high-energy photons. It also lacks the flexibility of simulating novel detector geometries which are being investigated intensively for small animal imaging.

The Monte Carlo N-particle transport code system (MCNP) [22] is a general-purpose Monte Carlo code that models complete physics and originally targets for radiation dosimetry. It provides the capability to model geometrically defined objects based on combinations of planes and quadratic surfaces. It has been rigorously validated for its accuracy. However, it is often inefficient in handling voxelized phantoms as it treats them as a collection of cubes and track photons through every each of them.

The Geant4 Application for Tomographic Emission (GATE) [23] is a MCS tool that is designed for SPECT and PET that has been the subject of much recent development effort. It provides many desirable features for emission tomography such as the ability to simulate voxelized phantoms and very complex scanner geometries and model effects such as bed movement and dead time of the scanner. It is developed based on the general-purpose

GEANT4 MCS code. Even though there is much current work to improve its efficiency, its computational speed is still notoriously slow. A method for combination of SimSET and GATE has been proposed [24] and provides improved simulation times compared to GATE. However, its overall efficacy may still be inadequate for applications that require simulation of multiple projection datasets such as optimization or mathematical and human observer studies [25–27].

We have previously developed an efficient and accurate MCS tools for simulating parallel-hole SPECT by combining SimSET and MCNP [28]. Taking advantages of both methods, the combined SimSET-MCNP method provides a MCS framework for accurate and efficient simulations of voxelized phantoms in emission imaging, as shown in Fig. 1. In this work, we extended this method to include the ability to simulate pinhole SPECT geometries, including single and multiple pinholes, and compared its computational speed with MCNP, GATE, and SimSET-GATE for MPH SPECT. This new tool has significant potential for use in the optimization of MPH designs and acquisition or post-processing parameters. It might also be applied into the development and evaluation of new quantitative image reconstruction methods for MPH SPECT by modeling the point response functions which include the geometric collimator-detector response, photon penetration, and scatter in the MPH collimator.

Materials and Methods

Implementation of the Multi-Pinhole Geometry in the SimSET-MCNP code

We modeled the basic pinhole geometry in MCNP code by using the “surface” and “cell” (union of the surfaces) parameters. Two cones with an optional cylinder between the cones were used to mimic a pinhole aperture with knife or keel edge geometries. A larger cylinder of a user-defined material, such as tungsten as used in this study, is defined to enclose the cones and cylinder defining the aperture. The intersection of these volumes comprises the full pinhole aperture, as shown in Fig. 2a. Multiple pinholes are defined using the same geometric elements but with different coordinates assigned for their origins. A detector with a user-defined scintillation crystal, such as NaI(Tl), was defined at a distance, i.e., the collimator length, away from the origins of the pinhole apertures. The detector is defined as a cell composed of surfaces in MCNP parameters file (Fig. 2b). This setup provides the flexibility to simulate arbitrarily defined MPH collimators with different materials, numbers, patterns, aperture sizes, and axes. The MCNP component itself of this combined MPH MCS tool can be executed independently for generating planar projections for simple analytical-defined phantoms.

Photon histories containing information about the photons exiting the voxelized phantom and being recorded as incidents on the SimSET target cylinder, including their position, propagation direction, scatter order, energy, and weight, are generated in the SimSET simulation of the object. Each photon is then tracked through the whole pinhole collimator-detector system, modeled with MCNP, to generate projection images or list mode data. Separate images of photons with various categories of histories in the object and collimator can be saved. The categories in the object are scattered and unscattered, while the categories in the collimator are geometrically collimated (i.e., photons passing through collimator holes) or photons scattered in or penetrating through the collimator. All combinations of these are saved independently providing images from a total of six categories of photon histories.

Validation of the Integrated SimSET-MCNP MPH Simulation Method

The combined SimSET-MCNP MCS framework has been validated previously for the energy spectra, shape of projections, ratios of counts in different photon classes for the parallel-hole collimators. In this study we focused on validating the implementation of the new multi-pinhole geometry features in MCNP with the experimental results. We verified the collimator response of our MCS tool extensively with physical experiments using a single pinhole, whose pinhole aperture axis is normal to the detector surface (conventional pinhole without tilting), a prototype four-pinhole and a commercial five-pinhole collimator with different tilted angles for the peripheral pinholes (Fig. 3a–c). Validations of the MCS tool with different pinhole aperture geometries assured the accuracy of the simulated collimator response for MPH. We compared point response functions, full-width-at-half-maximum, (FWHM), full-width-at-tenth-maximum (FWTM), and the detection efficiency decrease of a point source when placed in air as a function of imaging distance from the pinhole axis and image profiles between experiment and MCS. The point sources used in the experiments were prepared by soaking resin beads with diameters of less than 500 μm in a Tc-99m solution. A sphere phantom with 3.9 mm inner diameter was used in another experiment evaluating the integration of SimSET-MCNP tool for MPH SPECT. The four- and five-pinhole collimators were fitted on a dual-head compact small animal SPECT/CT system (XSPECT®, Gamma Medica-Ideas, Inc., Northridge, CA) installed in the Johns Hopkins Small Animal Imaging Center. The single pinhole collimator was fitted on a prototype small animal SPECT imager developed in our laboratory [29]. The commercial small animal imaging system had two pixellated NaI(Tl) detectors that were 12×12 cm in size and 6 mm in thickness. The detector matrix size was 80×80 with a pixel pitch of 1.5 mm. Our self-developed prototype system had a detector size of 11.2×11.2 cm with a 79×79 pixel array with 1.4 mm pixel pitch. The energy window for the experiments was centered at 140 keV with a width of 20%.

Single Pinhole Collimator—The FWHM and the FWTM of a 5.55 MBq Tc-99m point source for various positions along the off-pinhole axis, i.e., an axis perpendicular to the axis of the pinhole, were measured under a single pinhole collimator system with an aperture size of 1 mm (Figs. 3a and 4a). The FWHM was used to evaluate the accuracy of the MCS tool for modeling the collimator response attributed from primary photons, while the FWTM was an indicator of the collimator response resulted from scatter and penetrated photons. The experimental setup is illustrated in Fig. 4a. The source-to-aperture distance was fixed at 2.5 cm and the collimator length was 10.8 cm. The point source was placed in the center of the field of view initially ($z=0$ mm) and then moved gradually off-center with an interval of 2 mm. The detection efficiency decrease as a function of off-center distance was also measured.

Multi-Pinhole Collimators—Planar projection data of a 7.4 MBq Tc-99m point source were acquired using the prototype four-pinhole collimator (Figs. 3b and 4b). This collimator is comprised of four tilted pinholes with 1 mm aperture sizes and channel heights of 1 mm embedded in a 6 mm thick tungsten collimator plate. The tilt angles of the pinholes were 21° with the axes of all the pinholes converging at a point 3 cm from the center of the aperture plate at a position approximately directly over the center of the detector. The collimator length which is the distance from the detector surface to the center of the aperture hole was 7.71 cm. The distance between the two adjacent pinholes is 1.6 cm. The point response function was measured at the source-to-aperture distance of 4 cm.

A five-pinhole collimator with different pinhole and imaging geometries was used to further evaluate the accuracy of this MCS tool for modeling the MPH collimator-detector response (Figs. 3c and 4c). This collimator had four tilted peripheral pinholes and one non-tilted

pinhole located in the center of the collimator, all equipped with 1 mm aperture size and channel height of 0.5 mm. The tilt angles were 14° for the peripheral pinholes, all focused to an external point which is 3.5 cm away from the center of the aperture plate. The collimator length was 8.2 cm while the distance between the center pinhole and each peripheral pinhole was 0.87 cm. The planar projection data of a Tc-99m point source were acquired at the source-to-aperture distance of 2.3 cm and its point response function was measured. A spherical insert was filled with a solution containing 26 MBq of Tc-99m and secured in a hollow cylinder with an inner diameter of 2.8 cm and length of 2.8 cm. The planar projection was obtained for 5 min under the same five-pinhole collimator when the source-to-aperture distance was 4.5 cm. To assess the accuracy of modeling the scatter effect in the object, the cylinder was later filled with water and we acquired another 5-min planar projection. Image profiles were measured in one of the peripheral pinhole projections along the horizontal and vertical directions. We used the new MCS tool to simulate Tc-99m point source and hot sphere phantom planar projections using the same geometric parameters and acquisition settings as in the experiments described above.

Assessment of the Computational Speed for Different MCS Tools

Computational speed is another important factor in many simulation studies. To study the relative speed of the new method, we compared four MCS tools: MCNP, SimSET-MCNP, GATE, and SimSET-GATE. A 7.5-mm diameter hot sphere phantom filled with water was used in the simulation. For SimSET-MCNP and SimSET-GATE, voxelized phantom with voxel size of 0.375 mm was used. For MCNP and GATE, analytical defined objects are the generic options and were used in this study. One view and 120-view projections for five-pinhole geometry with aperture size of 1 mm were simulated using each MCS tool. A total of ten million photons were traced during each simulation, and photons with energy less than 10 keV were not followed. The variance reduction options, if available, were disabled in all simulation tools. We also compared the computational time for one, four, and five pinholes for a 120-view simulation in the SimSET-MCNP. All simulations were conducted on a single AMD Athlon® MP 2200 CPU with 1 GB of memory.

Simulation of a Voxelized Mouse Phantom with SimSET-MCNP

The novel 3D digital normal mouse whole body (MOBY) phantom [30] was used in this study to realistically model the anatomy and activity distribution of a normal mouse injected with Tc-99m Medronate (MDP; Fig. 5). Three types of pinhole configurations were simulated: one, four, and five pinhole. The collimator length, aperture size, and keel length were 100, 1, and 0.5 mm, respectively. The magnification factor was 2.0, and all geometric parameters are summarized in Table 1. We generated very low-noise projections using 10 Giga-simulated photons.

Results

Validations of the Accuracy of the Integrated SimSET-MCNP MCS Tool

Single Pinhole Collimator—We compared the FWHM and FWTM of point source response functions as a function of the distance from pinhole axis. There was very good agreement between the simulated and the experimental results (Table 2), indicating that fact that our MCS tool accurately model primary, scatter and penetrated photons for the pinhole collimator. The simulated detection efficiency decrease as a function of distance to the pinhole axis also matched well with the single-pinhole experimental results, indicating the accuracy of our MCS tool for modeling the change of the detection efficiency (Fig. 6).

Multiple Pinhole Collimator—Comparisons between the experimental and simulated point response functions are shown in Fig. 7, which compared our simulation code with a

prototype four-pinhole collimator. This figure shows the point response functions from one of the four projections obtained with the four-pinhole collimator measured both using MCS and experiment. The image profiles were asymmetric because all the pinholes axes were not perpendicular to the detector surface, the sources were off the pinhole axes, and keel-edge apertures were used. Again, both simulated and experimental results agreed well with each other, demonstrating the accuracy of the SimSET-MCNP in terms of modeling the collimator geometric response for tilted pinholes.

The point response functions of the point source and image profiles of the hot sphere phantom were also compared for MCS and experiment for the five-pinhole geometry. Again, the point response functions measured from a Tc-99m point source showed good agreement between experiment and simulation, as demonstrated in Figs. 8. Figure 9 shows the simulation and experimental results from the hot sphere phantom. The sphere was placed either in air or in water, and profiles were drawn and zoomed into the region corresponding to projections of one of the pinholes. Note the excellent agreement between the experimental and simulated results even for the tail region of the point response functions, indicating the accuracy of this MCS tool for modeling the penetration and scatter effects in the collimator and also the scatter effect in the object. The results of the simulations showed that when the sphere was placed in water, the scatter photons in the object were about 4.4 times more than that when the sphere was placed in air.

Assessment of the Computational Efficacy of Different MCS Tools

A five-pinhole simulation with a 7.5 mm diameter water sphere was performed using SimSET-MCNP, MCNP, SimSET-GATE, and GATE. The exactly same geometrical settings were used in all simulations, and a total of 10 million photons were simulated for each method with about the same noise level in the projection images. Figure 10 shows sample projections obtained from each of the simulation methods. Table 3 summarizes the simulation time required for each of the methods to simulate one and 120 projection views. For simulation of a single projection, MCNP provided the lowest simulation time (5.32 min). For simulating 120 projection views, SimSET-MCNP offered significant computational advantages (234.25 min) compared to other MCS tools. The time required for SimSET phase was 3.82 min (1.63%), and the time required for MCNP phase was 230.43 min (98.37%). The results also showed that for SimSET-MCNP, the computational time increased when simulating increased number of pinholes. For a 120-view simulation, the ratios of simulation time for one, four, and five pinhole were 1:1.8:2.1, respectively.

Simulation Results Using the Voxelized MOBY Phantom

Figure 11 shows samples of Monte Carlo-simulated Tc-99m MDP bone scan projections images of the MOBY phantom using one-, four-, and five-pinhole collimators with our developed SimSET-MCNP method. The low-noise images were generated using 10^9 simulated photons. The required simulation time increased as the number of pinholes modeled increased, as we demonstrated in the former hot sphere phantom simulations.

Discussion

To validate the accuracy of the developed MCS tool, simulations were conducted using parameters based on experimental measurements. Our laboratory has developed accurate and precise calibration methods [31] to determine the intrinsic parameters of the MPH collimator such as pinhole positions and collimator lengths. However, this method does not provide estimates of parameters such as aperture size and keel length. As a result, the parameters specified in the manufacturing process were used in the simulations. There are inevitable differences between the design and actual parameters, as well as errors in other

acquisition parameters such as the placement and movement of the sources, energy windows, energy resolution, etc. As a result, there are bound to be differences between experiments and simulations. Thus, the results from simulations and experiments agreed with each other very closely, but they are hard to be identical. The only way to provide exact match of the simulation parameters for validation is to compare our simulation tool with another fully validated MCS method. However, there is no such MCS tool available for the focused MPH case.

Unlike conventional single pinhole collimator, the peripheral apertures in a focused multi-pinhole collimator are tilted, i.e., the aperture axes are not perpendicular to the detector surface. They are focused to a point which is usually the center of the FOV. This design can not only increase the detection efficiency but also makes the characterization of the collimator properties difficult. The geometric response for a single pinhole collimator with aperture axis perpendicular to the detector has been analytical derived [32, 33]. However, due to the increased complexity of calculating the photon penetration for tilted apertures, and also the axis of the tilted pinholes is not normal to the detector surface but with the tilted angle, there have been no published formulations for the multi-pinhole cases. We have developed an accurate Monte Carlo simulation method that can be applied to address this problem. This method has the potential to be applied for modeling the total response function of the multi-pinhole collimator that include the geometric response function for the tilted apertures with user defined tilt axes, penetration and scatter components, which can be incorporated into the image reconstruction process and improve the accuracy of the system matrix. We are currently pursuing the use of simulated point response functions to model the aperture response and provide resolution recovery in iterative reconstruction.

The most time-consuming part of a SimSET-MCNP multiple-view simulation for a voxelized phantom is the tracking of photon interactions inside the collimator detector by MCNP. However, the computation of SimSET photon histories can be dominated when there are only a few projection views, and when the input digitized phantom is complicated. Our results showed that for one projection view simulation of a simple phantom, SimSET-MCNP did not show much advantage in terms of computational speed when compared to using MCNP alone. This suggests the MCNP simulation is a better choice for simulating planar images of simple phantoms that can be described geometrically, such as simulating point source for the point response function for MPH as we described earlier. However, MCNP is poorly suited to simulation of voxelized phantoms that are required for realistic modeling of small animal anatomy. The computational burden of MCNP also increases as the number of projection views increases. This is because it is difficult to model multiple views in one MCNP simulation as one has to run MCNP multiple times to generate multiple projection data. The photon interactions in the phantoms also needed to be repeatedly traced for different projection views, while the photon history files of the phantom for SimSET-MCNP can be saved and repeatedly used. Our results illustrated that MCNP required about 173% more time for simulating 120 projections when compared to SimSET-MCNP for a five-pinhole simulation, even though it was less time consuming for planar simulation when compared to SimSET-MCNP. The results are consistent with the results in our former study [28]. Thus, our results indicate that the SimSET-MCNP combination is a better choice for simulating multiple view projections and voxelized phantoms.

One issue with the SimSET-MCNP and other combined simulation tools is that the maintenance of two MCS packages may take more effort than that of just one package. However, both SimSET and MCNP are among the most frequently used MCS software. They have been very well developed and validated by numerous users. Based on our experience, the maintenance of both packages takes very little effort after the initial

installation. Since each of these two packages has advantages that cannot be replaced by the other, we believe the gain of having two packages can over offset the maintenance effort.

Recently, GATE has been intensively applied in nuclear medicine simulations due to its ease in modeling complex detector geometries and graphics interface [34, 35]. However, the lack of variance reduction techniques in GATE has limited its use for generation of multiple sets of projection data due to the long computational time. As a consequence, research in optimizations of system design, acquisition protocol, reconstruction, and compensation methods is severely limited if GATE simulation is used. Efforts have been made to address the speed problem for GATE by integrating SimSET and GATE in our group and showed significant improvement. However, our results demonstrated that for multi-pinhole simulation, the computational speed of SimSET-GATE is still inferior (~2.5-fold slower) compared to the SimSET-MCNP method we presented here.

Conclusions

We have developed and validated an efficient Monte Carlo simulation tool for studying multi-pinhole microSPECT system. The method was based on the combined SimSET-MCNP platform. Good agreement between experimental and simulated data for point and extended sources using single and multi-pinhole collimators was observed. Reductions in simulation times by more than a factor of 1.73 compared to MCNP for simulation of SPECT data with a hot sphere phantom. Our developed MCS tool provided an efficient way for MPH simulation while still offering very accurate physics modeling for multiple views simulation. As a result, the new simulation tool has great potentials for assessments and optimizations of multi-pinhole collimator designs, data acquisitions methods, pinhole SPECT image reconstruction and compensation methods, which are all important for pursuing quantitative molecular imaging on small animals.

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Fig. 1.

Flowchart for generating projection images from the combined SimSET-MCNP code. The photon history files, which contain a list of all photons exiting the object, are obtained from SimSET simulations and passed to MCNP for modeling of photon propagation in the collimator and detector.

Fig. 2.

Diagrams illustrating the ability of the newly developed MCS tool to simulate versatile geometric designs of the multi-pinhole collimator and the detector. **a** Pinhole aperture with keel/knife edge made of user defined material. **b** Arbitrary collimator length and pinhole numbers. **c** Pinhole apertures can be focused towards an external focal point by a specific tilted angle.

Fig. 3.

The collimators used in the study: **a** single pinhole collimator fitted on our prototype dedicated SPECT system and **b** a prototype four-pinhole collimator and **c** a commercial five-pinhole collimator fitted on a commercial small animal SPECT imager.

Fig. 4.

Diagrams illustrating the experimental configurations for the various experiments. For the single pinhole collimator (**a**), projections of the point source were acquired at different distances from the axis of the pinhole positions to measure the detection efficiency decrease, FWHM and FWTM. For the four-pinhole collimator (**b**), the point source response function was measured at the position illustrated. For the five-pinhole collimator (**c**), planar images were obtained from a point source (not shown in this figure) and from a cylindrical phantom containing a hot spherical insert at its geometric center. The phantom was first imaged with cylinder filled with air and then imaged with cylinder filled with water.

Fig. 5.

a The 3D digital MOBY phantom designed for simulation investigation of preclinical research was used. **b** The activity distribution used was based on that for a normal mouse injected with Tc-99m Medronate (MDP). **c** The corresponding attenuation map.

Fig. 6. Comparison of experimental and MCS detection efficiencies for a Tc-99m point source was measured at different distances from the pinhole axis relative to the efficiency for the source on the pinhole axis from experiments and MCS.

Fig. 7.

Profiles are shown through images of a Tc-99m point source imaged with a four-pinhole collimator in the horizontal (**a**) and vertical (**b**) directions acquired. They were taken across the *line* shown and zoomed in to the region indicated by the *box*.

Fig. 8. Image profiles were drawn from one of the projections along the horizontal (a) and vertical (b) directions acquired using a Tc-99m point source with a five-pinhole collimator.

Fig. 9.

The image profiles obtained from projections of the hot sphere phantom in air (**a, b**) and in water (**c, d**). Profiles were obtained in both the horizontal (**a, c**) and vertical (**b, d**) positions. The positions of the profiles are indicated by the *lines*.

Fig. 10.
Sample five-pinhole projections of a digital hot sphere phantom simulated under four different MCS tools: **a** SimSET-MCNP, **b** MCNP, **c** SimSET-GATE, and **d** GATE.

Fig. 11.

Sample simulated projections images of the MOBY mouse phantom using one-, four-, and five-pinhole collimators with a magnification factor equal to 2 and 10^9 simulated photons.

Table 1

The geometric parameters of the MPH collimators for the MOBY phantom MCS

	1-pinhole	4-pinhole	5- pinhole
Collimator length (cm)	10.0	10.0	10.0
Aperture size (mm)	1.0	1.0	1.0
Keel length (mm)	0.5	0.5	0.5
Radius-of-rotation (cm)	5	5	5
Magnification	2	2	2
Pinhole tilt angle	N/A	9.5°	9.5°
Distance between two holes (mm)	N/A	16.7	16.7

Comparison of the experiment and simulation results in terms of FWHM and FWTM for a point source at different distances from the pinhole axis

Table 2

	FWHM	FWTM	2		4		6		8	
			FWHM	FWTM	FWHM	FWTM	FWHM	FWTM	FWHM	FWTM
Z^a (mm)	0									
EXP	1.02	1.35	1.02	1.34	1.01	1.34	0.99	1.32	0.98	1.30
MCS	1.03	1.31	1.02	1.30	1.02	1.31	1.01	1.31	1.01	1.29

EXP experimental results

^a Axial location

Table 3

The computational time required for simulating a hot sphere phantom using different MCS tools

		SimSET-MCNP	MCNP	SimSET-GATE	GATE
1 view	Actual time (min)	5.89	5.32	10.72	14.17
	Time normalized to SimSET-MCNP	1	0.90	1.82	2.41
120 views	Actual time (min)	234.25	638.4	828.12	1718.53
	Time normalized to SimSET-MCNP	1	2.73	3.54	7.34