# Evaluation of the Geometric, Scatter and Septal Penetration Components in Fan Beam Collimators Using Monte Carlo Simulation

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*Abstract*

The quantitative analysis of SPECT data requires an accurate determination of the collimator point spread function (PSF). The aim of this work is to characterize the PSFs of fan beam and parallel collimators by using Monte Carlo simulation. Given a particular collimator configuration, a detailed hexagonal hole array is generated and information describing its geometry is stored in a look-up table. When a photon crosses the collimator front plane, a forty-hole array is placed around its impact position using this table. Each photon is then tracked up to the detector surface by using the Monte Carlo code PENELOPE and its associated geometry handling routines. Particle counters are defined that score the probability of impact on the detector as a function of the final photon position. Four sets of counters are employed so as to differentiate contributions to the geometric, septal penetration, coherent (Rayleigh) and incoherent (Compton) scatter components. Furthermore, sensitivity quantification and pulse-height energy spectra are calculated for different source locations. Monte Carlo results have been compared with sensitivity values obtained experimentally and good agreement was found. Our results show that for $^{99m}$Tc imaging, the geometric component represents about 95% of the fan beam PSF, whereas the incoherent scattering component is negligible.

## I. INTRODUCTION

Accurate modeling of the collimator is needed to perform iterative reconstruction and SPECT quantification. There are different approaches to modeling of this kind. Some works, based only on the geometric component of the point spread function (PSF), analytically determine the intersections between the aperture functions of round holes. The photon flux is then obtained as the integral of these functions over the collimator [1]. Other studies model the septal penetration component by means of numerical ray tracing techniques [2]. However, a global study including coherent (Rayleigh) and incoherent (Compton) scattering is not feasible with deterministic methods.

A complete characterization of the collimator response requires the use of Monte Carlo simulation techniques, thus enabling the incorporation of all the PSF components for any source energy. It has been shown that Monte Carlo calculations simulate radial PSFs and energy spectra for parallel collimators in reasonable computational time [3].

The aim of this work is to extend previous studies by analyzing the geometric, septal penetration, coherent and incoherent scatter components as a function of source position for a fan beam collimator with hexagonal holes. The modeling of the collimator hole is important since the sensitivity of the system may differ by up to 15% due to changes in its shape [3].

## II. MATERIALS AND METHODS

### *A. Description of the simulation program*

Simulation of photon transport was carried out by using the Monte Carlo code PENELOPE [4], which includes a set of geometry routines capable of handling any object formed by homogeneous bodies limited by quadric surfaces (such as planes, cylinders, spheres, etc). The user is required to write a simple main steering program, which, among other things, keeps score of the quantities of interest.

PENELOPE performs Monte Carlo simulation of electron-photon showers in arbitrary materials. The adopted scattering models, which give a reliable description of radiation transport in the energy range from about 1 keV up to 1 GeV, combine numerical total cross sections with simple analytical differential cross sections for the different interaction mechanisms. Coherent scattering of photons is described using the classical Thompson differential cross section (DCS) and an analytical atomic form factor. Incoherent scattering is described by means of a DCS calculated from the relativistic impulse approximation, thus accounting for electron binding effects and Doppler broadening, which are non-negligible at the low photon energies encountered in our application. Cross sections for photoelectric absorption, on the other hand, are interpolated from a table estimated to be accurate to within a few percent for energies above 1 keV.

Although PENELOPE includes the simulation of pair production and secondary radiation (x-rays from vacancies in the K-shell, Auger electrons, etc), they do not contribute to the image at the energy window considered in our application (126 to 156 keV for $^{99m}$Tc imaging).

In order to prevent the geometry routines from handling all the holes each time a photon travels through the collimator, an approach that would have represented an excessively large amount of data, the process of describing the geometry was split into two steps. Firstly, all the centers and elongation for each hole were stored in a look-up table which took into account the characteristic parameters, namely, focal length, collimator thickness, distance between collimator and scintillation crystal, distance between holes in the fan beam



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axis, distance between holes along the perpendicular axis, septal thickness, and width and length of the collimator. This table does not change during the simulation. In a second step, each time a photon reaches the front plane collimator, a set of forty holes is defined centered at the closest position from the impact point using the information stored in the look-up table described above.

Furthermore, to save computer time, photons were assumed to be emitted within a solid angle smaller than $4\pi$, but large enough to cover a relevant fraction of the collimator front surface. Simulation results were then corrected to account for this fact.

Each photon reaching the detector layer was flagged according to its past interactions as follows: 1 for geometric photons (no interaction suffered and no septa crossed); 2 for septal penetration (no interaction, one or more septa crossed); 3 for photons that have undergone a coherent interaction somewhere; and 4 for photons that have experienced an incoherent interaction. This allowed us to differentiate contributions to the final image from the different components.

## *B. Experimental measurements*

To validate the Monte Carlo calculation, sensitivity values obtained from simulated PSFs for a fan beam collimator were compared with those obtained from experimental PSFs. The sensitivity was calculated as the number of photons reaching the detector per emitted photon. To this end, a 6-cm long capillary with a diameter of 0.156 cm filled with 25 MBq of $^{99m}$Tc was situated at different heights (z equal to 5, 10, 15, 20, 25 and 30 cm) over the collimator. Images and pulse-height energy spectra were acquired with a double-headed Helix (Elscint, Haifa) camera with a fan beam collimator.

The fan beam employed had a focal distance F of 35.5 cm, a distance between hole centers (Rx) equal to 0.1643 cm in the fan beam axis, a constant distance between holes centers (Ry) of 0.17 cm along the perpendicular axis, a septal distance (s) of 0.02 cm and a width (L) of 4 cm. The distance (B) between the back face and the image formation plane was 0.8 cm.

# III. RESULTS

Figure 1 shows the total PSF obtained from the Monte Carlo simulation with the source at z=10 cm.

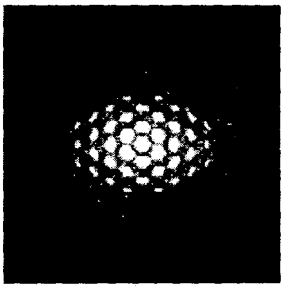

Figure 1. PSF with the source located at (x,y,z) =(0,0,10) cm.

Sensitivity results (S) are presented in table 1. The values of the first row indicate the absolute probabilities to detect a photon per particle emitted. The second row ($S_{MC}/S_{MC5}$) corresponds to the relative simulated sensitivities with respect to the sensitivity when the source is located at z =5 cm. The third row ($S_{EX}/S_{EX5}$) shows the relative experimental sensitivity.

| z (cm) | 5 | 10 | 15 | 20 | 25 | 30 |
|---|---|---|---|---|---|---|
| S ($10^{-5}$) | 8.13 | 9.76 | 12.13 | 16.08 | 23.76 | 45.24 |
| $S_{MC}/S_{MC5}$ | 1.00 | 1.20 | 1.49 | 1.98 | 2.92 | 5.56 |
| $S_{EX}/S_{EX5}$ | 1.00 | 1.17 | 1.55 | 2.04 | 2.89 | 5.30 |

Table 1. Sensitivity values and ratios at different heights.

Figure 2 shows the four PSF components. The images were obtained taking into account the flags assigned to the photons when they arrived at the detector surface, as described above. Each image is normalized to its maximum

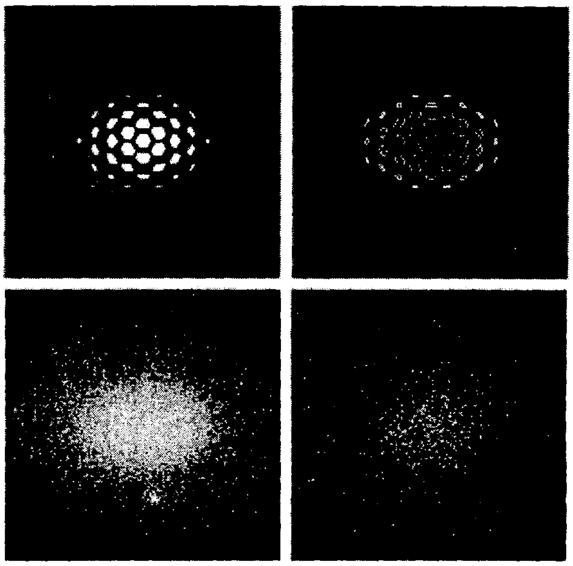

Figure 2. Simulated geometric (top left), septal penetration (top right), coherent scatter (bottom left) and incoherent scatter (bottom right) PSF components for a point source located at (x,y,z) = (0,0,10) cm.

| z (cm) | 5 | 10 | 15 | 20 | 25 | 30 |
|---|---|---|---|---|---|---|
| Geom | 95.3 | 95.0 | 95.1 | 95.1 | 95.2 | 95.2 |
| Septal | 3.5 | 3.9 | 3.7 | 3.7 | 3.7 | 3.6 |
| Coher | 1.1 | 1.1 | 1.0 | 1.1 | 1.1 | 1.1 |
| Incoher | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 | 0.1 |

Table 2. Percentage contributions to the PSF.

The results in table 2 show that for $^{99m}$Tc imaging the major contribution to the fan beam PSF is the geometric component, which represents approximately 95.1 % of total PSF. The incoherent scattering component is almost negligible, with an average contribution of 0.1%. Septal penetration is the second major contributor, situated at 3.7%, and Rayleigh photons are the third component, with a contribution of 1.1%.

## IV. DISCUSSION

Results of relative sensitivity from table 1 indicate that the Monte Carlo values closely match those obtained from the experimental measurements with differences lower than 5%.

On the other hand, results from table 2 show that for $^{99m}$Tc imaging, the largest contribution to the sensitivity is due to the geometric component and its variation with respect to variations of the source height is in accordance with the conclusions obtained by other authors [5]. This fact justifies the approximation which consists of estimating the total PSF (in $^{99m}$Tc imaging) only by means of the geometric component.

Septal penetration is the second most important contribution, its effect being equivalent to an enlargement of the size of the collimator holes. Coherent scatter represents the main scatter effect. Incoherent scattering does not appreciably contribute to the PSF. Since, for $^{99m}$Tc imaging, a large fraction of photons crossing the collimator do not change their previous direction (the sum of the geometric and septal penetration terms yields 98.9% in our case), collimator scatter corrections are expected to play a minor role in reconstruction algorithms.

## V. REFERENCES


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