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A Geant4 simulation code for simulating optical photons in SPECT scintillation detectors

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ABSTRACT: Geant4 is an object oriented toolkit created for the simulation of High-Energy Physics detectors. Geant4 allows an accurate modeling of radiation sources and detector devices, with easy configuration and friendly interface and at the same time with great accuracy in the simulation of physical processes. While most Monte Carlo codes do not allow the simulation of the transport and boundary characteristics for optical photons transport generated by scintillating crystal, Geant4 allows the simulation of the optical photons. In this paper we present an application of the Geant4 program for simulating optical photons in SPECT cameras. We aim to study the light transport within scintillators, photomultiplier tubes and coupling devices. To this end, we simulated a detector based on a scintillator, coupled to a photomultiplier tube through a glass window. We compared simulated results with experimental data and theoretical models, in order to verify the good matching with our simulations. We simulated a pencil beam of 140 keV photons impinging the crystal at different locations. For each condition, we calculated the value of the Pulse Height Centroid and

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the spread of the charge distribution, as read out by the anode array of the photomultiplier. Finally, the spatial and the energy resolutions of the camera have been estimated by simulated data. In all cases, we found that simulations agree very well with experimental data.

Contents

1 Introduction

Monte Carlo simulation techniques are becoming very common in the medical imaging community. Several topics were addressed by Monte Carlo simulations in the Nuclear Medicine field. Among them, it is worth remarking the optimization of imaging system design (including detector, collimator, and shield design), the development of correction methods for improved image quantitation, the evaluation of correction techniques (scatter, random, attenuation corrections, partial volume effect), the assessment of image reconstruction algorithms, ROC studies, pharmaco-kinetic modeling.

In Nuclear Medicine the use of Monte Carlo methods was profited from the possibility of using general purpose codes developed for high energy physics. Various general purpose Monte Carlo codes, initially developed to simulate particle transport in a broad context (such as EGS and Geant), can be used also for modeling SPECT and PET configurations. As they have been designed for a large community of researchers, these codes are well documented and in the public domain. Our group has already used and validated various Monte Carlo codes for simulating imaging systems with applications in Nuclear Medicine and industry [1–3].

Geant4 [4] is an object oriented toolkit for simulation of current (and next generation) High-Energy Physics detectors. It is also a showcase example of technology transfer from particle physics to other fields such as medical science [5]. Geant4 allows an accurate modeling of radiation sources and detector devices with easy configuration and friendly interface and at the same time with great accuracy on the description of physical processes. In the last releases the user is able to simulate electromagnetic interactions at energies as small as 1 keV. While most Monte Carlo codes do not allow the simulation of the transport and boundary characteristics for optical photons generated by scintillating crystal, in Geant4 two optical models can be used for this purpose: either GLISUR or UNIFIED model [6]. The purpose of this paper is to present an application of Geant4 program for simulating the optical photons transport in the different components of SPECT cameras. We aim to study the light transport within scintillators, photomultiplier (PM) tubes and coupling devices. To this end, we simulated a detector based on a scintillator, coupled to a PM through a glass window. Simulations were also compared with experimental results obtained in the same configuration.
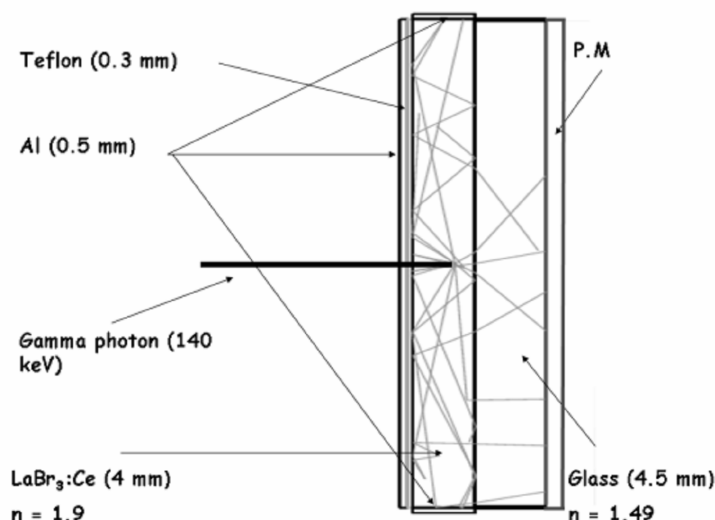
Figure 1. Example of the tracking of the optical photons simulated within the detector with Geant4. The detector is simulated as composed of three components: a crystal, a glass window for the optical coupling of the crystal with the photomultiplier, and the photomultiplier itself. The front surface of the crystal is composed of an Aluminum layer and a Teflon layer.

2 Materials and methods

The experimental setup is based on the $5 \times 5 \, cm^2$ scintillation gamma camera described in [7]. The detector consists on a multi anode PMT Hamamatsu Flat Panel H8500 [8], coupled to a $50 \times 50 \times 4 \, mm^3$ continuous LaBr$_3$:Ce crystal [9] and a 4.5 mm glass window. The crystal is surrounded by a thin layer of Aluminum. In the front crystal surface a very small layer of Teflon is positioned after the Aluminum. A 0.4 mm collimated ^{99m}Tc spot source was used to analyze the spread of the charge distribution on the anodic array and the intrinsic spatial resolution of the detector.

With Geant4 we simulated a system resembling the above described experimental apparatus. The scintillation light photons are generated as a pure Poisson process. The simulated crystal was wrapped in a material acting as a Lambertian reflector (Teflon on front) or Black absorber (Aluminum). The interface was modeled as *ground*, and the boundary processes followed the rules of the GLISUR model. In this model the user can select the smoothness or the roughness of each surface surrounding the crystal by using a parameter named *polish*. For example, *polish* equal to zero corresponds to the maximum roughness (photons are reflected according to a Lambertian distribution), whereas for polish equal to one the Snell's Law is applied. For each surface one can also select the value of reflectivity. The PM surface is simulated as a polished quartz window, assuming an experimentally derived value for quantum efficiency. The simulated setup also consists of monochromatic point sources (140 keV photons). The Geant4 application was run to record the spatial distribution of the detected optical light photons on the PM surface and to estimate the energy resolution of the crystal (figure 1).
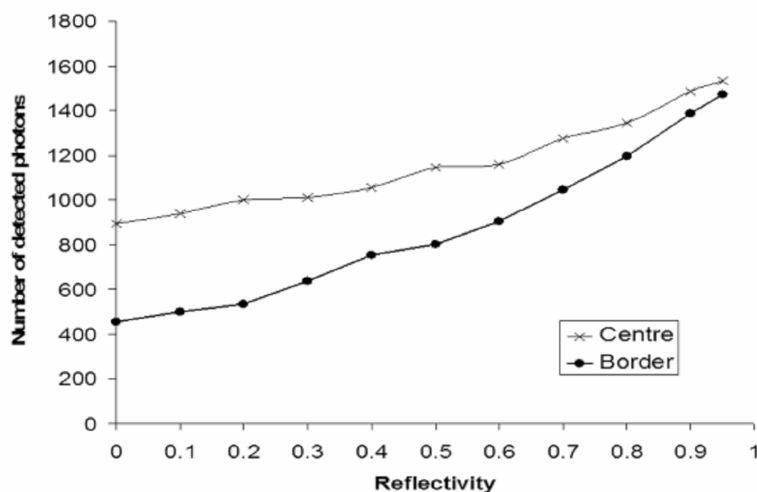
Figure 2. Number of detected photons with the gamma impinging at the centre and at the border of the crystal, as a function of the reflectivity of the crystal's lateral surfaces.

3 Results

We compared Monte Carlo results with experimental data and theoretical models, in order to verify the good matching with our simulations. First of all, with Geant4 we simulated a pencil beam of 140 keV photons interacting with the LaBr$_3$:Ce crystal. Figure 1 shows an example of the tracking of the optical photons inside the detection camera. Here, one 140 keV photon impinging the scintillator (LaBr$_3$:Ce) from the left generates some optical photons. Some of them travel directly through the glass window towards the photomultiplier. Some others are reflected by the lateral surfaces or by the front side of the crystal. The number of optical photons generated within the scintillation crystal was fixed at 63000/MeV and the mean energy of these optical photons was 3 eV (380 nm) [9]. The fraction of optical photons moving towards the glass resulted to be 44.9% in the simulation, while the theoretical expectation, based on purely geometric arguments, is about 45%. The fraction of optical photons moving towards the PM was 17.9%, to be compared with an expectation of about 19%. We assumed, as coming from experimental data, that the quantum efficiency of the PM was 0.22.

We have then estimated the number of optical photons detected by the PM, both when the gamma photon interacts at the centre and close to the border of the crystal. We calculated the number of detected optical photons in correspondence of different values of the reflectivity of the crystal outer surface. Experimental data show that the number of photons reaching the PM with the gamma at the border is about 25% less than the number of photons reaching the PM with gamma interacting at the centre. Figure 2 shows the number of detected photons with the gamma impinging at the centre and at the border of the crystal, as a function of the reflectivity of the crystal's lateral surfaces.

We found that the best agreement between experimental and simulated data is gained with *polish* equal to zero, R = 0.6 for the crystal's lateral surfaces (top, bottom, right and left), and R = 0.95 for the front surface. On the other hand, we applied the Snell's Law for the surface between crystal and PM glass (parameter *polish* fixed to 1).
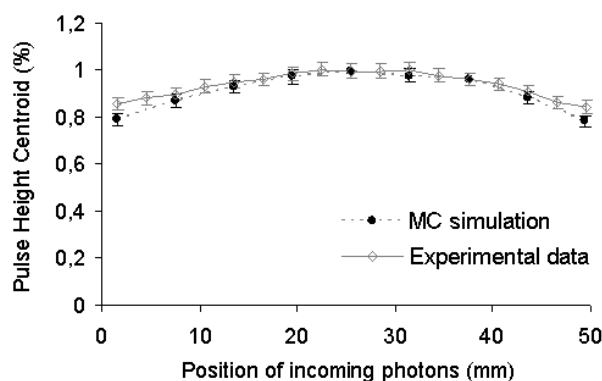
Figure 3. Pulse Height Centroid values for an impinging photon of 140 keV scanning the crystal.
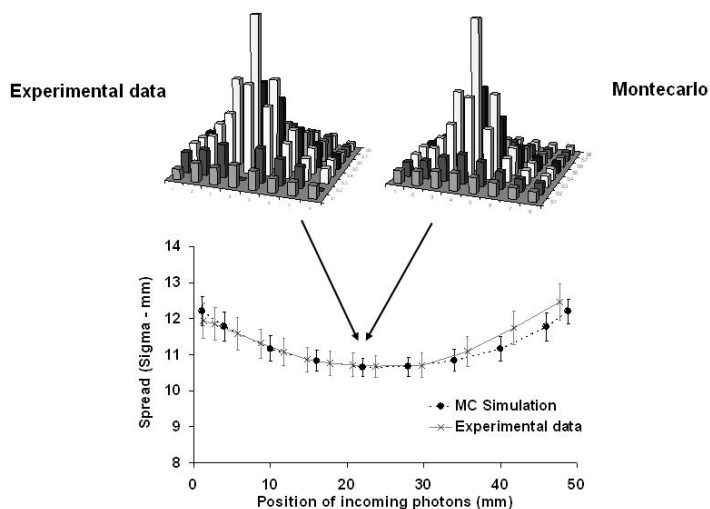

Figure 4. Charge distribution spread into the PM anode array for an impinging photon of 140 keV scanning the crystal.

We simulated the output of the PM as a 8×8 pixellated anode, where every pixel has a front surface of 6 mm ×6 mm, as in the experimental setup. We scanned the crystal, with a pencil beam of 140 keV energy photons, from one border to the other, passing through the centre. For each position of the impinging photon we estimated the Pulse Height Centroid, as acquired in the PM anode array. Figure 3 and 4 show the Pulse Height Centroid values and the spread of the charge distribution into the PM anodes for the different positions of the incoming photons, respectively. It is worth noting that there is an excellent agreement between the simulations and the experimental data.

Finally, we compared the spatial and the energy resolutions obtained with Geant4 with experimental data, by using a pencil beam of 140 keV energy photons that interacts in the centre of the crystal. With the simulation we obtained a spatial resolution of 0.9 mm (FWHM) and an energy resolution of 6.7% (FWHM), while the experimental data provide 1.1 mm and 6.9%, respectively. Again, simulations agree very well with experimental data.

In summary, we investigated some characteristics concerning the transport of light photons within a SPECT camera. We simulated the optical features of the various components of the camera (scintillator, glass coupling window, and photomultiplier), and compared results with the same experimental configuration. Simulated outcomes, in terms of Pulse Height Centroid values, charge spread distribution, spatial and energy resolutions agree very well with experimental data. The results of this work will be used in the near future to arrange the components of the camera and optimize its performance

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