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Monte Carlo simulation of discrete γ-ray detectors

A. Bakkali*, N. Tamda, M. Parmentier, J. Chavanelle, A. Pousse, B. Kastler

Laboratoire Imagerie et Ingénierie pour la Santé, Faculté de Médecine, Place Saint Jacques, 25000 Besançon, France

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Abstract

Needs in medical diagnosis, especially for early and reliable breast cancer detection, lead us to consider developments in scintillation crystals and position sensitive photomultiplier tubes (PSPMT) in order to develop a high-resolution medium field γ-ray imaging device. However the ideal detector for γ-rays represents a compromise between many conflicting requirements. In order to optimize different parameters involved in the detection process, we have developed a Monte Carlo simulation software. Its aim was to study the light distribution produced by a gamma photon interacting with a pixellated scintillation crystal coupled to a PSPMT array. Several crystal properties were taken into account as well as the intrinsic response of PSPMTs. Images obtained by simulations are compared with experimental results. Agreement between simulation and experimental results validate our simulation model.

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Keywords: Monte Carlo simulation; Nuclear medicine; Pixellated crystal; PSPMT array; SPECT

1. Introduction

Nuclear medicine is a very powerful functional imaging technique whose diagnosis capabilities are limited by detector spatial resolution. These last years, we witnessed an increased interest in development of high-performance medium field gamma cameras for applications as well in nuclear medicine as in other domains such as biology research. The new compact (R8520-00-C12) PSPMT produced by Hamamatsu, which offers improved technological performances, allows us to design a new generation of gamma cameras. Indeed, its small size, its weak dead edges and its square shape allow to juxtapose them in order to obtain an imaging device with the desired field of view while achieving good energy and spatial resolution.

Pixellated crystals were designed for the first time for applications in PET by coupling them with small standard PMT's. Recent improvements in scintillation crystals allow to use them for

*Corresponding author. Tel.: +33 3 81 66 56 09; fax: +33 3 81 66 56 11.
E-mail address: bakkali@edu.univ-fcomte.fr (A. Bakkali).

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energies lower than 150 KeV with good energy resolution. Now, manufacturers provide regular pixellated crystals with various whole sizes, pixels sizes, thickness and scintillation materials.

Simulation softwares of gamma photon transport by the Monte Carlo method were developed by many laboratories; but those are, either very general, or dedicated to a particular study and are not easily adaptable to our needs. Those simulation softwares often require work stations different from those that we have.

We developed our own simulation software of gamma and visible photons transport, called Pulsar, in order to have a complete tool to simulate our detectors. A complete library of computer tools has been developed at the laboratory for scintigraphic image acquisition and processing. The simulation software used many of them.

Developing our own simulation software enabled us to expend its capabilities according to our needs while keeping unchanged the simulation core which has been carefully tested [1,2].

2. Simulation

Simulation of gamma detector systems is regarded as a combination of two independent phases:

- Gamma simulation: is the first phase of Monte Carlo simulation which describes the interactions undergone by the gamma photons in the source and in different parts of the detector.
- Simulation of visible photons: The registered interactions which have occurred in the scintillation crystal allowed us to start this second phase of simulation which consists in generating and following the luminous photon history, until they reach the photocathode.

In our simulation program several radio-isotopic elements and source shapes are modeled. Intensity of incident photon beam is parameterized. Crystal parameters such as material, geometry, size, or structure (continuous, pixellated) can be modified by user.

2.1. Gamma simulation

The purpose of this simulation phase is the construction event by event of the whole story of every emitted gamma photon. Three interaction mechanisms between γ-ray photons and matter play an important role in the energy range used in medical and biological applications: photoelectric absorption, Compton scattering and Rayleigh scattering. All these processes lead to the full or partial transfer of gamma energy to electrons. They may occur in various probe elements, which results in important changes in the γ-ray history. If this energy transfer is situated in the scintillation crystal matter, a scintillation is thus produced at this position. If not, transferred energy is absorbed.

At every step, interaction kind is selected by using random number generated according to the relative cross sections given by Storm and Israel Tables.

If the selected interaction kind is the Compton scattering, the angles and photon energies after scattering are computed by the Kan (1956) method, which samples the Klein–Nishina distribution [7]. The azimuthal angle is randomly chosen using the Von Neumann (1951) technique. From the scattering and azimuthal angles, the direction cosines of the scattered photon are then easily computed.

If the selected interaction type is the photoelectric absorption, the energy deposited by the photon within the scintillator crystal is computed and the history ends. The photoelectric effect is a complex process which includes an extensive succession of events. When the photon interacts with a K layer electron of an atom, the electron is then ejected, a gap is created, and is immediately filled by an electron belonging to a more external layer (L, M, N…) from where emission of a characteristic fluorescence X-ray with energy (E_K–E_L or E_K–E_M) according to the electron origin. When this phenomenon occurs in small atomic number materials, the X-ray energy is very weak but it becomes important in the case of heavier elements. However, if we take into account all events accruing on every atomic layers, the program quickly proves very complex to manage.