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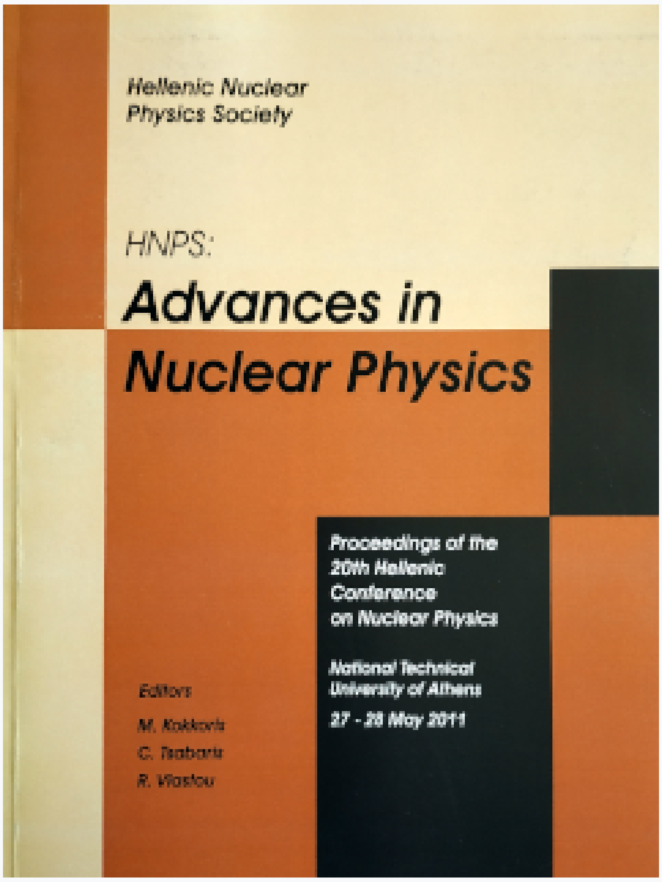

GEANT4/GATE Simulation Studies in the Emission Tomography

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Abstract

Radiotracer imaging studies for a small field, high resolution γ-Camera system and a clinical system for Positron Emission Tomography (PET) by means of GATE (GEANT4 Application for Tomographic Emission) simulations are presented in this work. In a validation phase, which preceded the main study, experimentally obtained results for planar images with the existing γ-Camera system were directly compared to simulated data. A simple phantom structure, consisting of four parallel capillaries filled with ^{99m}Tc water solution, was imaged by the γ-Camera system for several phantom-collimator distances and the measured and Monte-Carlo calculated spatial projections were compared. The major objective of this validation study was the optimal description of the most important components, the hexagonal, parallel-hole Pb-collimator and the pixelated CsI scintillation crystal of the γ-imaging system in terms of GATE components. In the main study, a GATE simulation setup for this γ-Camera detector is used and Monte-Carlo data are accumulated for simple geometrical phantoms with different monophotonic radiotracer energies and relative intensities. In parallel, a commercially available cylindrical shaped PET scanner ring, consisting of 32 sectors with $4 \times 6 \times 6$ LSO scintillation crystals, has been constructed in the GATE environment. Simulation data are obtained for the most usual positron emitters (^{18}F, ^{11}C and ^{15}O) and for several phantom geometries. The spatial resolution of both systems and their overall performance is presented and discussed in this study.

Key words: SPECT, PET, γ-Camera, Monte-Carlo Simulation, GEANT4

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1 Introduction

Nowadays, there is an increasing demand for high performance imaging systems that offer improved spatial resolution and detection efficiency. In the Single Photon Emission Computed Tomography (SPECT), mainly performed by γ-Camera systems, the spatial resolution is greatly affected by the scintillation crystal, the collimator, source-collimator distances, and the energy of the used radiotracers. In order to validate the effect of all these factors on the system's resolution a simulation study is presented in this work.

On the other hand, in cylindrical Positron Emission Tomography (PET) systems, the resolution is primary limited by the radial dimensions of the device, as well as by the positron energy of the radiotracer in use. In this work, we will focus on the most usual positron emitters used in biomedical imaging processes (^{18}F, ^{11}C and ^{15}O) with different positron annihilation ranges. The annihilation occurs several millimeters after the positron's emission point, which is introducing a limit to the system's spatial resolution. A powerful tool to evaluate the aforementioned aspects of various SPECT and PET systems, is the GATE (GEANT4 Application for Tomographic Emission) [1] Monte-Carlo simulation package.

2 Single Photon Emission Tomography: γ-Camera Simulation

In the past years, in our laboratory a prototype small field γ-Camera system based on a Position Sensitive PhotoMultiplier Tube (PSPMT) has been developed [2]. This small field (50 mm effective Field of View) γ-Camera system utilizes the resistive chain technique, in order to reduce the 16-X and 16-Y multianode wire-system to only four signals. The whole system comprises a parallel-hole Pb-collimator of hexagonal type, with a total area of $60 \times 60\ mm^2$ and a 4 mm thick CsI(Tl) pixelated scintillation crystal. Due to the applied signal reduction technique, the Data Acquisition (DAQ) System consists of a 4-channel fast PCI-1714 Analog-to-Digital Converter (ADC). In order to evaluate the GEANT4/GATE [1] results, the prior described hexagonal collimator and pixelated scintillation crystal system, together with a simple phantom structure was simulated.

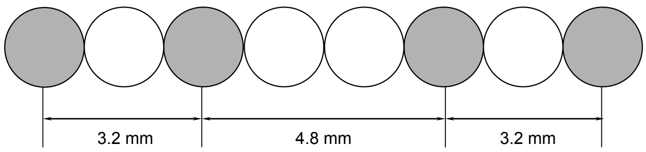

Fig. 1. Phantom layout of the four capillaries filled with ^{99m}Tc (shown in grey) water solution. Empty capillaries are used as spacers.

The phantom was consisting of four parallel capillaries filled with ^{99m}Tc water solution; its layout is shown in Figure 1. The simulation was performed for several phantom-collimator distances {0, 5, 10, 20, 50, 80 mm}.

Planar projections were extracted from the Monte-Carlo data and directly compared with the experimentally obtained planar images [3] by using the existing γ-Camera system. One of the most important disadvantages in the present simulation was that the optical photon transport inside the scintillation crystal is not taken into account. Although optical photon transport effects can be easily simulated by GATE, this is usually avoided due to the large number of generated optical photons for each detected γ-ray ($\sim$ 40 photons/keV), and consequently, the large computational time consumed. For this reason, GATE extracted results show a systematically better spatial resolution compared with the experimental ones. This effect is shown in the left part of Figure 2, where the simulated phantom profile is directly compared to the experimentally obtained projection.

In order to include the optical diffusion effect of the scintillation crystal, a Gauss distributed random variation is introduced in the event-by-event reconstruction procedure of the simulated data. Accordingly, the new spatial variable X_{corr} is defined through a gaussian random distribution $f(\sigma)$ by the equation:

$$X_{corr} = X \cdot (1 + f(\sigma)),$$

where X denotes the original event position. For an optimal value of $\sigma = 0.18$ (frame units), the simulated data can describe the experiment reasonably well (right part of Figure 2).

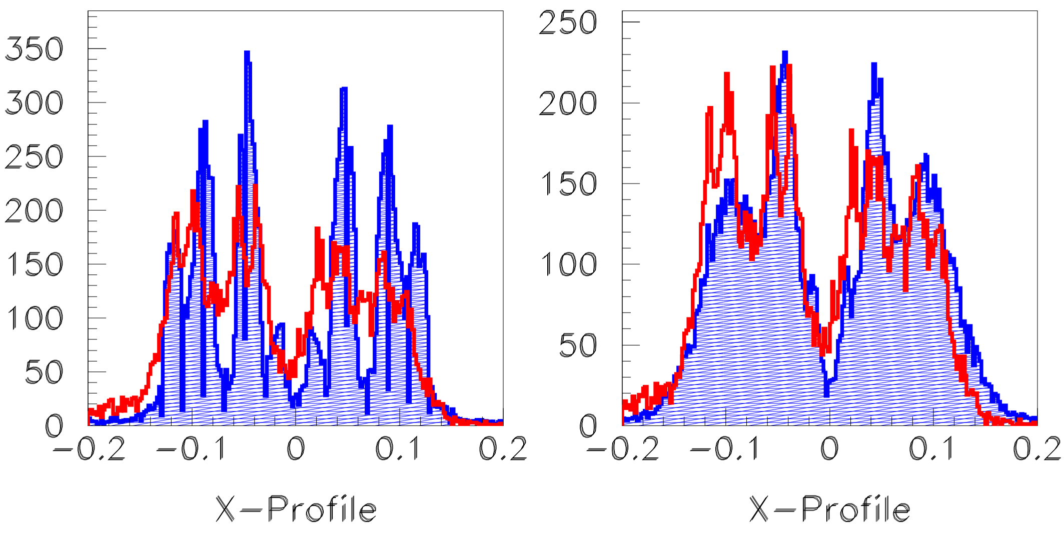

Fig. 2. Projections of phantom planar images: Experimental data (filled areas) compared with the simulation results (line) without (left) and with optical photon diffusion effects (right).

The same simple four-capillaries phantom was used to simulate the previous experiment using different radiotracers in order to evaluate their contribution to the tomographic spatial resolution. No significant differences are noticeable between ^{99m}Tc (140 keV), ^{123}I (159 keV) and ^{201}Tl (X-rays 70-90 keV).

3 Positron Emission Tomography (PET) Simulation

A common system, proximal to a commercially available cylindrical PET scanner consisting of 32 sectors (from $R_{min} = 80cm$ to $R_{max} = 100cm$) with 4 blocks of 6×6 LSO scintillation crystals ($2.0cm \times 2.5cm \times 17.0cm$), has been constructed in the GATE environment. To determine the positron annihilation range effect in the system's spatial resolution, simulations for the most usual positron emitters (^{18}F, ^{11}C and ^{15}O) were conducted. Initially, the event distribution among corresponding sectors of the ring detector was checked to ensure that the simulation results are acceptable. As shown in Figure 3, the system is properly simulated: Coincidence events detected within a given sector (N=1) are compared with associated events (back emitted photons) detected in other sectors of the cylindrical PET-System. Most of these events lie in the diametrically opposite sector (N=1+16). Secondly, a two-gamma back to back point source was used to calculate the systems intrinsic resolution. From the reconstructed planar image of the point source, the spatial resolution of the system was found to be better than 2 mm (see Figure 3).

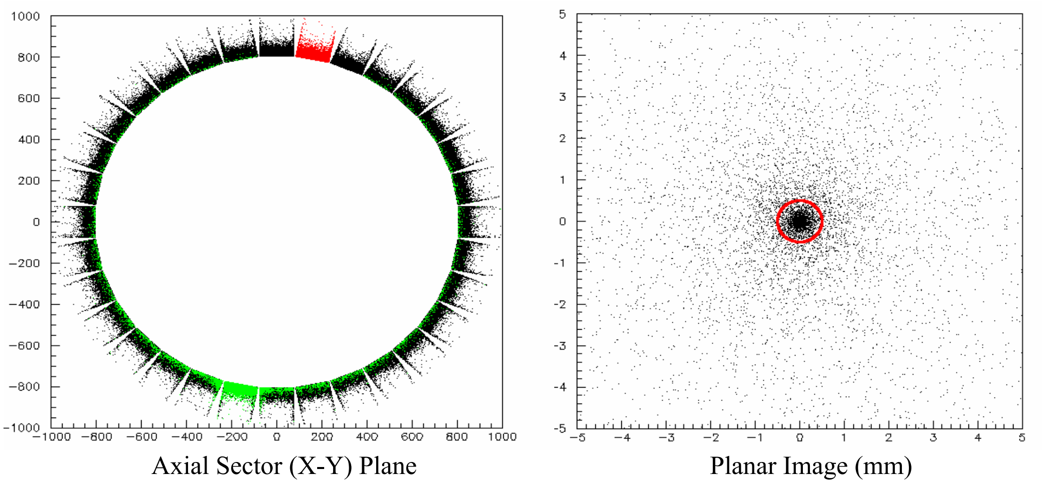

Fig. 3. *Left:* The axial (X-Y) reconstructed image of coincidence events detected by the simulated PET ring system. Coincident events detected within the first sector are shown in different color. *Right:* Planar image of a ^{18}F-positron emitter point source.

These results were compared with the obtained ones from ^{18}F, ^{11}C and ^{15}O sources, in order to estimate the effect of the positron annihilation range on the spatial resolution. The reconstruction is done on the Z=0 plane from the exact event coordinates recorded inside the LSO crystal. Due to the previously estimated 2 mm intrinsic spatial resolution of the system, different positron emitters, with a large variation in their positron energy spectra, produce almost identical axial profiles.

4 Concluding Remarks

Concerning SPECT, the GEANT4/GATE simulation study gives reasonable results. To overcome the disadvantages associated with the large time consumption of the optical transport simulation effects, a diffusion parameter was introduced. Assuming Gauss-like random distribution for the detected events, an optimal value of this parameter can be determined by directly comparing and adjusting simulation extracted results with the experimentally obtained data on an event-by-event basis. In the present study and for the 4 mm CsI(Tl) scintillation crystal, the extracted value of $\sigma = 0.18$ (in frame units) reflects the effect of the optical photon diffusion inside the scintillation crystal. With this value fixed, the simulated data can further describe the experiment sufficiently for all measured source-collimator distances.

On the other hand, in the PET simulation study, using a two-gamma back to back point source the system's spatial intrinsic resolution was determined to be 2 mm. The different positron emitters ^{18}F, ^{11}C and ^{15}O, commonly used in PET imaging, have a large variation of annihilation ranges, which are all lesser than the system's intrinsic spatial resolution. This fact leads to the production of almost identical axial profiles from these positron emitters.

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