Collimator Study of a γ -Camera System using GATE

Maria Mikeli, Dimitris Thanasas and Efstathios Stiliaris, Member, IEEE

Abstract—A collimator study for a small field, high resolution γ -Camera system by means of GATE (GEANT4 Application for Tomographic Emission) simulations is presented in this paper. The aim of this study was the optimal definition and design of the geometrical characteristics of a parallel hole Pbcollimator, suitable for our γ -Camera system, which is based on the R2486 (HAMAMATSU) Position Sensitive Photomultiplier Tube, for different radio-tracers. The methodology followed two basic steps: (a) A validation phase with an existing parallel hole Pb-collimator of hexagonal structure, which preceded the main study. In this phase, experimentally obtained results for planar images are 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. (b) A GATE simulation setup for the main collimator study geometry was constructed and the γ -Camera detector is repeated 36 times (in steps of 10^0) around a ring. This construction allows the simultaneous detection of data for further SPECT reconstruction studies. Simulation data are accumulated for three ellipsoidal sources placed at the center of the ring with different tracer energies, different relative intensities and for several collimator geometries. The collimator sensitivity is tabulated for each tracer energy according to the ratio D/T, where D represents the hole diameter and T the collimator thickness. Finally, the spatial resolution is defined for some basic collimator hole patterns (triangular, square, cylindrical and hexagonal). SPECT images are also reconstructed and the detected resolution is discussed.

I. INTRODUCTION

C OLLIMATORS play a very important role in medical imaging, in particular in the modalities where images are formed by selective absorption of the emitted radiation, because γ -rays, unlike optical photons, cannot be refracted and focused. For a γ -Camera system, the selective absorption is the only way for the creation of images and therefore the collimator is one of the most crucial system components. Since most of the gamma rays emitted by the radiopharmaceuticals are absorbed in the collimator, the selective absorption proves to be very inefficient. For the collimators used in nuclear medicine, only about one in ten thousand of the emitted gamma rays pass through it. Thus, the design of the collimator

has a significant effect on the overall performance of the $\gamma\text{-}$ Camera.

Collimators are in general characterized by their imaging properties, resolution and sensitivity. The geometrical parameters such as collimator thickness, septal thickness, and hole diameter, dictate most of their imaging properties. Unfortunately, many other effects, such as Compton scattering, scattering within the collimator or penetration of radiation through the collimator septa, need special attention in the design [1].

The aim of this study was the optimal definition and design of the geometrical characteristics of a parallel hole Pb-collimator, suitable for our small field, high resolution γ -Camera system, by means of GATE (GEANT4 Application for Tomographic Emission) simulations [2].

II. VALIDATION PHASE

A validation phase with an existing parallel hole Pbcollimator of hexagonal structure preceded the main study. In this phase, experimentally obtained results from planar images are directly compared to simulated data. A simple phantom structure was imaged by the γ -Camera system for several phantom-collimator distances and the measured and Monte Carlo calculated spatial projections were compared.

A. The Parallel Hole Collimator

The most important geometrical characteristics of the parallel hole Pb-collimator used in the validation phase are shown in Table 1. Its hexagonal front structure is also clearly shown in the closeup picture of Fig. 1.

$59.5 \times 60.4 mm^2$
26.8 mm
0.75 mm
0.25 mm
32
23

TABLE I GEOMETRICAL CHARACTERISTICS OF THE PARALLEL HOLE PB-COLLIMATOR

The γ -Camera system used to take the planar images is mainly based on a Position Sensitive Photomultiplier Tube (PSPMT), model R2486 by HAMAMATSU, equipped with a 4 mm thick pixelated CsI(Tl) scintillation crystal (1 mm pixel-width). The 3-inch in diameter cylindrical PSPMT has a 16X+16Y crossed-wired anodic grid arranged into two orthogonal groups. The anode output wires are connected to a resistive current divider network digitized with PCI electronics [3], [4].

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M. Mikeli, D. Thanasas and E. Stiliaris are with the National and Kapodistrian University of Athens, Department of Physics, 15771 Athens, Greece. Corresponding author: E. Stiliaris (e-mail: stiliaris@phys.uoa.gr)



Fig. 1. Front structure (photograph detail) of the hexagonal, parallel hole Pb-collimator used in the validation phase with the γ -Camera system, which is based on the R2486 (HAMAMATSU) Position Sensitive Photomultiplier Tube.

B. GATE Simulations and Experimental Verification

The collimator and the scintillation crystal of the γ -Camera system have been properly modeled within the GATE simulation environment. The scintillation crystal has been declared as *sensitive volume*, so that every interaction process which takes place inside the crystal is fully recorded. Many other details, like the aluminum housing of the system and interposed materials, have been included in the simulation. Results of an older study [5] with the same collimator and γ -Camera system have showed an excellent agreement between simulated and experimental data. The difference between experimental and simulated system sensitivities for different source-to-collimator distances was within 2%.

The phantom consists of four glass capillaries of cylindrical shape with an outer diameter of 1.6 mm forming an 1-0-1-0-0-1-0-1 arrangement (0: radioactive, 1:non-radioactive), the non-radioactive capillaries used as spacers. They are filled with water solution of 99m Tc with the same activity and placed parallel to the collimator face and in various distances from it (Fig. 2).

Measurements have been performed for following distances phantom-collimator front: $d = \{0, 5, 10, 20, 50, 80\}$ mm. Planar images and their projections along the horizontal axis have been directly compared with GATE simulation results. A typical result for the distance d=5 mm is shown in Fig. 3. Since the optical photon transport inside the scintillation crystal is not taken into account in the present study, the simulated data, as expected, show a systematically better spatial resolution with respect to the real data. A photon diffusion factor has therefore to be defined for the scintillator in use; this factor is kept constant in the further analysis.

III. COLLIMATOR STUDY WITH GATE

Having fixed the photon diffusion factor inside the scintillation crystal a series with simulation studies has been



Fig. 3. Experimental results. *Upper part:* Planar image of the 4-capillaries phantom captured with the γ -Camera system. *Lower part:* Image projection on the horizontal axis. The experimental plot (dark blue) is compared with the simulated result (light blue). The distance phantom-collimator is 5 mm.

performed. Again the γ -Camera system (collimator, CsI(Tl) scintillation crystal, aluminum case) is fully modeled in the GATE environment. Two different types of simulations have been performed and analyzed: In the first, a complicated phantom is used and the γ -Camera system has been rotated around the phantom. From the planar images accumulated and the SPECT reconstruction the resolution of the system for different collimator geometries has been examined. In the second group of simulations, only planar images are recorded for a point like source. They have been energy analyzed and the collimator effect on Compton scattering has been investigated.

A. SPECT Study

In this study, a MIRD type anthropomorphic head phantom has been used. Three radioactive ellipsoidal sources with



Fig. 2. The collimator and the scintillation crystal of the γ -Camera system have been properly modeled within the GATE simulation environment. The left part of this figure shows the hexagonal detail of the collimator structure. The simulated experimental setup is shown in the central part. The radiation source consists of four capillaries filled with water solution of 99m Tc with the geometry shown in the right part of the figure. The capillaries are placed parallel to the collimator face and in various distances from it.

different sizes (in the order of mm) and with activities 0.60 : 1.00 : 1.40 are placed in the center of the anthropomorphic phantom. Because of the strong absorption of the collimator and the long runtime needed for a full GATE simulation, the detector system was repeated 36 times (in steps of 10^{0}) in a ring around the phantom (Fig. 4). This method allowed a simultaneous accumulation of all the planar images needed for the SPECT reconstruction at once.



Fig. 4. The simulated γ -Camera system repeated 36 times in a ring around the phantom to allow simultaneous data accumulation for SPECT analysis.

Simulation results, such as collimator sensitivity and detected spatial resolution, are tabulated for several D/T ratio values, where D is the collimator hole diameter and T the collimator thickness. Four basic collimator hole patterns (triangular, square, circular and hexagonal) have been studied. Some typical planar images of the phantom and the 3D-SPECT reconstructed results are shown in Fig. 5.

B. Point Source Study

For several distances F from the hexagonal collimator front the projection of a 99m Tc point source is detected and analyzed. The geometric resolution of the collimator (denoted by R_g) is defined as the limiting radius r such that $r > R_g$ implies that no ray can pass through the collimator without penetrating a septum. It is well known that the geometric resolution for a collimator is given by the simple relation:

$$R_g(F) = \frac{D}{T}F\tag{1}$$

where D denotes the collimator hole diameter and T the collimator thickness.

For a given set of geometrical collimator characteristics, the radius R_g calculated by this simple relation, allows the definition of two regions on the detection surface: The inner and the outer region. Energy spectra for these two regions have been accumulated and the Compton effect has been investigated. The procedure is repeated for different collimator types and geometries. In Fig. 6 a typical example for a hexagonal type collimator for two different distances of the radiation point source is given.

Based on the position-energy information and the definition of the inner and outer regions, the number of Photo-peak and Compton events has been investigated. Their ratio as a function of the distance F is plotted in Fig. 7. In this figure,



Fig. 5. Simulation Results for three different hole diameters (D/T=0.02, 0.04 and 0.06) and for circular hole type collimator. Upper part: Detected planar images. Lower part: 3D-Reconstructed images.



Fig. 6. Analysis of simulated results with a hexagonal type collimator of thickness T = 20.0 mm and hole diameter D = 0.80 mm and a ^{99m}Tc point source. Upper part: Planar image detected for a source distance F = 30 mm (left, central) and F = 80 mm (right) from collimator front. Lower part: Energy plots for the corresponding planar images. Detected events inside the circle defined by the geometric resolution R_g of the collimator are light (red) colored. Events outside the circle are dark (blue) colored.

N denotes counted photons inside the defined region and O counted photons outside the region. The index Ph indicates Photo-peak (full energy) events, while the index C refers to Compton events.



Fig. 7. Ratios of Photo-peak (full energy) events (Ph) and Compton events (C) for the two different regions on the detector surface defined by the geometric resolution R_g . Counted events inside this circle are indicated with N, outside with O.

It is clear from this type of analysis that all of the ratios shown in the plot are independent on the distance F sourcecollimator. The only exception are the outside events, where the ratio of Compton scattered photons relative to Photo-peak events seems to be larger for small distances.

IV. CONCLUDING REMARKS

A collimator study for a small field, high resolution γ -Camera system by means of GATE has been performed. In the validation phase with an existing parallel hole Pb-collimator of hexagonal structure, which preceded the main study, and by comparing the experimentally obtained results with the simulated data, a photon diffusion factor has been defined for the scintillator in use and is kept constant during the next steps. The spatial resolution for planar and for SPECT reconstructed images has been tested for several collimator geometries. Finally, with the energy-position information on the detector surface, the ratio of Compton events relative to Photo-peak events has been investigated. It seems that the main collimator characteristics, such as resolution and sensitivity, for the ^{99m}Tc energies used in this study, are mostly defined by its geometric properties.

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