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GATE simulations for optimization of pinhole imaging

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Abstract

We validated the Monte Carlo package, GATE, for multi-pinhole gamma-ray imaging simulations using calculations and measurements. For these studies requiring large amount of photon histories, the newly designed cluster version of GATE was used. Accordingly that validated simulator allowed us then to evaluate design parameters for ^{123}I-experiments on a prototype multi-pinhole SPECT camera for which analytical calculations were failing due to scatter of high-energy photons.

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1. Introduction

Many examinations in microSPECT small animal imaging use radiopharmaceuticals with ^{125}I and ^{123}I as radionuclide. These results can be ported to human use since the 159 keV gamma-rays of ^{123}I have a sufficiently long path length. Literature [1,2] indicates that iodine-labelled agents will play an even more important role in the future. However, besides the high cost, the high-energy photons in the spectrum of ^{123}I form a disadvantage. These high-energy photons cause scatter and penetration through the collimator material, which results in image deterioration. When using a collimator with multiple pinhole apertures, the sensitivity is shown to increase [3], while the high system resolution can be preserved. The sensitivity and resolution of the pinhole apertures is still very often calculated from approximate formulas which is especially problematic for ^{123}I given its aforementioned high-energy peaks and the according low stopping power of scintillation detectors. However, Monte Carlo codes such as GATE [4] exist to address these specific problems since the processes taking place in the collimator (also for the ^{123}I high-energy peaks) can be thoroughly simulated. It is the purpose of this manuscript to validate this realistic simulator for multi-pinhole simulations versus calculations and measurements. Accordingly that validated simulator will allow us then to evaluate design parameters for ^{123}I-experiments on a prototype camera for which analytical calculations are failing due to penetration and scatter.

2. Methods

2.1. Multi-pinhole collimator

The acquisition setup (Fig. 1) that will be discussed in this manuscript consists of a prototype multi-pinhole tungsten collimator intended for rat brain imaging on a Siemens ECAM camera. The design is inspired by the work of Schramm et al. [5]. The collimator is made of tungsten and has seven pinhole apertures of 1.5 mm diameter with a focal length of 170 mm and an acceptance angle of 60°. The aperture configuration consists of one central aperture and six off-center apertures. The apertures are all inclined towards the same point at 50 mm in front of the collimator,

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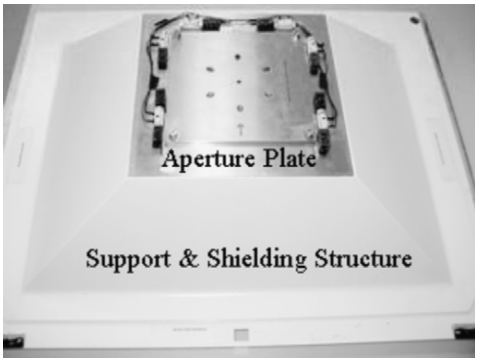

Fig. 1. Illustration of the acquisition setup.

yielding an inclination angle of approximately 37.5° for the noncentral pinhole apertures [6].

2.2. Analytical calculation and realistic simulations

For each individual pinhole aperture of a single or multi-pinhole collimator the sensitivity is calculated by ray tracing. Starting from each detector pixel a finite number of rays through a rectangular grid (in the plane through the pinhole center and parallel to the collimator planes, centered around the pinhole center) is considered and the fraction of photons that penetrates through the collimator material is calculated analytically. The GATE simulation model on the other hand incorporated all elements of the acquisition chain starting from the collimator plate with the knife edge apertures over the NaI-crystal in its casing before the light guide, the PMTs and the compression plate, further on to the air gap, the lead ending, and the shielding. Due to the inherent GATE macro-language for describing the geometry of the simulation model, design parameters of the prototype can easily be altered to investigate their optimization.

2.3. Validation

To evaluate the simulations, the measurement acquisition was mimicked as closely as possible. A 1 cm radius planar ^{99m}Tc source was put in a small container and was directly placed on the central pinhole and afterwards on one of the oblique pinholes (at 60°). The 25 MBq (675 μCi) source was simulated for six real-time seconds and no restrictions were applied to the emission angle to avoid bias in the scatter distribution. Furthermore, a 3.3 mm intrinsic crystal resolution was modelled as well as a 10% energy resolution at 140.5 keV which follows a $1/\sqrt{\text{energy}}$ behavior. The resulting distribution of detections was smoothed with a 10 pixel wide Gaussian kernel to compensate for noise on the simulations before profiles were selected. Afterwards, those profiles were normalized to the integral of the curve. Finally, the percentual differences between simulations versus calculations and measurements, respectively, were evaluated by dividing the total of the absolute value of the profile differences by the integral of the profile itself.

2.4. Evaluation

2.4.1. Plate thickness

Four batches of 25 simulations each were conducted in order to determine the optimal thickness of the pinhole plate. The respective plate thicknesses were: 0.6, 1, 2 and 4 cm of tungsten. We chose to keep the distance between the object and the collimator surface constant (which is for instance important for thyroid ^{123}I-studies) and we accordingly opted to vary the object-aperture distance which results in other spatial magnification factors but still enables us to perform a quantitative scatter analysis for constant object-collimator distances which is especially attractive from the experimental point of view. A circularly shaped two-dimensional source of 37 MBq (1 mCi) ^{123}I was contained in a 1 cm high, 3 cm radius water cylinder. It was placed at the collimator plate and simulated for a real-time full minute. Again, no restrictions were applied to the emission angle to avoid bias in the scatter distribution.

2.4.2. Scatter windows

To investigate the origin of the photons in the left and right scatter window (for triple energy window correction [7]) a simulation study was set up. A 3 cm height and 3 cm radius cylinder containing two 37 MBq spherical ^{123}I-sources of 1 mm radius was put on the central pinhole. The two sources were 2 mm separated from each other. The acquisition was simulated for 60 real-time seconds. In order to avoid any bias in the scatter events, no restrictions were applied to the emission angle. Since all parameters (also acquisition time) of this simulation are realistic, the study had to be performed on a computer cluster. Dedicated cluster software for distributed GATE computing was designed [8] and used in research for the first time. Accordingly, energy plots and projections of the phantom setup were simulated for the photopeak and for the two scatter windows to evaluate the spatial information content. The resulting profiles were normalized to their respective integral for qualitative comparison.

3. Results

3.1. Validation of the simulations

All data in this validation section is for ^{99m}Tc. Firstly we show the validation results for the central pinhole in Fig. 2(a,b). When we validate the simulations versus the calculation we can conclude an almost perfect agreement with a mismatch of only 3.3% for the simulated X-profile versus the calculations (including noise on the simulations) and of 3.1% versus the measurements (which had an uniformity correction). For the Y-profile, an error of 3.8% was found after comparison of the simulations with the calculations and an error of 1.9% when validating versus