Feasibility of a novel design of a high resolution/sensitivity animal PET scanner using thick and thin arrangement of monolithic scintillators

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***Abstract*– With the ever increasing use of transgenic and knockout laboratory animals to model human diseases, the need for high resolution and sensitivity small-animal PET scanners is becoming apparent. The well-established trade-off between spatial resolution and sensitivity is evident during the selection of crystal size. Higher thickness crystals provide a higher sensitivity but degrade the spatial resolution. In this work, we modeled two configurations of a small-animal PET scanner with 10 and 12 monolithic crystals using Monte Carlo simulations. In each configuration, half of the detector blocks have thick crystals (10 mm) whereas the second half has thin crystals (2 mm). This design is based on the Xtrim-PET preclinical scanner where in the first configuration, the block detectors with thick crystals face those with thin crystals and vice versa. In the second configuration, the block detectors with crystals of the same thickness (thick and thin) are arranged face-to-face in the full-ring polygonal geometry of the gantry. In addition, two modes of data acquisition were simulated: stationary and rotating. The gantry has no motion in the stationary mode, whereas the gantry recurrently rotates back and forth over the scan time with the angular step corresponding to half the size of the crystals in the rotating mode. The resolution and sensitivity evaluated using the NEMA NU4-2008 standards. The proposed design enables to achieve sub-millimetric spatial resolution (0.7 mm and 0.6 mm) and high sensitivity (4.3% and 3.1%) at the centre of the FOV for the first and second configurations, respectively. It can be concluded that the proposed design configuration enables to overcome the conventional trade-off between sensitivity and spatial resolution, while achieving sub-millimetric spatial resolution and high sensitivity.**

I. INTRODUCTION

WITH the increasing demand for animal models in biomedical research, small-animal PET became popular in a number of preclinical applications. The well-established trade-off between spatial resolution and sensitivity is evident during the selection of crystal size. Thicker crystals provide a higher sensitivity but degrade the spatial resolution and vice-versa [1]. In this work, we modeled two configurations of a small-animal PET scanner with 10 and 12 monolithic crystals using Monte Carlo (MC) simulations. In each configuration, half of the detector blocks contain thick crystals (10 mm) while the second half contain thin crystals (2 mm). The design is based on Xtrim-PET preclinical scanner where in the first configuration, the block detectors with thick crystals face those with thin crystals and vice versa. In the second configuration, the block detectors with same crystal thickness are arranged face-to-face in the full-ring polygonal geometry of the gantry. In addition, two modes of data acquisition were simulated: stationary and rotating. The gantry has no motion in the stationary mode, whereas the gantry recurrently rotates back and forth over the scan time with the angular step corresponding to half the size of the crystals in the rotating mode. The resolution, sensitivity, NECR and image quality were then evaluated using the NEMA NU4-2008 standards [2].

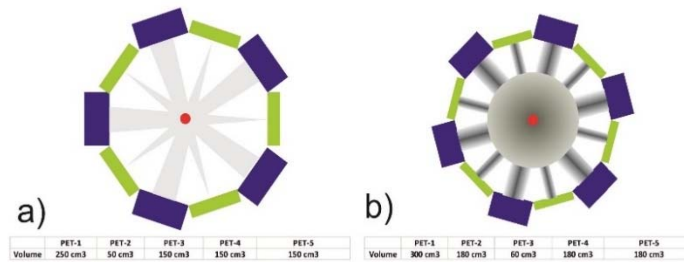

Fig. 1. Schematic representation of the simulated setup: a) configuration one and b) configuration two. The amount of total crystal volume is also mentioned.

II. MATERIALS AND METHODS

Two PET scanners based on different arrangements of monolithic crystals with and without geometrical symmetry were simulated. The first group contain scanners consists of 10 block detectors while the second group is composed scanners with 12 detector modules. Furthermore, each configuration consists of five different types containing isodiametric and non-isodiametric monolithic crystal thicknesses as summarized in Table 1.

TABLE 1. NUMBER OF DETECTORS AND THEIR CORRESPONDING THICKNESS FOR VARIOUS PET SCANNER MODELS.

PET model	# Detector	Crystal thickness	PET model	# Detector	Crystal thickness
10B-10	10	10 mm	**12B-10**	12	10 mm
10B-2	10	2 mm	**12B-2**	12	2 mm
10B-6	10	6 mm	**12B-6**	12	6 mm
10B-10-2	5 5	10 mm 2 mm	**12B-10-2**	6 6	10 mm 2 mm
10B-10-2-R	5 5	10 mm 2 mm	**12B-10-2-R**	6 6	10 mm 2 mm

Manuscript received December 31, 2019. This work was supported by the Swiss National Science Foundation under grant SNFN 320030-176052.

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978-1-7281-4164-0/19/$31.00 ©2019 IEEE

A. Monte Carlo simulations

Monte Carlo simulations of the scanner geometries were performed using the Geant4 toolkit. All the physical processes were considered including optical processes which were handled by G4OpScintillation.

B. Geometry

Depending on how thick and thin the crystals are laid out, two general types of structures were considered.

1) First configuration: Scanner with 10 modules

The most important feature, which makes this configuration different from regular geometries is that half of the modules used in this scanner (figure 1a) are equipped with thick crystals (10 mm thickness) to improve the sensitivity while in the second half thin crystals (2 mm thickness) were used to improve the spatial resolution. The crystals with various thicknesses are in front of each other (thin crystals are located in front of thick crystals). We also simulated three types of regular scanners with same crystal thickness to assess the impact of using two different crystal thicknesses. These three scanner geometries have similar physical characteristic features, namely ten LYSO monolithic crystals and same SiPM photo detectors. The only difference in these three types of scanners are the crystals thicknesses: 10 mm, 2 mm and 6 mm in 10B-10, 10B-2 and 10B-6, respectively. 10B-10 belongs to the group of high sensitive scanners while 10B-2 shows high resolution capability. 10B-6 with an average crystal thickness and the same total crystal volume as 10B-10-2 was simulated to evaluate the influence of using different crystal thicknesses. Furthermore, we simulated 10B-10-2-R, the dynamic version of 10B-10-2 whose gantry recurrently rotates with angular steps of 18° after passing half of the scan time.

2) Second configuration: Scanner with 12 modules

In the second configuration (figure 1b), the crystals with same thickness are in front of each other (thick in front of thick and thin in front of thin). The main reason for using 12 instead of 10 modules in the second configuration is motivated by the fact by using 10 modules; the scanner loses its symmetry resulting in two modules with the same crystal thickness placed beside each other. This causes non-uniformity in the final reconstructed image. Apart from the above-mentioned features, all the physical characteristics in this configuration are similar to the previous one. For comparison, three regular scanners with 12 modules were simulated. The rotating model of this configuration rotates 15 degrees for each step during scan time.

C. Image reconstruction

A Matlab code was developed for image reconstruction exploiting the position of each event taking place within the monolithic crystal based on the Correlated Signal Enhancement (CSE) positioning algorithms [3].

The scintillation photons reaching the SiPM's pixels were counted and stored in a root file where each of the 144 pixels was labeled by number of detected scintillation photons and its position along X and Y directions. The CSE algorithm was applied to the scintillation photons distribution to estimate the origin of the scintillation event for each detector block. A line was plotted between two scintillation positions as a line of response (LOR). The LORs were labeled with its distance and angle from the axes of the scanner. Single-slice rebinning was applied to assign oblique LORs to the image slice where the LOR crosses the scanner axis. All the LORs were stored in a histogram and reconstructed using the OSEM algorithm implemented within the STIR package (5 iterations and 4 subsets).

D. Performance evaluation

The performance of the designed configurations was appraised using the NEMA NU4-2008 standards by calculating S

The validation strategy used in this study was based on a comparison between the real and simulated model of a commercial scanner called Xtrim-PET preclinical scanner [4].

III. RESULTS & DISCUSSION

A. Spatial resolution

Figure 2 shows the spatial resolution (FWHM) in radial and axial directions of two design configurations at six distances from the axial center.

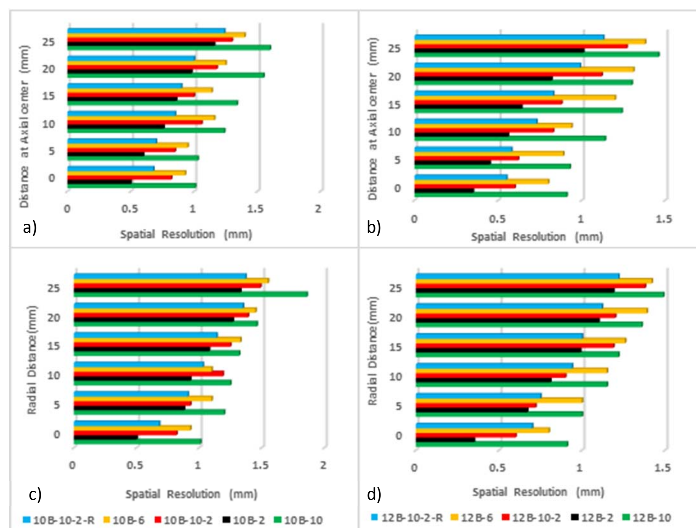

Fig. 2. Spatial resolution of the simulated PET scanner models along the axial (a,b) and radial (c,d) directions.

The suggested PET models with thin and thick crystal thicknesses (10B-10-2 and 12B-10-2) resulted in outstanding performance, leading to sub-millimetric spatial resolution of 0.9 and 0.6 mm FWHM, respectively, thus outperforming the 10B-6 and 12B-6 PET models with 1.2 to 0.8 mm FHWM, respectively.

B. Sensitivity

Figures 3a and 3b show the absolute sensitivity of the PET configurations with 10- and 12-detector blocks, respectively.

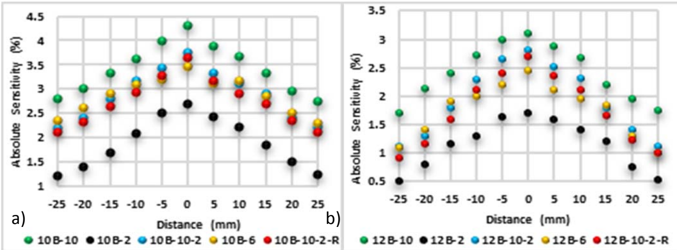

Fig. 3. Absolute sensitivity calculated at different distances from the center of the FOV along the Z-axis for PET scanner models consisting of: a) 10 detector modules and b) 12 detector modules.

In preclinical research, improving the performance capabilities of PET instrumentation, including spatial resolution and sensitivity is essential. In small-animal imaging, a spatial resolution of less than ~1mm is an asset. Therefore, the use of 2mm thick LYSO crystal improves the spatial resolution but degrades the sensitivity.

The 12B-10-2 PET model achieved an absolute sensitivity of 2.8% compared to the 12B-6 PET model with a sensitivity of 2.45%. Applying an arrangement of detector blocks with thick and thin crystal thickness moderates the uncertainty on the assigned LOR for one side of paired detectors in 10B-10-2 and half of the paired detectors with thin crystals in 12B-10-2 model. This gives rise to higher positioning accuracy and hence better spatial resolution. Although the depth of interaction was not taken into consideration, a sub-millimetric spatial resolution was achieved, comparable with the resolution achieved with low thickness crystal scanners (10B-2, 12B-2).

IV. Conclusion

We have designed, simulated and evaluated the performance of novel designs of small-animal PET scanners using monolithic LYSO crystals with two different crystal thicknesses coupled to SiPMs. Half of the detector modules used in this scanner are equipped with thick crystals (10 mm thickness) to improve the sensitivity while the second half of the detector modules used thin crystals (five crystals with 2 mm thickness) to improve spatial resolution. This innovative design attained optimal trade-off between spatial resolution (0.7 mm) and sensitivity (3.74%) at the center of the FOV.

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