Optimization of Dual Layer Phoswich Detector Consisting of LSO and LuYAP for Small Animal PET

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Abstract—Phoswich detectors for small animal PET have been developed to measure the depth of interaction and to improve resolution performances. The aim of this study was to perform simulations to design the optimum lengths of crystals composing a dual layer phoswich detector. A simulation tool, the Geant4 Application for Tomographic Emission (GATE), was used and validated against a commercially available small animal PET using a dual layer phoswich detector. The newly designed small PET system employed cerium doped lutetium oxyorthosilicate (LSO) —cerium doped lutetium-yttrium aluminum perovskite (LuYAP) phoswich detector modules, which consisted of 8 × 8 arrays of dual layer crystals, with a 2 × 2 mm sensitive area, coupled to a Hamamatsu R7600-00-M64 position sensitive photomultiplier tube (PSPMT). The sensitivities and variations of the radial resolutions were simulated by varying the length of the LSO front layer from 0 to 10 mm, while the total length (LSO + LuYAP) was fixed to 20 mm for 10 and 19 cm diameter ring scanners. The results support the validity of the simulation tool. The radial resolution uniformity was markedly improved using the depth of interaction (DOI) information, and the optimal lengths of the crystal layers for minimizing the variation of the radial resolutions also existed. In the 10 cm ring scanner configuration, the radial resolution was kept below 3.4 mm, over 8 cm field of view (FOV), while the sensitivity was higher than 7.4% for the LSO 5 mm : LuYAP 15 mm phoswich detector. The resolution variations were minimized to less than 3.6 mm, over 16 cm FOV, using a LSO 6 mm : LuYAP 14 mm phoswich detector for the 19 cm ring scanner. In this study, the optimal length of the dual layer phoswich detector was derived to achieve a high and uniform radial resolution.

Index Terms—Depth-of-interaction, phoswich detector, small animal PET.

I. INTRODUCTION

As an effective imaging probe in the area of animal models of human disease, gene expression and therapy, and drug discovery and development, small animal PET imaging is being used increasingly [1]–[3]. An ideal small animal PET should have a high sensitivity and uniform resolution across the field of view to achieve high image quality. However, the combination of a long narrow pixellated crystal array and the small ring diameter of small animal PET leads to degradation of the spatial resolution of the imaging object located off-center. The annihilation event that originates off-center might be registered to an inaccurate line of response (LOR) and blur image resolution, because obliquely incident gamma rays in a PET might penetrate several pixellated crystals before interacting in a crystal, presenting only the information of the crystal of interaction. This degradation of resolution can be improved by determining DOI in the crystal, and by taking into account the information when sorting the coincident events [4].

A number of DOI determination schemes have been proposed. These include the use of a phoswich detector constructed of several different scintillators with different decay times [5]–[7], stacking scintillators with different concentrations of doping material [8] and coupling photosensitive detectors, such as PSPMT; photodiodes and avalanche photodiodes, to opposite ends of the crystals [9], [10]. Other approaches have employed controlling light sharing between crystals using various surface treatments [11] and a multistage rectangular block of crystals segmented along the depth to extract DOI information from the light distribution property in crystals [12].

Among those DOI identification schemes, the dual layer phoswich detector has been widely investigated by many research groups, due to its practicability and effectiveness of extracting DOI information. In a commercially available small animal PET scanner, ATLAS (Advanced Technology Laboratory Animal Scanner) [13], which was developed at the National Institute of Health (NIH), Bethesda, MD, has a DOI measurement capability by employing this technique. However, the effects of each crystal length composing the dual layer phoswich detector on the DOI measurement capabilities and image qualities have not been fully characterized. In order to minimize the DOI effect, the length of each layer of the phoswich detector should be optimized.

The goal of this work was to perform simulation studies to characterize and optimize the lengths of two different crystal layers of a phoswich detector for a small PET to achieve a high and uniform resolution. For this purpose, a Monte Carlo simulation tool, GATE [14], a simulation platform developed for PET and SPECT, was used. A validation study of the simulation method for the dual layer crystal performances was performed against ATLAS [13]. The radial resolution and sensitivity of a PET scanner being designed in our laboratory were simulated for the combined LSO front layer and LuYAP back layer phoswich detector.
II. MATERIALS AND METHODS

A. Monte Carlo Simulation Tool, GATE

The Monte Carlo simulation tool used in this study was GATE, an object oriented simulation platform for a versatile solution dedicated to PET and SPECT [14]. GATE was built on top of the well-proven simulation tool GEANT4 [15], and a user can model various aspects of a PET experiment to simulate most of the phenomena encountered in PET using a scripting language. One may specify the ring-type PET geometry, and any number of radioactive sources with different properties. The scanner geometry, such as the number of rings, detector modules arranged in those rings, number of crystals in a detector module and lengths and materials composing the crystal layers can be parameterized. Movements, such as rotations of the scanner and translations of the phantom as a function of time can be scripted. Radioisotope decays can be specified, and the decay time and interactions with scanner materials (photoelectric effect, Compton scattering, Rayleigh scattering and gamma ray conversion) are computed from the activity, the radioisotope half-lives and the properties of the materials. Single and coincident detections of gamma rays by the crystals can be stored on an event-by-event basis into multiple output files with different file formats.

B. Validation of Monte Carlo Simulation Tool With ATLAS

A small animal PET scanner, ATLAS, using a dual layer phoswich detector, having DOI measurement capability for imaging animals up to 6 cm in diameter [13], was chosen for validation purposes. ATLAS is based on the cerium doped lutetium gadolinium oxyorthosilicate (LGSO) cerium doped gadolinium oxyorthosilicate (GSO) phoswich detector module, which consisted of a 9 x 9 array of 2 x 2 x 15 mm phoswich elements, with a 2.25 mm pitch. Each element consisted of a 7 mm long LGSO front layer and an 8 mm long GSO back layer. The end of the GSO was optically coupled to a Hamamatsu R7600-C8 PSPMT, with 18 modules arranged around a ring with an 11.8 cm diameter. The layer of interaction was identified by measuring the decay time difference between the LGSO (40 ns) and GSO (60 ns) of each event.

The variation in the resolution across the field of view and the sensitivity of the ATLAS were simulated, and compared to the measured data of Seidel et al. 2001. The spatial resolutions of the ATLAS were simulated by moving a 0.5 mm diameter point source, with 4 mm increments in the radial direction, from 1.3 out to 31.3 mm from the scanner center. Images of the source at each position were reconstructed using 2-D filtered backprojection and a Ramp filter. The radial profiles of the point source images were fitted to a Gaussian function to measure the spatial resolution. The simulated sensitivity, the fraction of annihilation yielding detected coincidence events, was measured using a point source located at the center of the scanner for low energy thresholds of 100 and 250 keV.

C. Design Parameters of Our Small PET

Two small PET systems were designed, one with a 10 cm ring diameter for rodents, and the other with a 19 cm ring diameter for primates. These two designs were simulated to characterize the effects of the phoswich detector lengths on correcting parallax errors as a function of the ring diameters.
Fig. 4. Reconstructed images of the point source obtained by moving a source from the center to the radial offset of the scanner’s FOV, at 10 mm intervals, and their profiles for the 10 cm scanner. (a) 20 mm LSO single layer detector, without DOI information, (b) LSO 5 mm : LuYAP 15 mm phoswich detector, with DOI information.

The simulated small PET system employed phoswich detector modules arranged in a ring, comprising of a LSO front layer and a LuYAP back layer with DOI capability. LSO was chosen for the detector due to its high stopping power, high light output and fast decay time [16]. LuYAP has almost the same density as LSO, while the decay time is about 2 times faster [17]. A detector module, consisting of $8 \times 8$ arrays of dual layer crystals, with a $2 \times 2$ mm sensitive area (2.3 mm pitch), was coupled to a 64 channel Hamamatsu R7600-00-M64 PSPMT. Two small PET systems, with diameters of 10 and 19 cm, had 4 rings with 16 and 32 modules per ring, respectively. The total crystal length (LSO+LuYAP) was fixed at 20 mm to allow sufficient sensitivity, with the lengths of the front and back layers varied to evaluate the effects of the DOI measurement for the improvement of the parallax errors.

**D. Simulation for Characterization of Phoswich Detector Lengths**

Fig. 1 illustrates the geometrical representation of the spatial broadening for various phoswich detector layer lengths. The thick arrows represent the direction and mean free path (1.15 cm at 511 keV for LSO, [18]) of 511 keV photons obliquely incident on the LSO-LuYAP crystals. The dashed and dotted lines illustrate the possible LORs from the front and back layers of the phoswich detector, respectively. Off-center events incident on the single layer crystals resulted in blurred images, due to inaccurate LORs, as shown in Fig. 1(a). As the front layer length in dual layer phoswich detector was increased, the spatial broadening of the LORs decreased and reached the minimum [Fig. 1(b)–(d)]. Then, the spatial broadening of the LORs were further increased [Fig. 1(e)–(f)]. Therefore, optimum lengths of the dual layers existed to minimize image blurring and preserve the spatial resolution.

The effects of each crystal length, consisting of the dual layer phoswich detector, on a blurred image were investigated by the Monte Carlo simulation. The length of the front layer was varied from 0 to 10 mm, with 1 mm intervals, while the total length (LSO+LuYAP) was fixed at 20 mm. For each combination of front and back layer lengths of the phoswich detector, the radial resolutions and sensitivities of the proposed scanners were estimated.

A 0.1 mm diameter point source was placed at the center of the field of view to measure the sensitivity, which was defined as a fraction of the annihilations yielding valid coincidences. The energy window was set between 250 and 650 keV. To calculate the spatial resolutions of PET systems consisting of various phoswich detectors, a 0.1 mm diameter point source was positioned out to 40 and to 80 mm, in 10 mm steps, starting at the center of the 10 and 19 cm diameter scanners, respectively. The simulated events were stored in a list mode format (LMF) that recorded the interacting positions, deposited energies and time stamps of each event. After images of the source at each position had been reconstructed, using 2-D filtered backprojection with a ramp filter, the full-width at half-maximums (FWHMs) of the radial profiles were estimated by Gaussian fitting.
III. RESULTS

A. Validation of Monte Carlo Simulation Tool With ATLAS

The simulated sensitivities were 2.8% and 2.0%, with lower level discriminator (LLD) values of 100 and 250 keV, respectively. The measured sensitivities were 2.7% and 1.8%, with 100 and 250 keV LLD thresholds, respectively. The simulated and measured sensitivities closely agreed with the 4% discrepancies. Fig. 2 shows the simulated and measured radial resolutions obtained by stepping a point source at 4 mm increments in the radial direction from the center to a 31.3 mm radial offset for the ATLAS scanner. The FWHMs obtained by the simulations and measurements ranged from 2.0 mm to 2.5 mm and 1.9 mm to 2.6 mm, with mean values of 2.2 mm and 2.2 mm, respectively. The discrepancies between the simulated and measured resolutions were under 5% over the entire FOV of the ATLAS.

B. Optimization of Phoswich Detector Lengths

Fig. 3 shows the simulated sensitivities of the 10 and 19 cm diameter ring scanners as a function of the front layer length. These curves were obtained with a 250 to 650 keV energy window. The simulated sensitivities increased from 7.1 to 8.6% and from 5.4 to 6.5%, proportional to the front layer (LSO) length, for the 10 and 19 cm diameter scanners, respectively.

The effects of the crystal layer lengths of the phoswich detector on the DOI measurements and the image qualities were demonstrated as a function of the front layer length of the phoswich detector. Fig. 4 illustrates reconstructed images, and the profiles of their point sources obtained by moving the source from the center to the radial offset of the scanner’s FOV, at 10 mm intervals for the 10 cm diameter scanner with a LSO single layer of 20 mm and with a LSO 5 mm : LuYAP 15 mm phoswich detector. This figure demonstrates the effects of the DOI measurements on correcting the parallax error and the marked, especially at off-center, improvement in resolution.

The variations in the radial resolution for each combination of phoswich detector lengths, as a function of the source position for two different scanner ring diameters, are shown in Fig. 5. Fig. 6 shows the variations in the radial resolution as a function of the front layer length. As described in Fig. 1, the radial resolution initially decreased, but then increased, after reaching the...
minimum value, as the length of front layer increased. As illustrated in Figs. 5 and 6, the radial resolutions at 40 mm off-center were 5.6, 3.4, 4.1, and 7.9 mm when the ring diameter was 10 cm and the front layer lengths were 2, 5, 10, and 20 mm, respectively. For the 19 cm diameter scanner, the radial resolutions at 80 mm off-center were 6.2, 3.6, 4.6, and 9.6 mm when the front layer lengths were 2, 6, 10, and 20 mm, respectively. The minimum radial resolution was achieved when the front layer lengths were 5 and 6 mm for the 10 and 19 cm diameter scanners, respectively.

IV. DISCUSSION AND CONCLUSION

The simulated sensitivity and radial resolution variation of the ATLAS scanner were in good agreement with those measured. These results support the validity of the Monte Carlo simulation tool, GATE, for the sensitivity and resolution estimation of the small animal PET using a phoswich detector.

The radial resolution uniformity was considerably improved using the DOI information. When a dual layer phoswich crystal is employed, optimum lengths of layers exist, which can minimize the radial resolution variations, as shown in Fig. 6. Fig. 6 demonstrates that better spatial resolution can be obtained when the front layer is shorter than the back layer.

In the 10 cm diameter ring type PET scanner configuration, radial resolutions less than 4 mm were provided over an 8 cm FOV when the length of the front layer ranged from 4 to 8 mm, and the best resolution uniformity was achieved when the front layer length of the phoswich detector was 5 mm. Using the LSO 5 mm: LuYAP 15 mm phoswich detector, the radial resolution was markedly improved, from 8.0 to 3.4 mm, at a 40 mm off-center, compared to the 20 mm LSO single layer detector.

When the ring diameter was 19 cm, the minimum variation of the radial resolution was achieved with a 6 mm front layer length for the phoswich detector, and the radial resolutions were kept below 3.0 and 3.6 mm over 12 and 16 cm FOVs, respectively.

The sensitivities increased proportionally to the front layer length. LSO has a higher stopping power than LuYAP, as shown in Fig. 3. Since the optimum front layer length was relatively short compared to that of the back layer in the proposed phoswich detector, the sensitivity of the proposed system was low. It may be possible to improve the sensitivity without decreasing the resolution by changing the sequence of crystals in phoswich detector and by using a longer LSO crystal. In order to increase the sensitivity, an optimization study for a phoswich detector composed of LuYAP front and LSO back layers is in progress. However, the light output of LuYAP is about 3 times less than that of LSO. An experimental approach to evaluate the possibility of measuring the light outputs from a LuYAP front layer is required for the application of the crystal identification methods for distinguishing the LSO and LuYAP layers, such as decay time measuring and light pulse shape discrimination schemes [19].

In this study, the effects of the crystal lengths in a dual layer phoswich detector on the DOI capability were characterized, with the optimal crystal lengths derived for small animal PET, with 10 and 19 cm diameters, to achieve high and uniform radial resolutions.

REFERENCES