Performance of High-Resolution PET Detectors Employing Long Semi-Monolithic Scintillator Slabs

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Abstract

Conventional positron emission tomography (PET) scanners use either highly segmented or monolithic scintillator detectors. Depth of interaction (DOI) information is vital for high-resolution PET scanners that use either segmented scintillator detectors with a large crystal-length-to-width aspect ratio or monolithic scintillator detectors with a large crystal-thickness-to-spatial-resolution ratio. Semi-monolithic scintillator detectors maintain the intrinsic DOI encoding capability of monolithic detectors, but with a substantially smaller edge effect. The objective of this study was to compare the performance of semi-monolithic scintillator detectors with different slab thicknesses, slab surface treatments,

Full Text

Preamble

Performance of high-resolution PET detectors based on long semi-monolithic scintillator slabs∗

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Conventional positron emission tomography (PET) scanners use either highly segmented or monolithic scintillator detectors. Depth of interaction (DOI) information is vital for high-resolution PET scanners that use either segmented scintillator detectors with a large crystal-length-to-width aspect ratio or monolithic scintillator detectors with a large crystal-thickness-to-spatial-resolution ratio. Semi-monolithic scintillator detectors maintain the intrinsic DOI encoding capability of monolithic detectors, but with a substantially smaller edge effect. The objective of this study was to compare the performance of semi-monolithic scintillator detectors with different slab thicknesses, slab surface treatments, and reflector types. Four long semi-monolithic detectors consisting of lutetium yttrium oxyorthosilicate (LYSO) slabs of 0.96 mm\$$\times 56 mm \times 10 mm and 0.81 mm \times 56 mm \times$\$10 mm, with and without black paint on both the end and front surfaces, were measured. In addition, semi-monolithic detectors using either barium sulfate (BaSO4) or an enhanced specular reflector (ESR) as the inter-slab reflector were compared for the first time. The semi-monolithic detectors were read out by a 4 × 16 silicon photomultiplier array with a row and column summing readout circuit, and the signals were processed using electronics developed in our laboratory. Black paint treatment of the two ends and front surfaces degraded the energy resolution but improved both the spatial resolution in the monolithic direction and DOI resolution, thereby improving the overall detector performance. The detector using an ESR reflector provided clearer individual slab identification in the flood histogram and a similar spatial resolution in the monolithic direction, DOI resolution, and energy resolution. The squared centroid of gravity (COG) method improved the spatial resolution in the monolithic direction by ~30% compared with the COG method. The long semi-monolithic scintillator detectors optimized in this work provide clear identification of LYSO slabs of 0.96 and 0.81 mm thick, a spatial resolution in the monolithic direction of ~1.7 ± 0.3 mm, a DOI resolution of ~2.1\$$\pm 0.7 mm, and an energy resolution of$ 17.5±\$2.0%. These detectors can be used to develop high-performance small animal and organ-specific PET scanners.

Keywords: Positron emission tomography (PET), PET detector, semi-monolithic scintillator, silicon photomultiplier, depth of interaction.

INTRODUCTION

Positron emission tomography (PET) is a non-invasive medical imaging tool that is used for the early detection of many major diseases such as cancer [1, 2]. Achieving a high spatial resolution in a PET scanner allows for the accurate measurement of biochemical processes in the organs and tissues of living subjects by reducing the partial volume effect [3]. This is particularly important for small-animal imaging [4–6] and clinical applications such as neuroimaging [7].

The depth of interaction (DOI) uncertainty reduces the spatial resolution of PET scanners, particularly for small-animal and organ-specific PET scanners that use detectors with a high crystal-length-to-width aspect ratio [6, 8]. Owing to crystal penetration, events may be incorrectly assigned to the incorrect line of response when detectors that lack DOI measurements or have poor DOI resolution are used. The error resulting from DOI uncertainty increases as the aspect ratio of the crystal increases. In the most common cylindrical detector geometry, the DOI uncertainty error increases with both the radial offset and ring difference. DOI encoding in PET detectors is important for achieving a uniformly high spatial resolution.

At present, state-of-the-art PET scanners use either pixelated or monolithic scintillator crystals that are read out by silicon photomultiplier (SiPM) photodetectors. Pixelated detectors can achieve a high timing resolution because the scintillation photons are constrained in a smaller area and the photodetector can achieve a high signal-to-noise ratio. They can also achieve superior planar position resolution using small scintillator crystals [9, 10]. However, DOI information is not intrinsically present in pixelated detectors, and modified detector designs, such as dual-ended readout or multiple-layer crystals, are required to measure the DOI, which increases the cost and complexity of the detectors [11–15]. Pixelated detectors also have a lower detection efficiency owing to the dead space occupied by the inter-crystal reflectors [5]. In monolithic scintillator detectors, the DOI information is intrinsically presented, as it can be extracted from the scintillation photon distribution [5, 7]. The efficiency of monolithic detectors is superior and their cost is lower compared with pixelated detectors. However, monolithic detectors exhibit the disadvantage of large edge effects. Owing to the loss and reflection of scintillation photons at the edge of the detector, fewer scintillation photons are detected, and the measured planar positions are compressed for the interactions occurring close to the edge of the detector, resulting in degradation of both the planar and DOI resolutions. Both the planar spatial and DOI resolutions deteriorate, and the edge effect increases as the detector thickness increases [16–23].

Semi-monolithic scintillator detectors exploit the advantages of both pixelated and monolithic scintillator detectors. They maintain the inherent DOI-encoding capability, although the scintillation photon distribution is limited to fewer photosensors along the monolithic direction. Semi-monolithic detectors have a smaller edge effect compared with monolithic detectors, which can be further reduced using longer scintillator slabs. Semi-monolithic scintillator PET detectors were proposed and preliminarily evaluated by Chung et al. [24, 25] around 2010 using detectors consisting of one or more scintillator slabs. Later, least-squares minimization and maximum likelihood positioning algorithms were developed [26] and slab surface treatments were optimized [27, 28] by our group for semi-monolithic detectors. In recent years, more studies have been conducted on the development of semi-monolithic detectors for small-animal [29], dedicated brain, and whole-body [30–32] PET scanners. It has also been demonstrated that machine-learning-based positioning algorithms can improve both the spatial resolution in the monolithic direction and the DOI resolution, as well as reduce the edge effect [32–34].

In this study, four semi-monolithic detectors using long lutetium yttrium oxyorthosilicate (LYSO) slab arrays with different slab surface treatments, slab thicknesses, and inter-slab reflectors were evaluated. The performances of a semi-monolithic detector using two different inter-slab reflectors were compared for the first time. The positioning resolutions in the monolithic direction obtained using the conventional centroid of gravity (COG) and squared COG algorithms were also compared.

II. MATERIALS AND METHODS

A. Detector modules

Figure 1 [Figure 1: see original paper] shows a schematic of the detector module. The detector module was composed of LYSO slabs that were read out by a SiPM array with a lightguide between them. Table 1 shows the detailed parameters of the four detector modules used in this study. The semi-monolithic LYSO arrays were manufactured by Epic Crystal Co. (Shanghai, China). The reflector between the individual slabs of detectors 1, 2, and 4 was barium sulfate (BaSO4), whereas the enhanced specular reflector (ESR) of 3M Company was used in detector 3. The thickness of the BaSO4 and that of the ESR plus optical glue were both 0.08 mm. The optical glue used was EPO-TEK 301 (EXPOXY Technology INC., MA, USA). The two end and front surfaces of detectors 1, 3, and 4 were unpolished and painted with a black marker pen, whereas the surfaces of detector 2 were unpolished and left unpainted. For all detectors, the two large surfaces of each slab and the bottom surface interfacing with the readout SiPM were polished.

Each detector module was read out by a 4 × 16 SiPM array coupled to the bottom of the LYSO array. The SiPM array consisted of 64 single SiPM pixels (S14160-3050HS; Hamamatsu Inc., Hamamatsu, Japan). Each single SiPM had a size of 3.4 mm × 3.4 mm and an active area of 3 mm × 3 mm. The pitch of the SiPM array was 3.65 mm. All measurements were performed at a SiPM bias voltage of 44.5 V. The lightguide was made of 1.5 mm thick k9 glass with a refractive index of 1.51. To enhance slab identification, two edge grooves, 0.2 mm wide and 1 mm deep, were cut into the lightguide. The grooves were filled with the BaSO4 reflector. For detectors 1 to 3, the grooves were 1.91 mm from both edges. For detector 4, the grooves were 2.05 mm from both edges. Optical grease with a refractive index of 1.41 was used between both the lightguide and scintillator slab array and the lightguide and SiPM array.

B. Experimental setup

The experimental setup is illustrated in Fig. 2 [Figure 2: see original paper]. All measurements were conducted in a light-tight plastic chamber covered with a black cloth, and the operating temperature of the detectors was 14 °C. The flood histogram was measured by placing a 0.3 mm diameter 22Na point source with an activity of 165 kBq 24 mm from one lateral face of the detector. Monolithic direction spatial, DOI, and energy resolution measurements were performed in coincidence with a reference detector. The reference detector was a single LYSO crystal of 1 mm × 1 mm × 20 mm wrapped with Teflon and read out by a single Hamamatsu S14160-3050HS SiPM with an active area of 3 mm × 3 mm. A collimated 511 keV beam was produced by placing the 22Na point source between the reference detector and a 5 mm thick tungsten collimator with a 1 mm diameter drilled hole. The 1 mm hole of the collimator, 22Na point source, and reference detector were well aligned and placed on a motorized translational platform. The semi-monolithic detector was placed on a stationary platform. The translational platform could move in both the monolithic direction (y-axis) and DOI direction (z-axis spanning from the top of the detector to the SiPM array). The semi-monolithic scintillator detector was irradiated from a series of (y, z) positions by moving the translational platform. As shown in the top part of Fig. 3 [Figure 3: see original paper], detectors 1 and 4 were irradiated at 27$×$5 positions starting 2 mm from one end and 1 mm from the front, with a stepping size of 2 mm in both the monolithic and DOI directions. To reduce the measurement time, detectors 2 and 3 were irradiated only at 27 y positions along the center z and five z positions along the middle y, as shown in the bottom part of Fig. 3, and only the results from these positions were used to compare the performances of the four detectors. The irradiation time for each position was 2200 s. The percentage of useful coincidence events relative to the total number of single events was ~0.02% for an energy window of 350 − 650 keV for both detectors.

C. Electronics and data acquisition

The 64 signals from the SiPM array were aggregated by a row-column summing circuit to form four row and 16 column signals, as shown in Fig. 4 [Figure 4: see original paper]. The four row signals were used for slab identification (x), whereas the 16 column signals were used for both the y- and z-position measurements. The 20 signals were propagated to a pre-amplifier board, where all of the signals were first amplified using voltage feedback amplifiers (model AD8056, Analog Devices, MA, USA). A timing signal was produced by summing the four pre-amplified row signals. The timing signal was amplified using a fast amplifier (model AD8045; Analog Devices, MA, USA). A 50 mV threshold signal was used together with the timing signal to generate three differential timing signal pairs using three high-speed comparators (model AD-CMP604; Analog Devices, MA, USA).

The three differential timing signal pairs and 20 energy signals of the test detector, as well as one differential timing signal pair and one energy signal of the reference detector, were propagated using micro-coaxial cables to a singles processing unit (SPU) originally developed for our SIAT bPET scanner [35], as shown in Fig. 5 [Figure 5: see original paper]. The SPU board could process eight independent dual-ended readout detectors, each containing eight energies and one differential timing signal pair. Three and one SPU electronics blocks were used to read out the test and reference detectors, respectively.

In the SPU, the energy signals from the pre-amplifier boards were first shaped and amplified. Second, the waveforms of the energy signals were sampled at a rate of 62.5 MHz using analog-to-digital converters (ADCs). Third, the digital signals were processed in a field-programmable gate array (FPGA) to determine the signal energies by calculating the areas under the waveforms. This was achieved by summing 18 waveform samples and subtracting the baseline, which was the average of four samples obtained before the rising edge of the waveform. For each electronics block, a differential timing pair was sent to a tapped delay line time-to-digital converter (TDC) to obtain the timestamp of the event, which was also used as the starting signal for the area calculation of the energy. Finally, from each SPU electronics block, eight energy values and a timestamp for each event were sent to the host PC using an Ethernet-based user datagram protocol (UDP) [36–39].

Software-based data selection and coincidence processing were carried out on the host PC. A coincidence timing window of 10 ns was used. The coincidence data containing 20 energies of the test detector and the time difference between the reference and test detectors were stored as listmode data and used for further analysis.

D. Data analysis

1. Planar position

The (x) and (y) coordinates of the interaction were calculated using the conventional COG algorithm, as follows:

$$x = \frac{\sum_{j=1}^{4} j \times q_j}{\sum_{j=1}^{4} q_j}$$

$$y = \frac{\sum_{i=1}^{16} i \times q_i}{\sum_{i=1}^{16} q_i}$$

The (y) coordinate was also calculated using the squared COG algorithm, as follows:

$$y = \frac{\sum_{i=1}^{16} i \times q_i^2}{\sum_{i=1}^{16} q_i^2}$$

where i is the column number of the signals and q__i is the amplitude of the i-th column signal. j is the row number of the signals and q__j is the amplitude of the j-th row signal.

From the calculated x, y coordinates, a flood histogram showing the 2D distribution of the gamma interaction positions in the detector were plotted to demonstrate the slab identification of the detector. The flood histogram could be segmented to obtain a slab lookup table that could later be used to assign events to different slabs. For the coincidence measurement of the irradiation of a specific (y, z) position of the detector, histograms of y coordinates could be obtained for individual slabs using either the COG or squared COG algorithm [40]. The histograms were fitted using a Gaussian function to obtain the peak positions. For each (y, z) position, the peak position of the y histograms was determined as the average of all slabs. The curve of the peak positions and true y irradiation position values for a specific z was fitted using a cubic polynomial function to obtain the fitting parameters. The measured y histogram of each (y, z) position could be converted from the pixel value into mm using the fitting parameters. The converted y histograms were then fitted using Gaussian functions, and the full width at half maximum (FWHM) y resolutions were obtained for all measured positions.

2. Energy

The detector energy was calculated by summing the amplitudes of the 16 column signals. The energy histograms for each irradiation position were populated for all individual slabs. Gaussian fitting was performed and the energy resolution was calculated as the ratio of the FWHM to the mean.

3. DOI

The DOI of the gamma interaction was estimated using the inverse standard deviation of the amplitudes of the 16 column signals, as shown in Equation (4):

$$\mathrm{DOI} = \frac{1}{\sqrt{\frac{1}{16}\sum_{i=1}^{16}(q_{ni} - \bar{q}_n)^2}}$$

where q_{ni} is the normalized amplitude of the i-th column signal and $\bar{q}$_n is the average amplitude of the 16 column signals. Five DOI histograms of each y position were obtained for each slab, and Gaussian fitting was performed to obtain the FWHMs and peak positions of the histograms. The FWHM was converted into mm using the peak positions of the neighboring DOI histograms and the known DOI interval of 2 mm. An energy window of $350 - 650$ keV was used for all results in this work. The irradiation beam width, which was estimated to be ~1 mm, was not subtracted from the y and DOI resolutions.

4. Timing

The timing of the detector was defined as the timing difference between the reference and test detectors. The timing spectra of each irradiation position were populated for all individual slabs using a timing window of 40 ns. Gaussian fitting was performed and the FWHM timing resolution was obtained.

III. RESULTS

A. Flood histograms

The flood histograms of the four detectors are shown in Fig. 6 [Figure 6: see original paper]. The flood histograms show the x and y positions of the interactions of the gamma rays with the detectors, where the grayscale value of the color bar represents the number of interactions occurring at these positions. The profiles through the middle of each flood histogram are also shown in Fig. 6. The average peak-to-valley ratios of the four detectors were 3.01$±0.75, 4.88±1.27, 5.08±1.45, *and*2.97±$0.85, respectively. All slabs were clearly resolved for detectors 1 to 3 using 0.96 mm thick slabs. As shown in the flood histogram, along the x coordinates of the detector, slab identification was best achieved in detector 3, which used the ESR reflector. The second and third slabs near the edges could not be clearly resolved for detector 4 using 0.81 mm thick slabs. The positions of the cuts in the lightguide likely need to be further optimized. Black painting of the two end and front surfaces of the slabs reduced the scintillation photon reflection at those surfaces and mainly resulted in longer flood histograms in the monolithic direction, implying a better y position resolution, while the slab identification was almost unchanged.

B. Energy resolution

The energy spectra of the middle slabs of the four detectors measured at the five DOIs are shown in Fig. 7 [Figure 7: see original paper]. Detector 3, which used a specular ESR reflector, had the lowest light output; however, the photopeak amplitudes did not change with the depth. The other three detectors, which used the diffusive BaSO4 reflector, had a much higher light output; however, the photopeak amplitude changed significantly with the depth. A depth-dependent energy calibration is required for these detectors. The average energy resolutions of detectors 1 and 4 measured at the 27$×$5 (y, z) positions are listed in Table 2. Average energy resolutions of 17.4% and 17.6% were achieved for the two detectors, implying that the thickness of the slab had a small effect on the energy resolution. The average energy resolutions of the four detectors measured at the 27 y positions along the middle DOI are listed in Table 3 . The average energy resolutions for detectors 1 to 4 were 15.8%, 14.7%, 15.8%, and 16.4%, respectively. Detector 2 (without black paint) exhibited the best energy resolution because the black paint absorbed some scintillation photons, thereby degrading the energy resolutions of the other three detectors.

C. Spatial resolution in the monolithic direction

The curves of the peak positions of the COG and squared COG algorithms for different y irradiation positions measured at three depths are shown in Fig. 8 [Figure 8: see original paper] for detectors 1 and 4. The curves were linear at the middle of the detectors and became nonlinear at both ends owing to scintillation photon reflection and truncation. The nonlinearity decreased as the depth increased. Nonlinearity increases the challenge of detector calibration and degrades the spatial resolution in the monolithic direction. The curves were similar for different slabs of the detector (data not shown). Figure 9 [Figure 9: see original paper] shows the y profiles of the 27 different y positions and two DOIs of detector 1 obtained using the two positioning methods. The horizontal coordinates of the y profiles were converted into mm using the curves shown in Fig. 8. For both methods, the resolvability of the profiles deteriorated more towards both ends owing to the edge effect. To demonstrate the effects of the positioning methods and depths on the y spatial resolution more clearly, y profiles of a DOI of 5 mm and y of 42 mm obtained using the COG and squared COG methods, and y profiles of DOIs of 1 and 5 mm and y of 42 mm obtained using the squared COG method are shown in Figs. 9 (e) and (f), respectively.

Figure 10 [Figure 10: see original paper] shows the spatial resolutions of all irradiation positions of detectors 1 and 4 using the COG and squared COG methods. For both methods, the y spatial resolution improved as the DOI moved towards the SiPM. The y spatial resolution degraded as the y position moved towards both ends owing to edge effects. At the DOI near the SiPM, a variation in the y spatial resolution with changes in the y positions was observed because of the gaps between the SiPM pixels and inactive areas at the edge of the SiPM pixels. The squared COG method showed a better y spatial resolution than the COG method. As shown in Table 2 , the y spatial resolutions averaged over the entire detectors were 1.68$±0.29*and*1.67±0.27*mmfordetectors*1*and*4,*respectively.AsshowninTable*3,*theaverageyspatialresolutio*
mm for detectors 1 to 4, respectively.

D. DOI resolution

Figure 11 [Figure 11: see original paper] shows the DOI profiles of the four detectors measured at the center y position (28 mm). The DOI resolution degraded significantly as the DOI moved away from the SiPM. This is because the change in the scintillation photon distribution width with the DOI decreased as the DOI moved farther from the SiPM. Figure 12 [Figure 12: see original paper] shows the DOI resolutions at all irradiation positions for detectors 1 and 4. The DOI resolution also degraded towards both ends of the detector owing to the edge effect. The average DOI resolution results are summarized in Tables 2 and 3. The DOI resolutions averaged over the entire detectors were 2.14$±0.76*and*2.28±$0.67 mm for detectors 1 and 4, respectively. Detector 2

Note: Figure translations are in progress. See original paper for figures.

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