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Detector Design of PET Measuring Depth of Interaction through Energy Spectrum Analysis

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A depth of interaction detector was designed using three layers of the scintillation pixel array and silicon photomultiplier through DETECT2000 simulation. The upper and lower layers used diffuse reflectors, and the middle layer used specular reflectors to distinguish the light signal arising from each layer. The signals obtained at each layer were characterized by different locations at which photoelectric peaks were formed in the energy spectrum, which could be analyzed to track the layers in which gamma-rays and scintillation pixels interacted. Based on the simulation results, the basic experiment was conducted to obtain the energy spectrum. In the experiment, three photoelectric peaks were identified in the energy spectrum as in the simulation, and the layers interacted with gamma-rays, and scintillation pixels for each layer were distinguished by analyzing each photoelectric peak. It is anticipated that by applying the detector design obtained from this study to future small animal PET operating with MRI, the depth at which gamma-rays and scintillators interact will be measurable, thus improving the spatial resolution outside the FOV.

Keywords : depth of interaction, DETECT2000, Reflectors, PET, MRI, magnetic field

1. Introduction

Positron Emission Tomography (PET) detectors for small animal applications use long, thin scintillators to improve spatial resolution and sensitivity [1]. Additionally, the small gantry is used to visualize small animals with improved sensitivity without sacrificing spatial resolution at the center of the field of view (FOV). Importantly, however, activity outside the FOV causes a decrease in spatial resolution due to the parallax error [2]. Photons generated at the center of the FOV are detected by a single scintillator pixel as they are incident orthogonal to the face of the detector module. In contrast to this, photons arising from areas outside the FOV are instead incident at an angle away from the surface normal of the detector module, leading to signal in multiple scintillation pixels, which subsequently degrades the spatial resolution during image reconstruction [3]. This problem of resolution degradation has been approached in a number of ways, including configuring the scintillation pixel in multiple layers and analyzing the properties of the scintillator, utilizing multiple layers and multiple sensors, and analyzing the ratio of signals acquired from the sensor [4-8]. Each of these methods carries its share of challenges and problems. In scintillators consisting of multiple layers of scintillation pixels, it is challenging to accurately characterize the properties of a single scintillation layer. In the case of multiple sensors, costs are increased with the necessitation of complex signal processing circuits, not to mention the costs of the additional sensors themselves. Moreover, analyzing the signal ratio of a sensor requires post-processing that includes the attenuation correction for gamma-rays and scintillators by its signal ratio [9].

In the present study, we build upon a prior detector design [10] with an aim to measure the depth of interaction within a scintillation pixel of a multi-layer detector to resolve the issue of spatial resolution degradation due to parallax errors. The proposed detector consists of three layers of scintillation pixels backed by a light sensor and silicon photomultiplier (SiPM) for operation with magnetic resonance imaging (MRI). In order to maximize the

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amount of light delivered to the light sensor, the scintillator was treated with a reflector. Depending on the type of reflector, the signal from the light sensor varies, manifesting in the position of different photoelectric peaks in the energy spectrum. Positional analysis of these photoelectric peaks can in turn determine the position of gamma-ray sources and scintillators. The determination of interaction depth in this manner was verified through a DETECT2000 [11] simulation, and the energy spectrum was obtained by experiments using a single-pixel scintillator.

2. Material and Methods

A simulation in DETECT2000 generates light in the scintillator that then interacts with variously treated scintillator surfaces to simulate the process of entering the sensor through reflection, refraction, and absorption. The material of the scintillator can be modeled via the refractive index. The designed detector consists of three scintillation layers and SiPM, as shown in Fig. 1. The Gadolinium Aluminum Gallium Garnet (GAGG) [12] scintillator (Furukawa Co., Ltd, Ibaraki, Japan) was simulated with the refractive index set to 1.9. Each scintillation pixel had a size of 3 mm × 3 mm × 5 mm and consisted of three layers in a 4 × 4 array.

The reflector treatment of the scintillator for each layer was set differently so that the signal size of the light incident on the SiPM was differentiated. The upper and lower layers were set as diffuse reflectors, excluding the parts connected with different scintillators and sensors, and the middle layer was set as specular reflectors. All surfaces through which the light is transmitted were treated to be optically connected, and optical grease (refractive index: 1.465) was used to ensure that the light was transmitted effectively. The sensor used to detect light from the scintillator was the MatrixSM-9-30035 [13] (SensL, Cork, Ireland). The MatrixSM-9-30035 consists of 144 individual 3 mm × 3 mm SiPM elements grouped in a larger 3 × 3 array. A single 4 × 4 pixel array element was simulated in this study. The material in the area that is optically connected to the scintillator in the SiPM was set to epoxy with a refractive index of 1.5.

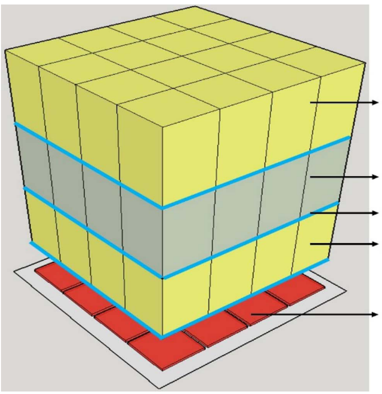

Fig. 1. (Color online) Schematic of the detector module for DETECT2000 simulation. Each scintillation crystal pixel had a size of 3 mm × 3 mm × 5 mm and consisted of three layers in a 4 × 4 array.

Fig. 2. (Color online) Preliminary experiment set-up. An energy spectrum was obtained by detecting the light generated by the interaction between the scintillator and the gamma ray using the SiPM.

In order to determine the gamma-ray response generated in the three layers, a signal was obtained by generating the light produced in the scintillator due to gamma-ray interactions at 0.3 mm intervals in all directions within each of the 48 scintillation pixels. The total simulated emission was established to correspond to the 511 keV response of a GAGG scintillator, taking into account the light collection efficiency of the sensor. The 16 channels of the light signal acquired were reduced to 4 channels using the Anger equation, and the image was reconstructed.

Basic experiments were conducted using GAGG scintillation pixels connected to SiPMs. The size of the GAGG scintillation pixels used in the experiment was 3 mm × 3 mm × 10 mm, and three layers were used to obtain the energy spectrum of a Na-22 source. The reflector treatment for each layer was set to the same as in the simulation. Figure 2 shows the connection of the SiPM and GAGG scintillation pixels to measure the energy spectrum.

3. Results and Discussion

The energy spectrum was acquired from the light signals obtained through the DETECT2000 simulation. As shown in Fig. 3, the simulation generates as many lights as 511 keV, which was different from the spectrum of a Na-22 source and showed only the part corresponding to the photoelectric peak. The position of the photoelectric peak for each layer in the simulated detector module differed. Diffuse reflectors applied to the upper and lower scintillation layers shifted the photopeak to higher channels. Conversely, the specular reflector of the middle layer shifted the peak to lower channels. Additionally, signals arising from the lower layers appear in distinguishably higher channels than those arising from the upper layers of the scintillator.

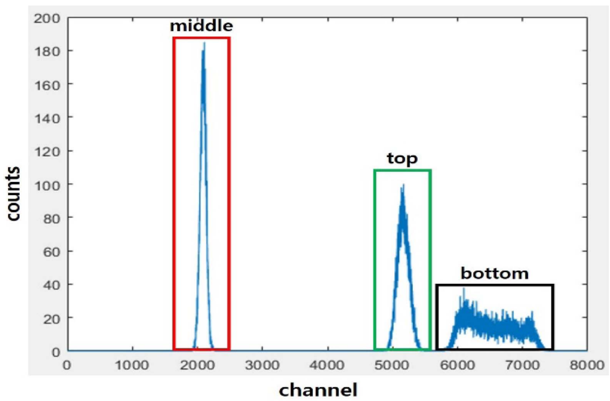

Fig. 3. (Color online) Energy spectra at the simulation. Photoelectric peaks were recorded at different locations in the energy spectrum because the amount of light acquired from SiPM was different for each location of the scintillator.

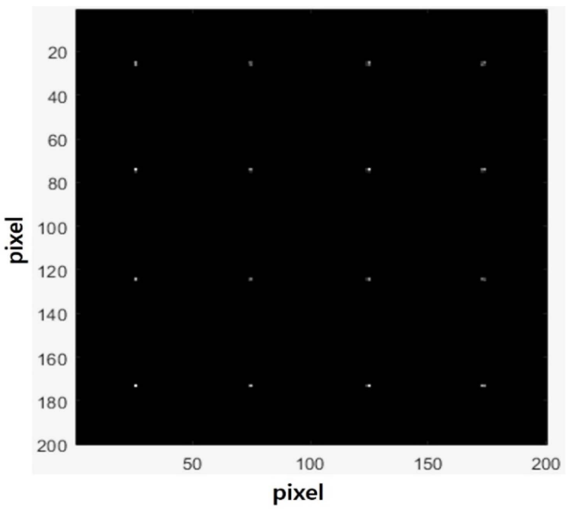

Fig. 4. (Color online) Flood image at the simulation. An image corresponding to the scintillator 4 × 4 array was acquired, and layers can be distinguished by analyzing the energy spectrum in the image of each scintillator point.

Figure 4 is an image reconstructed from the Anger calculation based on the light signal obtained from the sensor. It can be seen that the images are shown in 4 × 4; the position is the same for each layer. By analyzing the separation of the photopeak that arises due to interactions in different layers of the detector, a three channel image may be acquired.

The energy spectrum obtained from the basic experiment is shown in Fig. 5. It was obtained using a Na-22 source, and three photoelectric peaks can be identified as shown in the simulations. Top, middle, and bottom represent the photoelectric peak of the upper, middle, and bottom layers, respectively. All three layers show photoelectric peaks corresponding to 511 keV at different positions, and energy spectrum analysis shows that three layers of scintillator pixels can be distinguished.

Different reflectors applied to different layers in a multi-layer scintillator setup resulted in the appearance of 511 keV photoelectric peaks in the energy spectrum at different locations in both the simulations and the basic experiments. The simulation showed that the position of the photoelectric peak was farther than the experimental result; however, it is expected using the same configuration in both the simulation and physical experiments will result in the same photoelectric peak. The physical experiment is limited in this regard because the reflector must be manually wrapped around the scintillator. Additionally, it is observed that the photoelectric peak portion of the lower layer scintillation pixel is distributed more widely than that of the other layers in the simulation spectrum. This is the result of the light emitted in the vicinity of the sensor with a scintillation pixel directly

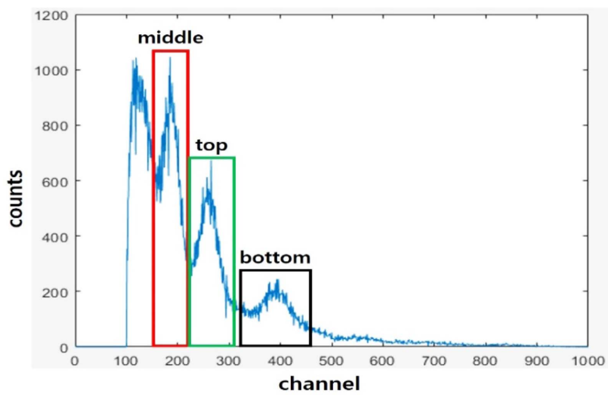

Fig. 5. (Color online) Energy spectra at the experiment for Na-22 source. Three photoelectric peaks were obtained in the experiment constructed using three scintillators, which can be analyzed and distinguished into three layers.

connected to the lower layer light sensor that is distributed widely with relatively more light transmitted to the light sensor than at other locations, forming a higher channel. This feature is unique to the scintillation pixels treated with a diffuse reflector and a position directly connected to the sensor.

4. Conclusion

In this study, using DETECT2000 simulations and preliminary physical experiments, we designed a detector module that tracks the depth of interaction through the use of three scintillating layers. By applying different types of reflectors to each layer, the signals arising from each layer are distinguishable such that the positions of the photoelectric peaks appear in different positions in the energy spectrum. The determination of the response depth was performed by analyzing the energy spectrum. Since the position of the photoelectric peaks on the energy spectrum appear at different locations, separate measurements can be used to track the layers in which gamma-rays and scintillation pixels responded.

It is anticipated that by applying the detector design obtained from this study to future small animal PET operating in a magnetic field, the depth at which gamma-rays and scintillators interact will be measurable, improving the spatial resolution outside the FOV.

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References

[1] H. Peng and C. S. Levin, Curr. Pharm. Bio. **11**, 6 (2010).
[2] L. R. MacDonald and M. Dahlbom, IEEE Trans. Nucl. Sci. **45**, 4 (1998).
[3] R. S. Miyaoka, T. K. Lewellen, H. Yu, and D. L. McDaniel, IEEE Trans. Nucl. Sci. **45**, 3 (1998).
[4] M. Streun, G. Brandenburg, H. Larue, H. Saleh, E. Zimmermann, K. Ziemons, and H. Halling, IEEE Trans. Nucl. Sci. **50**, 3 (2003).
[5] Y. Shao, R. W. Silverman, R. Farrell, L. Cirignano, R. Grazioso, K. S. Shah, G. Visser, M. Clajus, T. O. Tumer, and S. R. Cherry, IEEE Trans. Nucl. Sci. **47**, 3 (2000).
[6] Y. Yang, P. A. Dokhale, R. W. Silverman, K. S. Shah, M. A. McClish, R. Farrell, G. Entine, and S. R. Cherry, Phys. Med. Bio. **51**, 9 (2006).
[7] A. Vandenbroucke, A. M. K. foudray, P. D. Olcott, and C. S. Levin, Phys. Med. Bio. **55**, 19 (2010).
[8] S-J. Lee and C-H. Baek, Nucl. Inst. Meth. A **887** (2018).
[9] M. Ito, S. J. Hong, and J. S. Lee, Bio. Eng. Lett. **1** (2011).
[10] S-J. Lee and C-H. Baek, New. Phy: Sae. Mulli. **69**, 10 (2019).
[11] F. Cayouette, D. Laurendeau, and C. Moisan, Proceeding SPIE, **4833** (2003).
[12] http://www.furukawa-denshi.co.jp/cgi-bin/pdfdata/20140428162950.pdf
[13] http://www.sensl.com/downloads/ds/PB-MatrixB.pdf