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Digital Position and Depth of Interaction Measurement of the PET Detector Through the Signal Ratio

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A new detector was designed to improve the spatial resolution of positron emission tomography (PET) and acquire digital coordinates of the detector's scintillation pixels. In order to solve the spatial resolution deterioration phenomenon due to parallax error occurring outside the field of view (FOV), a method of measuring the depth of interaction was developed, and this was accomplished with the acquisition of digital coordinates. A detector using a 4 × 4 × 2 GAGG scintillator was designed using the DETECT2000 simulation tool to acquire digital coordinates of the scintillation pixels and measure the depth of interaction of the two layers. A gamma-ray reaction was generated in all the scintillation pixels, and the signals were obtained from SiPM pixels in a 4 × 4 array. The 16-channels of optical sensor signals were reduced to signals of 4 channels, and these were calculated as a ratio of each signal. The ratio of the signal was obtained from all the flash pixels, and the position was obtained as digital coordinates by comparing it with the ratio of the signal by the gamma ray response generated at the new position. In order to evaluate the accuracy of acquiring the digital coordinates and the accuracy of the layer where the scintillation pixel in which the scintillator and the gamma ray reacted, a signal was obtained by generating a gamma ray response for the entire length of each scintillation pixel. Gamma-ray reactions were generated at intervals of 0.2 mm from 0.1 mm to 19.9 mm. The obtained signals through these reactions were compared with the signals of each scintillation pixel obtained in advance. Then, the accuracy of measured positions on the X, Y, and Z axes were evaluated. The accuracy of both the X and Y axis showed perfect results, and the accuracy of the Z axis was 91.46 %.

Keywords : PET, depth of interaction, digital position acquisition, DETECT2000

1. Introduction

Positron Emission Tomography (PET) makes images by detecting extinction radiation of the lesion, which generated from radioactive isotopes that emit positrons injected into the human body [1]. A smaller PET compared to a clinical PET has been developed for imaging specific organs or animal models [2, 3]. This kind of PET detectors have a long length to detect high-energy gamma rays, and use a small scintillator to obtain excellent images.[4] In addition, this PET has a smaller gantry for high sensitivity and superior images compared to the clinical PET. Due to the small gantry, a parallax error occurs, which is a phenomenon spatial resolution is deteriorated outside the field of view (FOV) in certain organs and full-time PETs [5]. The error occurs because all detectors in PET are arranged looking at the center of the FOV. So gamma rays generated outside the FOV enter the detector diagonally as shown in Fig. 1. Even if the gamma rays incident on the detector obliquely are gamma rays incident in the same direction, the position measured by the scintillator of the detector varies due to the transmittance of the gamma rays. In other words, the position measured in the depth direction changes. Due to this, the line of response (LOR) for the position of the flash pixel measured by the co-factor appears across several flash pixels, so the spatial resolution is deteriorated. A lot of research has been conducted to solve this phenomenon of spatial resolution degradation [6-10].

In this study, a detector with a two-layer scintillator structure that measures the depth of reaction was designed to solve the deterioration of the spatial resolution occurr-

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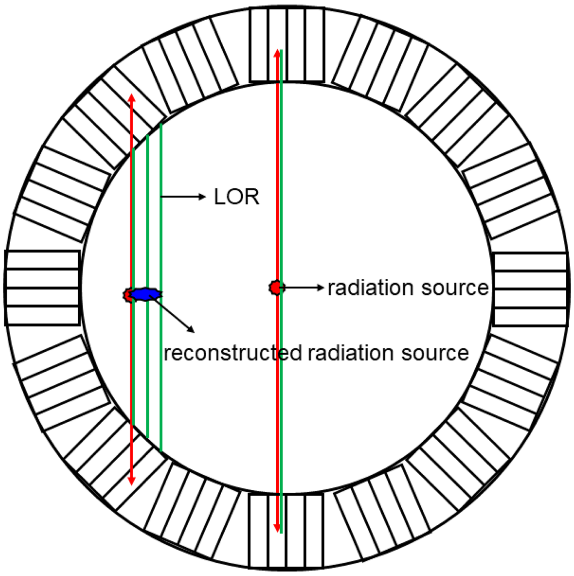

Fig. 1. (Color online) Schematic of PET detector module for line of response.

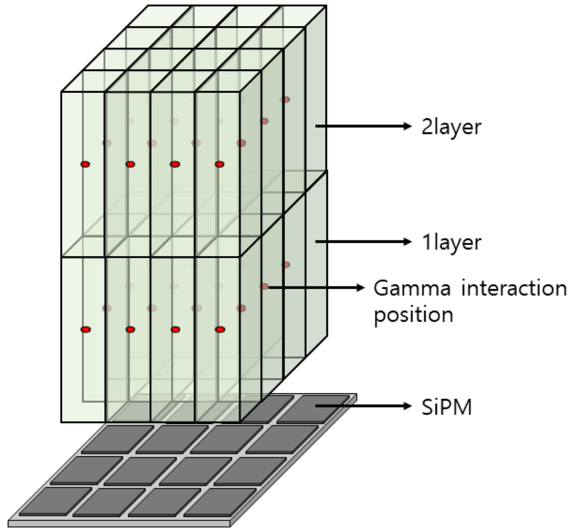

Fig. 2. (Color online) Schematic of PET detector module for generation LUT.

ing outside the FOV. In addition, the detector can directly obtain the position coordinates of the scintillation pixel as a digital signal through the ratio of the signal obtained from the optical sensor. By directly acquiring the position coordinates of the scintillation pixel as a digital signal, there is no need to perform a separate operation for each region for each scintillation pixel. DETECT2000 [11], which can simulate the light generated by the interaction between gamma rays and scintillators, was used to measure the new depth of reaction and evaluate the characteristics of the detector which acquires digital coordinate signals.

2. Material and Methods

DETECT2000 can simulate a detector which detects gamma rays using a scintillator. The scintillator interacts with gamma rays to generate light. At this time, DETECT2000 can simulate the movement, absorption, scattering and reflection of light generated within the scintillator as well as acquisition of signals through an optical sensor. In addition, multiple scintillator materials can be simulated, and materials are determined through refractive index.

As shown in Fig. 2, a 4 × 4 array of two-layer detectors was designed to measure the depth of reaction. Gadolinium Aluminum Gallium Garnet (GAGG) with size of 3 mm × 3 mm × 10 mm was used as the scintillation pixel, and the spacing between the pixels was 3.1 mm. The GAGG scintillator has a density of 6.63 g/cm^3 and detects high-energy gamma rays well with a high density. In addition, by generating light of 50,000 photons/MeV, excellent energy resolution and images can be obtained. In order to transmit the light generated from the scintillator to the optical sensor, the scintilation pixel was treated with a reflector except for the surface that was in contact with the optical sensor. By using a reflector, the light generated in the scintillator can be reflected and finally transferred to the optical sensor. A diffuse reflector was used as the reflector, and the reflectance was set to 98 %. The optical sensor designed to detect light is a 4 × 4 array of silicon photomultipliers (SiPM). SiPM is a compact size compared to the photomultiplier tube used in the existing gamma ray detector and is not affected by the magnetic field, so it is widely used in PET detectors. The designed SiPM has a size of 3 mm × 3 mm and a pitch of 3.2 mm. An optical lubricant was used between GAGG and SiPM to minimize total reflection of light due to the difference in refractive index and loss due to refraction.

As shown in Fig. 2, the light generation rate (corresponding to the energy of the extinction gamma ray, 511 keV) and the number of lights (corresponding to the light detection rate of SiPM) of the GAGG scintillator to simulate the light generated by the gamma ray abnormal interaction with the scintillator as shown in Fig. 2. It was generated at the center of the scintillator for each layer. The generated light passes through processes such as movement, reflection, absorption, and scattering within the GAGG scintillator, and is then incident and measured by an optical sensor. Signals were acquired from 16 SiPM pixels using a 4 × 4 array of SiPM, and these were reduced to 4 signals to detect the image and the layer of the depth of reaction.

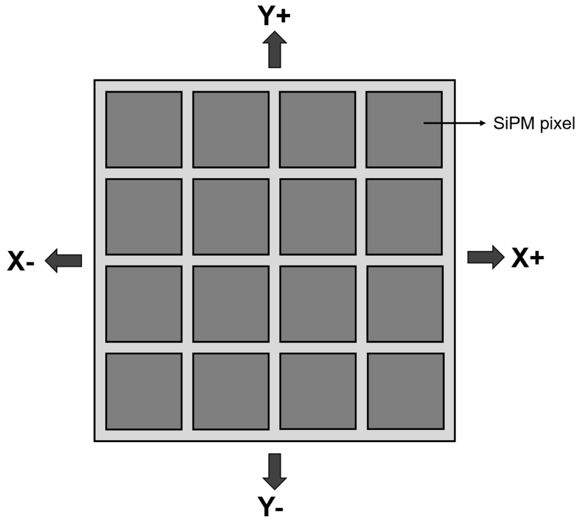

Fig. 3. The process of obtaining a signal by giving a weight according to the distance of the SiPM pixel.

The 16 SiPM pixel signals were reduced to 4 signals of X+, X-, Y+, and Y- as shown in Fig. 3. The average value was measured by 1,000 gamma ray reactions for one scintillation pixel.

The layer of the depth of reaction where the scintillator and the gamma ray interacted was measured through the acquired ratio of the four signals. Using the ratio of the signals to the direction and the ratio of the signal to the Y-axis direction, the positions of the X-axis and Y-axis scintillation pixels were obtained as digital coordinates. Then, through this signal ratio, the Z-axis coordinate, which is the coordinate for the height, was obtained. To evaluate the measurement about the layer of the depth of reaction, light was generated at intervals of 0.2 mm from 0.1 mm to 19.9 mm in height for each scintillation pixel.

3. Results

Through the DETECT2000 simulation, the ratio of the light signals generated from the 4 × 4 array of GAGG scintillators was obtained. After obtaining the ratio of the signals from 16 scintillation pixels, this ratio was compared with the ratio of the signals of light generated at the new location. So, the position coordinates of the scintillation pixels where the light was generated were digitally acquired. In order to obtain the layer of depth of reaction and the X, Y coordinates of scintillation pixel, the light generation point at the center of each flash pixel was changed according to the height.

Table 1 shows the results of obtaining the ratio of signals for each channel after reducing 16 signals to 4 signals. The ratio of signals for each channel was calculated as follows; X+: X+/X-, X-: X-/X-, Y+: Y+/Y-. Y-: Y-/Y-. It can be seen that different values of signals are obtained according to each flash pixel, which can be confirmed to have different values along the response depth, that is, the Z-axis. Since signal values are different along the X, Y, and Z axes, digital coordinates can be obtained by comparing the two ratios; the ratio of signals appearing by the light generated at a new point, and the ratio of the signals of each scintillation pixel that has already been acquired.

Table 1. Ratio by channel for each scintillation pixel obtained through DETECT2000 simulation.

position		ch.	X+	X-	Y+	Y-	position		ch.	X+	X-	Y+	Y-
z1	y1	x1	0.1410	1	0.1410	1	z2	y1	x1	0.1528	1	0.1529	1
		x2	0.5912	1	0.1415	1			x2	0.5945	1	0.1540	1
		x3	1.6454	1	0.1415	1			x3	1.6331	1	0.1540	1
		x4	6.4076	1	0.1411	1			x4	5.9170	1	0.1532	1
	y2	x1	0.1414	1	0.5911	1		y2	x1	0.1539	1	0.5944	1
		x2	0.5911	1	0.5911	1			x2	0.5944	1	0.5945	1
		x3	1.6446	1	0.5910	1			x3	1.6310	1	0.5945	1
		x4	6.3825	1	0.5908	1			x4	5.8773	1	0.5947	1
	y3	x1	0.1415	1	1.6458	1		y3	x1	0.1541	1	1.6327	1
		x2	0.5910	1	1.6449	1			x2	0.5944	1	1.6317	1
		x3	1.6443	1	1.6444	1			x3	1.6308	1	1.6307	1
		x4	6.3782	1	1.6444	1			x4	5.8766	1	1.6320	1
	y4	x1	0.1411	1	6.4061	1		y4	x1	0.1531	1	5.9204	1
		x2	0.5909	1	6.3831	1			x2	0.5945	1	5.8817	1
		x3	1.6446	1	6.3826	1			x3	1.6314	1	5.8791	1
		x4	6.3944	1	6.3987	1			x4	5.9087	1	5.9087	1

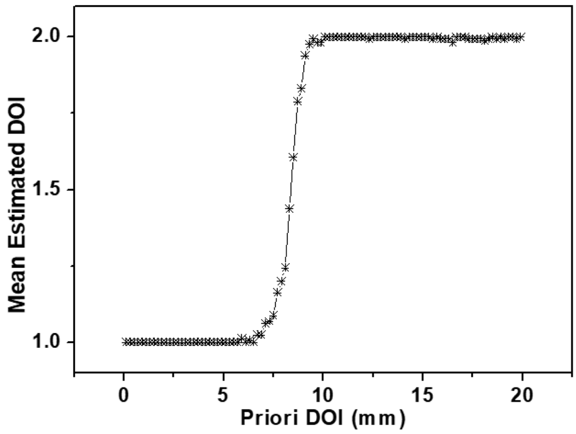

Fig. 4. DOI positioning results in each layer. The horizontal axis is the true position from simulation input, and the vertical axis is the mean estimated position for different true positions.

When evaluating the accuracy of measured position of the X, Y, and Z coordinates, the X and Y axes were perfectly measured, while the Z axis showed an accuracy of 91.5 % for all scintillation pixels. The error of the Z axis appeared at the point where the layers were changed. Figure 4 is a graph showing the average of the accuracy of layer discrimination according to the height of each scintillation pixel that generated light. The layer discrimination is represented by the average of the 4 × 4 array of scintillation pixels. The X-axis of the graph represents the height of the scintillation pixel, and the Y-axis represents the scintillator layer. From about 8 mm, the layer was not clearly distinguished, and the light generated from the first layer was measured in the second layer. The measurement accuracy for each layer was 83.2 ± 2.1 % on average in the first layer and 99.76 ± 0.35 % in the second layer, which means that the location was more accurately measured at the second layer than the first layer.

Table 2. The accuracy of layer discrimination by coordinates of scintillation pixels.

z1 (1st layer)				
	x1	x2	x3	x4
y1	84.8 %	84.0 %	86.0 %	81.4 %
y2	84.2 %	84.2 %	85.2 %	80.0 %
y3	85.0 %	82.8 %	85.6 %	78.8 %
y4	82.8 %	82.0 %	80.4 %	83.2 %
z2 (2nd layer)				
	x1	x2	x3	x4
y1	100.0 %	99.8 %	100.0 %	99.0 %
y2	100.0 %	100.0 %	100.0 %	99.6 %
y3	100.0 %	100.0 %	100.0 %	99.6 %
y4	99.0 %	99.4 %	99.8 %	100.0 %

Table 2 shows the accuracy of layer discrimination by coordinates of each scintillation pixel. The lowest layer discrimination accuracy was shown at 78.8 % at the coordinates (4, 3) from the first layer, while the highest accuracy was shown at 86.0 % at (3, 1) from same layer. The layer discrimination accuracy of the second layer was 100 % in almost all pixels.

4. Discussion and Conclusion

Through the DETECT2000 simulation, the ratio of the signal of each scintillator layer of the detector was obtained by generating light at the center of the scintillation pixel. Using the acquired data, based on the light generated at the location where the scintillation pixel and the gamma ray interact, the ratio of the signals acquired at the new location and the data that has already been acquired are compared to X, Y where the gamma ray and the flash pixel interact Z coordinates, which are coordinates and depth directions, were obtained. The accuracy of the position measurement of the X and Y axis of the scintillation pixel was perfect, but that of the Z axis was 91.46 %. Compared to the second layer, the accuracy of layer discrimination on the first layer was somewhat lower. This error seems to have occurred while obtaining data in advance, when the location where light is generated is set as the center of the scintillation pixel for each layer. Furthermore, since the amount of light emitted from the first layer is different depending on the depth of occurrence, the signal of the first-layer scintillation pixels generated near the second layer seems to be measured as the second layer. All the light generated from the second layer passed through the first layer and finally entered the SiPM and was measured, on the other hand. Another possible cause of the error is that the light spreads into the space of the optical grease used to connect the scintillation pixels of the first and second layers, so the area of the first layer adjacent to the second layer seems to be measured as the second layer.

In this study, a detector was designed to measure the depth of interaction between the scintillator and gamma rays through the ratio of the signals measured by the optical sensor. The digital position of the scintillation pixel was obtained by obtaining the signal ratio of each pixel in advance and comparing it with the ratio of the light signal generated by interacting at a new location. A signal was obtained by generating a gamma ray reaction at 0.2 mm intervals in all directions in each scintillation pixel. The accuracy of layer discrimination was measured by obtaining the coordinates of scintillation pixel as a digital signal. The accuracy of the measured depth of interaction was 83.2 % in average at the first layer and 99.76 % in average at the second layer. When this detector is applied to a PET system, deterioration phenomenon of the spatial resolution occurring outside the FOV can be solved by acquiring the location where the scintillator and gamma rays interact in three dimensions.

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