Published in final edited form as:

J Nucl Sci Technol. 2008 ; 45(7): 634–638. doi:10.3327/jnst.45.634.

Detector Light Response Modeling for a Thick Continuous Slab Detector

Robert S. MIYAOKA¹, Sung-Kwan JOO², and Kisung LEE^{3,*}

¹Department of Radiology, University of Washington, Seattle, WA, 98195, U.S.A.

²School of Electrical Engineering, Korea University, Anam-dong, Seongbuk-gu, Seoul, 136-701, Korea

³Department of Radiologic Science, Korea University, JeongReung3-dong, Seongbuk-gu, Seoul, 136-703, Korea

Abstract

We investigate a method to improve the position decoding for thick crystal versions (i.e., ≥ 8 mm) of the continuous miniature crystal element (cMiCE) PET detector by more accurately modeling the detector light response function (LRF). The LRF for continuous detectors varies with the depth of interaction (DOI) of the detected photon. This variation in LRF can result in a positioning error for two-dimensional positioning algorithms. We explore a method to improve positioning performance by deriving two lookup tables, corresponding to the front and back regions of the crystal. The DETECT2000 simulation package was used to investigate the light response characteristics for a 48.8 mm by 48.8 mm by 10 (8) mm slab of LSO coupled to a 64-channel, flat-panel PMT. The data are then combined to produce the two-dimensional light collection histograms. Light collection histograms that have markedly non-Gaussian distributions are characterized as a combination of two Gaussian functions, where each Gaussian function corresponds to a DOI region of the crystal. The results indicate that modest gains in positioning accuracy are achieved near the central region of the crystal. However, significant improvements in spatial resolution and positioning bias are achieved for the corner section of the detector.

Keywords

positioning algorithm; light response modeling; depth of interaction; statistics-based positioning algorithm; continuous slab detector; continuous crystal; positron emission tomography

I. Introduction

Position decoding for the continuous crystal is one of the key issues to determine the performance of scintillation-based photon detectors. In our previous work,¹⁾ we explored a continuous miniature crystal element (cMiCE) detector consisting of a 25 mm by 25 mm by 4 mm slab of LSO coupled to a position-sensitive PMT. In that study, we introduced a statistics-based positioning (SBP) algorithm that improved the positioning characteristics near the edge of the crystal. We now investigate a design using a 48.8 mm by 48.8 mm by 10 (8) mm slab (s) of LSO coupled to a Hamamatsu H8500, 64-channel, flat-panel PMT.

©Atomic Energy Society of Japan

*Corresponding author, E-mail: kisung@korea.ac.kr

The goal of this work is to investigate whether the intrinsic spatial resolution of the detector can be improved by modeling changes in detector light response characteristics (i.e., mean and standard deviation) with depth. An optimum spatial resolution with a minimum positioning bias can be achieved through the use of statistical positioning methods if the detector light response characteristics are fully known. In principle, one cannot directly measure the three-dimensional light response function (LRF) and systems are characterized using two-dimensional light distribution characteristics.²⁻⁴⁾ Milster et al.⁴⁾ used a 5-bit compressed energy signal as part of their light response characterization. Gagnon et al.⁵⁾ and Tomitani et al.⁶⁾ have proposed methods to characterize DOI for large NaI(Tl) detectors using maximum likelihood positioning methods. In their approaches, the three-dimensional light response function is determined by mathematical modeling of their system. However, they did not address how to model the light response function near the edge of the detector, where mathematical modeling is very difficult.

In this work, the light response characteristics versus depth are derived from the PMT data. While it may be feasible to extract some depth of interaction information from the collected data, the main focus of this work is to improve the positioning accuracy and precision of the detector.

II. Materials and Methods

1. Detector Simulation

The DETECT2000 simulation package⁷⁻⁹⁾ was used to model the detector module. The target object for the simulation is illustrated in Figs. 1(a) and 1(b). The crystal was modeled as a 48.8 by 48.8 by 10 (8) mm³ slab of LSO (index of refraction = 1.85). The two 48.8 by 48.8 mm² surfaces were polished. One side was directly coupled (i.e., no light guide) to the PMT with glue of 1.44 index of refraction and 0.5 mm thickness. The other side was backed by a diffuse reflector with a reflection coefficient (RC) of 0.98. The short sides were painted with low-reflectivity paint (RC = 0:10). An 8 by 8 array of anode pads (i.e., DETECT surface), 5.8 mm by 5.8 mm with 6.08 mm center-to-center spacing, was placed on the back surface of a 2-mm-thick glass PMT window. 2500 light photons were produced per detected event. This accounts for the light produced by LSO and the quantum efficiency of the PMT photocathode. The crystal was divided into 0.1-mm-thick DOI slices. Because of the attenuation within the crystal, the probability of interaction in the crystal changes with DOI. The linear attenuation coefficient of LSO was utilized to determine the number of interactions in each DOI slice. Within each 0.1 mm zone, the probability of interaction was equally distributed.

The grid shown in Fig. 1(b) was used to characterize a region of the detector. Symmetry was used to generate the full detector lookup table (i.e., 33 by 33). The grid spacing was 1.52 mm (i.e., 1/4 the PMT anode pixel pitch distance). Each dot represents a point photon flux of 511 keV photons perpendicular to the crystal surface. A flux of 100,000 photons was used to characterize the detector and a flux of 20,000 photons was used to evaluate the positioning characteristics.

2. Statistics-Based Positioning (SBP) Method

Suppose that the parent distribution of observing PMT outputs $M = M_1, M_2, \dots, M_n$ for the scintillation position x is independent Gaussian with the mean μ and standard deviation σ .

The probability of making any single observation m_i from the parent distribution M_i given x is

$$P_i[m_i|x] = \frac{1}{\sigma_i(x) \sqrt{2\pi}} \exp\left(-\frac{(m_i - \mu_i(x))^2}{2\sigma_i^2(x)}\right). \quad (1)$$

Considering the entire set of n independent observations from each channel, the probability for observing a particular set is given by the product of the individual probability functions,

$$P[m_1, m_2, \dots, m_n|x] = \prod_{i=1}^n P_i[m_i|x]. \quad (2)$$

The log of Eq. (2) reduces to

$$\ln P = -\left(\sum_{i=1}^n \frac{(m_i - \mu_i(x))^2}{2\sigma_i^2(x)} + \sum_{i=1}^n \ln \sigma_i(x)\right). \quad (3)$$

The maximum likelihood solution is achieved by minimizing the quantity inside the bracket in Eq. (3). Since it was experimentally shown that the second term did not affect the estimation accuracy,¹⁾ the estimation of the event position was determined by

$$\hat{x} = \underset{\forall x}{\operatorname{argmin}} \left(\sum_{i=1}^n \frac{(m_i - \mu_i(x))^2}{\sigma_i^2(x)} \right), \quad (4)$$

which is equivalent to minimizing the Chi square error (CSE). Usually, the observations m_i are assumed to follow Poisson statistics. However, the energy resolution for LSO has been shown to not correlate with the resolution predicted by assuming Poisson statistics based on the amount of light photons collected. Furthermore, because of uncertainties, such as the depth of interaction and surface effects, the distribution is more likely to be Gaussian, based on the central limit theorem.

3. Lookup Table (LUT) Generation

A sample light collection histogram, i.e., likelihood function, for a single PMT channel is illustrated in Fig. 2(a), where the amount of light photons collected by the PMT channel varies significantly with DOI. The incoming photon flux was perpendicular to the crystal surface and located at the exact center of the channel grid. The energy level of each incoming photon was 511 keV. The dotted line in Fig. 2(a) represents the histogram of the light collected by a PMT channel in the center region of the crystal shown in Fig. 1. The nonexponential shape of the high-end tail (the righthand side of the dotted line) is a result of the depth-dependent light collection.

Lookup tables representing the mean and standard deviation of the detector response function (DRF) for each PMT channel versus grid position were generated from the individual light collection histograms. The initial tables were 33 by 33 by 64, where 33 by 33 is the number of grid positions and 64 is the number of PMT channels. Simulations were not performed for each grid position. Instead, the symmetry of the detector was used to generate the full LUTs. Linear interpolation was used to expand the LUTs to 129 by 129 (or 0.38 mm sampling) by 64. The LUTs were used in the SBP algorithm to estimate the location of the detected event.

There are three different sets of LUTs in this study. The first set of LUTs (LUT1) was created by numerically calculating the mean and standard deviation of the PMT signals using a single depth for all the data at each grid position. For the second set of LUTs (LUT2), the data were divided into two DOI regions from the known simulation results (e.g., 0-4 and 4-10 mm for the 10-mm-thick crystal), then means and variances of two separate depth regions were calculated. LUT2 was used as the ground truth in comparison with the results of the proposed method. In order to acquire the third set of LUTs (LUT3) for the proposed method, the data were also separated into two DOI regions, as illustrated in Fig. 2(b). In the figure, the vertical line effectively divides the histogram into events that occurred in the front region of the crystal and events that interacted in the back region of the crystal. For each of the two DOI regions, a Gaussian was fit to the data. Using the Gaussian fits, the mean and standard deviation were calculated for each DOI region. Using the positioning algorithm described in Sec. II-2, the maximum likelihood solution was determined using a three-step search routine. This resulted in the determination of both DOI tables and one global maximum so that the event could be binned to an X, Y position.

When we compose LUT3, in principle, one does not know the DOI of the photons for separating the data into two DOI zones. Therefore, a technique was developed to estimate the likelihood functions for the two DOI regions (i.e., 0-4 and 4-10 mm for the 10-mm-thick crystal) from the composite histogram. The technique utilizes knowledge of the expected change in the amount of light collected versus DOI and the linear attenuation coefficient of the scintillator. For the PMT channel located directly below the point where the gamma interacts in the crystal, the amount of light collected varies significantly with depth. This leads to an asymmetric light collection histogram for the channel characterized by a high-end tail.

For asymmetric light collection histograms, the data were divided into two distributions according to the amount of light collected. This is illustrated in Fig. 2(b) by the vertical line. The vertical line represents the median value of the distribution. Events where the amount of light collected is lower than the median amount correspond to events that interacted in the front section of the crystal furthest from the PMT. Events where the amount of light collected is higher than the median amount correspond to events that interacted in the back section of the crystal. The data from the two distributions were then fit with Gaussian likelihood functions.

In Fig. 2(b), the first set of fits, represented by the solid lines, was applied to the data separated by our proposed technique. The second set of fits, represented by the lines with x's, was applied to data separated according to the known depth of interaction. As is illustrated in the figure, the two sets of Gaussian fits are nearly identical.

The asymmetry of the light collection histogram was determined by the ratio of the number of histogram bins above and below the most likely bin (*i.e.*, the mode of the histogram). Since our technique requires that the light response varies with depth, if the light response histogram is symmetric, it means that the light response does not vary significantly with depth. In our proposed method, we selected an asymmetry ratio of 1.5. When the ratio was much less than 1.5, it was considered that the separation of the light histogram into two depths would be artificial and not accurate. The ratio for the data plotted in Fig. 2. is ~ 6 . An added constraint was the ratio of the area under the curves, which is the Gaussian fit of the data, being equal to the ratio of the expected number of counts from the two DOI regions of the crystal. The relationship between the amount of light collected by a given PMT channel and the depth of interaction is strongest for the channel directly under the interaction point. In the case where the event occurs at the midpoint between four of the anode channels, all four channels are slightly asymmetric. Thus, although we collect 64 channels worth of information for each event, the light response histogram for a subset of channels is depth dependent. Since we need to divide the data into different DOI regions to build the LUTs for each region, we use the light

response histogram of the channel that varies the most with depth to divide all the data (i.e., the data from the rest of the 64 PMT channels) between DOI regions.

III. Results

The intrinsic spatial resolution was determined for a 9 by 9 array of points in the corner and center sections of the crystal, as shown in Fig. 1. Light gray dots within the corner and center sections in Fig. 1 represent the points at which DOI simulations were performed.

The intrinsic spatial resolution and estimation bias results are summarized in Tables 1 and 2. The average FWHM of the intrinsic spatial resolution and offsets from the center of the x and y directions for the center and corner sections are listed. LUT1, LUT2, and LUT3 in Tables 1 and 2 represent the three LUTs acquired in Sec. II.3. Results for the 10-mm- and 8-mm-thick crystal detectors are illustrated in Figs. 3-5 and Figs. 6-8, respectively. The results indicate that there is a definite improvement in the case of using two LUTs associated with two DOI regions of the crystal compared with the case of using a single LUT. The average intrinsic spatial resolutions for the corner section of the 10-mm-thick or 8-mm-thick crystal were 1.3 (1.0), 1.1 (0.92), and 1.1 (0.96) mm full width at half maximum (FWHM) in the cases of using a single LUT, two LUTs from the known DOI data, and two LUTs with DOI derived from the shape of the light collection histogram, respectively. The average intrinsic spatial resolutions for the central section of the 10-mm-thick or 8-mm-thick crystal were 0.97 (0.84), 0.94 (0.79), and 0.93 (0.79) mm in the same cases, respectively. The bias in the position estimate was negligible for the central section of the crystal. For the points in the corner, the average bias ranged from 0.10 to 0.31 mm.

IV. Conclusion

The light response function in continuous crystal detector designs is depth dependent and can lead to the broadening of the intrinsic spatial resolution and positioning bias. An optimum spatial resolution with a minimum positioning bias can be achieved through the use of statistical positioning methods if the detector light response characteristics are fully known. In principle, one cannot directly measure the three-dimensional LRF and systems are characterized using two-dimensional LRFs. Simulation studies indicate that the light response functions for the front section of our 10-mm-thick crystal are fairly uniform (see Fig. 9); however, the response functions can change significantly with depth for the back section of the crystal nearest to the PMT. Since approximately half of all first interactions occur in the first 4 mm of a 10-mm-thick LSO crystal, we decided to characterize the crystal using two depths. While in principle the crystal may be segmented into more DOI regions, for proof of principle, we chose to limit the number of regions to two. As future work, we will investigate whether segmenting the crystal into more DOI regions will further improve performance.

Acknowledgements

This work was supported in part by Public Health Service grants R21EB001563, R01EB002117, and R24CA88194.

References

- 1). Joung J, Miyaoka RS, Lewellen TK. cMiCE: A high resolution animal PET using continuous LSO with a statistics based positioning scheme. Nucl. Instrum. Methods Phys. Res., Sect. A 2002;489 (13):474–488.
- 2). Gray RM, Macovski A. Maximum a posteriori estimation of position in scintillation cameras. IEEE Trans. Nucl. Sci 1976;23:849–852.
- 3). Clinthorne NH, Rogers WL, Shao L, Koral KF. A hybrid maximum likelihood position computer for scintillation cameras. IEEE Trans. Nucl. Sci 1987;34(1):97–101.

- 4). Milster TD, Selberg LA, Barrett HH, Landesman AL, Seacat RH III. Digital position estimation for the modular scintillation camera. *IEEE Trans. Nucl. Sci* 1985;32:748–752.
- 5). Gagnon D, Pouliot N, Laperriere L, Therrien M, Olivier P. Maximum likelihood positioning in the scintillation camera using depth of interaction. *IEEE Trans. Medical Imaging* 1993;12(1):101–107.
- 6). Tomitani, T.; Futami, Y.; Izeki, Y., et al. Depth encoding of point-of-interaction in thick scintillation cameras; *Proc. IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC)*; Seattle, U.S.A.. Oct. 24-30, 1999; 1999.
- 7). Knoll GF, Knoll TF, Henderson TM. Light collection scintillation detector composited for neutron detection. *IEEE Trans. Nucl. Sci* 1988;35(1):872–875.
- 8). Tsang G, Mosian C, Rogers JG. A simulation to model position encoding multi-crystal PET detectors. *IEEE Trans. Nucl. Sci* 1995;42(6):2236–2243.
- 9). Cayouette F, Laurendeau D, Moisan C. DETECT2000: an improved Monte-Carlo simulator for the computer aided design of photon sensing devices. *Proc. SPIE*, 4833, Applications of Photonic Technology 2003;5

Fig. 1.
 (a) Target object for simulation and (b) grid locations (1.52 mm spacing) used to characterize a portion of the detector. PMT is 52 mm by 52 mm.

Fig. 2. Sample light histogram for a PMT channel. (a) Simulation data and (b) comparison of Gaussian fits to data separated by simple thresholding (i.e., vertical line) of the composite light histogram and by known DOI regions from simulation. As illustrated in the graph, the Gaussian fits using both techniques are almost identical.

Fig. 3. Results for 9×9 point flux arrays for the corner (a) and center (b) section of the 10-mm-thick cMiCE detector using a single LUT. There is a 1.52 mm spacing between the spots.

Fig. 4. Results for 9×9 point flux arrays for the corner (a) and center (b) section of the 10-mm-thick cMiCE detector using dual LUTs, where the known DOI locations were used to generate the tables. There is a 1.52 mm spacing between the spots.

Fig. 5. Results for 9×9 point flux arrays for the corner (a) and center (b) section of the 10-mm-thick cMiCE detector using dual LUTs, where the depth-dependent detector light response characteristics were derived from the data. There is a 1.52 mm spacing between the spots.

Fig. 6. Results for 9×9 point flux arrays for the corner (a) and center (b) section of the 8-mm-thick cMiCE detector using a single LUT. There is a 1.52 mm spacing between the spots.

Fig. 7. Results for 9×9 point flux arrays for the corner (a) and center (b) section of the 8-mm-thick cMiCE detector using dual LUTs, where the known DOI locations were used to generate the tables. There is a 1.52 mm spacing between the spots.

Fig. 8. Results for 9×9 point flux arrays for the corner (a) and center (b) section of the 8-mm-thick cMiCE detector using dual LUTs, where the depth-dependent detector light response characteristics were derived from the data. There is a 1.52 mm spacing between the spots.

Fig. 9.

The overlap of light collection histograms for the front half of the crystal limits the number of distribution functions that can be extracted from the data.

Table 1
Intrinsic spatial resolution and bias results: 10-mm-thick crystal

		X FWHM (mm)	Y FWHM (mm)	X bias (mm)	Y bias (mm)
Center section	LUT1	0.97	0.97	0.00	0.00
	LUT2	0.94	0.94	0.00	0.00
	LUT3	0.93	0.93	0.00	0.00
Corner section	LUT1	1.3	1.3	0.31	0.31
	LUT2	1.1	1.1	0.15	0.14
	LUT3	1.1	1.1	0.18	0.18

Table 2
Intrinsic spatial resolution and bias results: 8-mm-thick crystal

		X FWHM (mm)	Y FWHM (mm)	X bias (mm)	Y bias (mm)
Center section	LUT1	0.84	0.84	0.00	0.00
	LUT2	0.79	0.79	0.00	0.00
	LUT3	0.79	0.79	0.00	0.00
Corner section	LUT1	1.1	1.0	0.19	0.18
	LUT2	0.92	0.92	0.10	0.10
	LUT3	0.95	0.96	0.13	0.13