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Continuous Depth-of-Interaction Encoding Using Phosphor-Coated Scintillators

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Abstract

We investigate a novel detector using lutetium oxyorthosilicate (LSO) scintillator and YGG (yttrium aluminum gallium oxide:cerium, $Y_3(Al,Ga)_5O_{12}:Ce$) phosphor to construct a detector with continuous depth-of-interaction (DOI) information. The far end of the LSO scintillator is coated with a thin layer of YGG phosphor powder which absorbs some fraction of the LSO scintillation light and emits wavelength-shifted photons with a characteristic decay time of ~ 50 ns. The near end of the LSO scintillator is directly coupled to a photodetector. The photodetector detects a mixture of the LSO light and the light emitted by YGG. With appropriate placement of the coating, the ratio of the light converted from the YGG coating with respect to the unconverted LSO light can be made to depend on the interaction depth. DOI information can then be estimated by inspecting the overall light pulse decay time. Experiments were conducted to optimize the coating method. 19 ns decay time differences across the length of the detector were achieved experimentally when reading out a $1.5 \times 1.5 \times 20$ mm³ LSO crystal with unpolished surfaces and half-coated with YGG phosphor. The same coating scheme was applied to a 4 by 4 LSO array. Pulse shape discrimination (PSD) methods were studied to extract DOI information from the pulse shape changes. The DOI full-width-half-maximum (FWHM) resolution was found to be ~ 8 mm for this 2 cm thick array.

Keywords

positron emission tomography (PET); mouse imaging; continuous depth of interaction

1. Introduction

An ongoing goal in our laboratory is to design a compact and relatively simple PET scanner with competitive performance specifically for mouse imaging in the laboratory setting. Because of the small cross-sectional profile of a mouse, the ring diameter of such a scanner can be much smaller (6-8 cm) than current preclinical PET systems (12-24 cm). This also reduces the number of detectors and electronic channels leading to a compact and possibly lower cost system. A detector that can provide depth-of-interaction (DOI) information is however necessary, because very significant parallax errors will otherwise severely degrade spatial resolution in such a small diameter system.

Many approaches have been investigated for acquiring DOI information. One common design is the phoswich detector which is made of multiple layers of scintillators with different decay times (Seidel *et al.*, 1999). PET scanners utilizing this type of DOI detector has been

commercialized. For example, the GE eXplore VISTA dual-ring small-animal PET scanner (Wang *et al.*, 2006) is assembled from phoswich detectors made of $1.45 \times 1.45 \times 7 \text{ mm}^3$ LYSO and $1.45 \times 1.45 \times 8 \text{ mm}^3$ GSO layers. The ClearPET scanner has 80 two-layer phoswich detectors consisting of 8×8 LYSO and 8×8 LuAP arrays with crystal element sizes of $2 \times 2 \times 10 \text{ mm}^3$ (Sempere Roldan *et al.*, 2007). However, the DOI resolution of a phoswich detector is limited by the number of layers and the thickness of the scintillator in each layer, and thus it only provides discrete and relatively coarse DOI information. To date, commercial implementations have used only 2 layers, thus DOI information is confined to a binary assignment of events to one of the two layers.

Another method that has been developed is to place photodetectors on both ends of a scintillator array and acquire DOI information based on the ratio of the signal amplitudes detected on the opposing photodetectors (Moses and Derenzo, 1994; Yang *et al.*, 2008). This dual read-out design can provide very good ($\sim 2\text{-}3 \text{ mm}$) and continuous DOI information, but the number of photodetectors utilized doubles, as does the number of electronic channels.

Several other methods can be regarded as being derived from these two basic detector designs. For example, Tsuda *et al.* (Tsuda *et al.*, 2004) used four layers of the same scintillator but with different reflector designs to get position information from events in each layer. A similar method is to use two layers of the same crystals (LSO), with the upper LSO layer shifted about half the element pitch in both X and Y directions (Liu *et al.*, 2001). The crystals in both layers can be identified by calculating the centroid of the output light distribution. However, like the phoswich method, these two methods can only provide discrete DOI information and the resolution is limited by the thickness of each layer. Array fabrication also is rather complicated. Miyaoka and colleagues (Miyaoka *et al.*, 1998) proposed a single read-out DOI detector by applying different reflectors along the sides of the crystals. The concept is to control the light sharing between crystals and acquire depth-dependent information by observing the peak positions in the flood histogram. Detectors using orthogonally placed wavelength shifting (WLS) fibers for depth-encoding can be regarded as derivatives of a dual read-out detector (Worstell *et al.*, 1994; Du *et al.*, 2007; Du *et al.*, 2008). This method is being developed in a whole-body clinical PET/CT scanner, although the signals from WLS fibers at present are used to improve detector identification and energy resolution rather than to acquire DOI information (Worstell *et al.*, 2004).

A different approach to measure DOI is introduced in this paper (Figure 1). A thin layer of phosphor powder is coated on the far end of the scintillator while the near end is placed directly onto a photodetector. The phosphor is chosen such that it has a comparable, or preferably somewhat longer, decay time compared with the scintillator. It is also important that there be good overlap between the emission spectrum of the scintillator and the excitation spectrum of the phosphor. If these conditions are met, then the phosphor will convert part of the scintillation light into phosphor light. Thus the signal measured by a photodetector following a gamma ray interaction in the scintillator consists of two components, scintillation light photons that come directly from the scintillator, and scintillation photons that interact with the phosphor, are converted and reach the photodetector. These converted photons from the phosphor are shifted in wavelength, but also delayed due to the decay time of the phosphor. We hypothesize that by only coating the scintillator toward the far end of the crystal, the fraction of “phosphor-converted” light reaching the photodetector can be made depth-dependent. If a gamma photon interacts very close to the near end of the scintillator, most of the light reaching the photodetector is the scintillation light with a relatively short decay time (close to its characteristic decay time). However, if the gamma energy deposition occurs on the far end the scintillator, much of the light received by the photodetector is the “phosphor-converted” light with a longer decay time. If this is the case, by inspecting the pulse shape measured by the photodetector, DOI information can be extracted. Conventional phoswich detectors also utilize

scintillation materials with different decay times. However the detector we propose is different in that the phosphor coating is not used for detection, rather it is used to increase the decay time of the original scintillation light in a depth-dependent manner, and thus it does not require segmentation of the scintillator array into layers and can provide continuous DOI information with only a single-ended readout.

In this work, we first investigated different phosphor coating arrangements on a single crystal coupled to a photomultiplier tube (PMT). The original idea was to only coat the far end of the scintillator. However, to allow more photons to be absorbed and converted by the phosphor, it may be helpful to coat the sides of the scintillation crystals as well. The arrangement that produced the best DOI response was then applied in the fabrication of a 4 by 4 phosphor-coated array. This array was irradiated at different depths by electronic coincidence with a second detector. Flood histograms and energy spectra were acquired. To extract DOI information from the pulse shape changes, different pulse discrimination methods (PSD) were compared. The PSD method with best depth discriminating capability was used to process all the pulses and DOI resolution was calculated. By virtually segmenting the scintillator array into multiple bins, DOI accuracy was calculated by comparing what fraction of events at a known depth were assigned to each particular depth bin. Lastly, simulations were conducted to compare how the quantum efficiency (QE) spectra of different photodetectors effect the shape and decay time of the light signal acquired to determine whether Si-based photodetectors might be superior to PMTs for this application.

2. Materials and Methods

2.1. Materials

LSO (Siemens Medical Solutions, Knoxville, TN) was chosen as the scintillator for this study because of its brightness and fast decay time (40 ns). The phosphor used was yttrium aluminum gallium oxide: cerium ($\text{Y}_3(\text{Al,Ga})_5\text{O}_{12}:\text{Ce}$), denoted as YGG (Phosphor Technology Ltd., Stevenage, UK). The decay time of the YGG sample was measured to be 51 ns. The emission spectra of LSO and YGG samples were measured under x-ray excitation from a Philips X-ray tube with a copper target operated at 40 kVp and 20 mA. The setup employed a 302 McPherson monochromator (600 gr/mm grating) and a cooled Burle C31034 photomultiplier (PMT) with a GaAs:Cs photocathode. The excitation spectrum of YGG emission was measured using a custom made McPherson spectroscopy system. During this measurement the emission monochromator (McPherson 2035) was fixed at 525 nm, while the excitation monochromator (McPherson 234/302) was scanned from 250 nm to 500 nm. A GG475 filter was placed in the front of the detection PMT (Hamamatsu R2059) in order to prevent the excitation light from being registered as an emission. A deuterium lamp (McPherson 632) was used for an excitation source. As shown in Figure 2(a), the emission spectrum of LSO matches very well with the excitation spectrum of YGG. LSO has its peak emission at ~420 nm and the excitation peak for YGG is at ~435 nm. The YGG emission spectrum is shown in Figure 2(b) and is mainly in the green-yellow range with its peak around 550 nm. The LSO crystals used for experiment were all $1.5 \times 1.5 \times 20 \text{ mm}^3$ in size. Both polished and “as-cut” crystals were studied.

2.2 Comparison of Coating Schemes

Four phosphor-coating schemes were applied to the same $1.5 \times 1.5 \times 20 \text{ mm}^3$ LSO crystal and compared. These schemes are illustrated in Figure 3. “End + Sides” means the far end (back surface) and four side surfaces of the crystal were all coated with the phosphor. “End + $\frac{1}{2}$ Sides” means the far end together with half the length of the crystal sides (the 10 mm furthest from the photodetector) were coated. “End Only” means that the crystal was only coated on the far end. Lastly, “No Coating” means no coating on any surfaces. The YGG phosphor powder was dissolved in a mixture of water and ethyl alcohol and then sprayed onto the crystal

surfaces. This process was repeated until a ~ 0.25 mm layer of phosphor was coated on the crystal surfaces. After coating, the LSO crystal was wrapped with two layers of Teflon tape. The near end of the crystal was coupled to a single-channel PMT (Hamamatsu R2102). The crystal was irradiated at three depths ($z = 3$ mm, 10 mm and 17 mm) by electronic coincidence using a 0.5 mm ^{22}Na source with collimation beam with of ~ 2 mm. The collimating detector was a $2 \times 2 \times 10$ mm³ LSO crystal coupled to another single-channel PMT (Hamamatsu R670). The signals from these two single-channel PMTs were first passed through a pre-amplifier (NIM Model 778, Philips Scientific, Ramsey, NJ) and then sent to a constant fraction discriminator (CFD TC 453, Oxford Instruments Inc. Oak Ridge, TN). CFD signals from these two single-channel PMTs were then passed into a quad-four-fold logic unit (Model 756, Philips Scientific, Ramsey, NJ) to determine coincidence events. The coincidence signal was used to trigger a LeCroy WavePro 7100 oscilloscope. At each irradiation depth, 1000 individual pulses from the LSO-YGG crystal were recorded by the oscilloscope with a sampling rate of 10 GHz. The pulses were then averaged and fit with a single exponential function (empirically observed to provide a good fit to the measured data) to estimate the decay time. The experimental set-up is summarized in Figure 4. The same coating schemes were applied to a polished and an “as-cut” LSO crystal.

2.3 Evaluation of Phosphor Coated LSO Array

2.3.1 Experimental Set-up—A LSO array was fabricated with YGG phosphor coating. Sixteen $1.5 \times 1.5 \times 20$ mm³ LSO crystals had one half of their length (0–10 mm with respect to the PMT) wrapped with a single layer of Teflon tape. The 16 such crystals were then assembled into a 4 by 4 array. The other half of their length (10–20 mm from the PMT) and the end surface of the array were all coated with YGG phosphor. The outer surfaces (four side surfaces and one end surface) of the array were then covered with Teflon tape. Figure 5(a) and (b) are photographs of the resulting LSO-YGG array (the outer layer of Teflon tape was removed for the pictures). The same experimental set-up as shown in Figure 4 was used except that the single phosphor-coated LSO crystal was replaced with the LSO-YGG array and the single channel PMT R2102 was replaced with a multi-channel PMT (MC-PMT Hamamatsu H7546-M64) (MC-PMT). Signals from the 64-channel MC-PMT were multiplexed to four channels by a charge-division circuit (Siegel *et al.*, 1996). The four signals were amplified and summed by a fan-in-fan-out (LeCroy 428F). Coincidence signals between the H7546 and R670 PMTs were used to trigger the oscilloscope to digitize and store pulse shapes. The 20 mm depth of the scintillator array was virtually segmented into 2, 3, 4, and 5 bins by irradiating the center of each bin. Events falling within an energy window of 375–775 were used in the analysis.

2.3.2 Flood Histogram and Energy Resolution—After the pre-amplifier, the four signal channels from the MC-PMT were passed to a shaping amplifier (Model N568B C.A.E.N. Viareggio, Italy). Using the coincidence signal as the trigger, these four shaped signals were digitized by a customized DAQ board (Judenhofer *et al.*, 2005), shown as the dotted line in Figure 4. Flood histograms and energy spectra were acquired for irradiation depths of 2, 6, 10, 14, and 18 mm.

2.3.3 DOI Resolution and Accuracy—The summed pulses from the four MC-PMT channels were digitized by the oscilloscope. 3000 digitized pulses were stored at each irradiation depth. The recorded pulses were down-sampled to a 1 GHz sampling rate. There are several possible ways to quantify changes in the pulse shape for use in estimating the DOI information (Seidel *et al.*, 1999; Chandrikamohan and DeVol, 2007). Five pulse shape discrimination (PSD) methods were compared for the pulses obtained from this LSO-YGG detector. These methods and their parameters are illustrated in Figure 6. The parameter related to DOI for each of the PSD methods was defined as follows:

1. Constant Fraction Discrimination (CFD) method: DOI related to time between time zero (t_0) and the time at a fixed fraction ($\epsilon\%$) of the maximum pulse amplitude ($t_1 - t_0$ in Figure 6(a));
2. Rise Time Discrimination (RTD) method: DOI related to time different between the pulse crossing a lower fraction ($\epsilon_1\%$) and a higher fraction ($\epsilon_2\%$) of the maximum pulse amplitude ($t_2 - t_1$ in Figure 6(b));
3. Constant Time Discrimination (CTD) method: DOI related to the amplitude of the pulse at a fixed delay (D) after t_0 normalized to the maximum amplitude (A_1 divided by A in Figure 6(c));
4. Charge Comparison (CC) method: DOI related to integrated signal from t_0 to $t_0 + W$ normalized by the maximum amplitude;
5. Delayed Charge Integration (DCI) method: DOI related to ratio of the integrated signal in a fixed window (W) with and without a delay (D), i.e. integration from t_0 to $t_0 + W$ divided by the integration from $t_0 + D$ to $t_0 + D + W$.

The data sets recorded at 2 mm and 18 mm irradiation depth were processed by each of these five PSD methods. Two DOI histograms representing events interacting at 2 mm and 18 mm depth were plotted. To compare the PSD methods, a figure-of-merit (FOM) was defined as:

$$\text{FOM} = |\overline{\text{DOI}}_{2\text{mm}} - \overline{\text{DOI}}_{18\text{mm}}| / (\sigma(\text{DOI}_{2\text{mm}}) + \sigma(\text{DOI}_{18\text{mm}}))$$

where $\overline{\text{DOI}}_{2\text{mm}}$ and $\overline{\text{DOI}}_{18\text{mm}}$ are the mean values of the DOI-related PSD parameter distribution at 2 mm and 18 mm respectively, and σ is the standard deviation of those distributions. The free parameters for each PSD method were optimized to produce the maximum FOM. The method giving the largest FOM was then applied to pulses from all the different irradiation depths using the same optimized parameters.

The peaks of the DOI-related PSD parameter histograms corresponding to irradiation depths of 2, 6, 10, 14 and 18 mm were plotted as a function of the irradiation depth. By applying a linear fit to this data, the DOI-related PSD parameter is calibrated to actual DOI (in mm). With this calibration, the full-width at half maximum (FWHM) of the DOI distribution irradiation for a given depth can be measured to provide an estimate of the DOI resolution (Yang *et al.*, 2006).

To compare with more traditional phoswich DOI detectors, we segmented the crystal array into virtual depth bins. Using the data that corresponded to irradiation at the center of each bin, we estimated how many of the events were assigned to the correct depth bin. The actual depth was obtained on an event-by-event basis using the same calibration procedure described in the previous paragraph. The accuracy was defined as the number of events which were assigned to the correct bin divided by the number of total events detected.

2.4 Simulation of Decay-Time Changes for Different Photodetectors

The light received by the photodetector consists of two components: one part is the direct scintillation light from LSO with a relatively fast decay time and short wavelength (blue light range). The other part is the “YGG-converted” light, which has a slower decay time that can be described as the convolution of the LSO light signal and YGG light signal. This converted light also has a longer wavelength than the direct LSO light and falls in the green-yellow range of the spectrum (see Figure 2). For better detection of the “YGG-converted” light and thus improved DOI performance, we hypothesize that a photodetector with higher QE in the green

might be preferable. A simple simulation was therefore performed to compare photodetectors with different quantum efficiency profiles to guide future development of this DOI detector concept. For each 511 keV interaction, 12,500 LSO photons were generated with 40 ns decay time and wavelength distributed according to the LSO emission spectrum in Figure 2(a). We assume $\alpha\%$ of these photons were absorbed by YGG phosphor and converted according to the wavelength distribution shown in Figure 2(b). The sum of these two components forms the simulated pulse shape. The parameter α was varied from 0% to 100% in steps of 5%. The photodetectors compared were the Hamamatsu MC-PMT H7546-M64 used in the experimental portion of this work, an avalanche photodiode (APD) from Radiation Monitoring Devices, Inc (McClish *et al.*, 2005), and a Hamamatsu Multi-Pixel-Photon-Counter (MPPC) S10362-11-025. The QE or photodetection efficiency (PDE) spectra for these different detectors are shown in Figure 7.

To implement the simulation in Matlab, each photon was modeled with two random variables – emission time and wavelength. First, detection times were generated according to a Poisson distribution with a characteristic decay time of 40 ns, showing the time from when the gamma photon hit the scintillator to the time LSO photons were detected. Wavelengths were generated according to the known emission spectra of LSO. Since the geometry of the scintillators was not considered in the simulation, the detection time only represented the statistics of the light emission process, but did not include the light propagation time inside the scintillator. The process by which some of the LSO photons are converted into YGG photons was modeled by adding a delay to the detection time. This delay was added according to a Poisson distribution with a 51 ns characteristic decay time. The converted photons were assigned wavelengths based on the probabilities given by the YGG emission spectrum. Each simulated photon therefore had a certain detection time and wavelength. The QE of the photodetector was then used to determine the probability that the photon generated a photoelectron in the detector. The photodetectors were modeled as noise-free with no additional timing degradation in the pulse shape. For each incident gamma photon simulated, all the photoelectrons detected were then histogrammed according to their detection times to generate a simulated pulse. 1000 pulses were generated for each photodetector with different light conversion ratios (α), and then the pulses were processed using DCI method with the same optimized parameters as for the experimental data. The mean values and standard deviations were calculated. The resulting pulses were normalized in amplitude for direct comparison of their temporal characteristics.

Using these simulated pulses, the DCI value was predicted as a function of the light conversion ratios for the different photodetectors. The simulated data was compared with the experimental measured data to estimate what fraction of the LSO light was converted into YGG light with the different coating methods that were measured in Section 2.2.

3. Results

3.1 Comparisons of Coating Schemes

Table 1 summarizes the measured decay times at three irradiation depths for the four different coating arrangements on the unpolished crystal. No depth dependence was observed in the pulse shape for an uncoated crystal, as expected (Figure 8, left). The largest decay time difference (19.6 ns) between 3 mm and 17 mm irradiation depths was obtained when coating the unpolished crystal in the “End + ½ Sides” arrangement (Figure 8, right). Coating the crystal only at the end did not seem to provide enough phosphor surface area to efficiently convert LSO scintillation light into the YGG phosphor light, and decay time differences were only 4.5 ns between the two ends of the crystal. Coating the entire sides increased the decay time at all depths, but reduced the difference between the ends of the crystal, thus reducing potential DOI information. Based on the measured decay times of the LSO (40 ns) and the YGG (51 ns) materials used in these detectors, and the measured decay times in the YGG-coated LSO

crystals, it is possible to estimate the fraction of LSO scintillation light, α , converted at each depth and for each coating arrangement. This also is shown in Table 1. The characteristic decay time of LSO is 40 ns so ideally α is zero for “No Coating” scheme in all depths. Small deviations were found in the measured decay time (~ 42 ns instead of 40 ns) and conversion ratio (around 0.1) which indicated some errors in the method. Curve-fitting and decay time calculating may not be the most accurate way to interpret the pulse shape changes however the conclusions are not changed. The decay time from a crystal with polished surfaces had no significant depth-dependence for any of the coating arrangements and was not investigated further. Unpolished crystals with the “End + $\frac{1}{2}$ Sides” coating arrangement were used for all the further experiments.

3.2 Evaluation of Phosphor Coated LSO Array

3.2.1 Flood Histogram and Energy Spectrum—Figure 5(c) shows the flood histogram obtained by irradiating the LSO-YGG array uniformly. There is no major degradation in the flood histogram after coating the LSO array with a layer of YGG phosphor compared with the flood histogram of the same array without any coating. Figure 9 shows the flood histograms obtained when irradiating the LSO-YGG array at depths of 2, 6, 10, 14 and 18 mm. Because of the geometry of the experimental set-up, the radiation beam striking the LSO array was about 2×2 mm² in cross-section. Thus only one row of crystals in the array was irradiated. The flood histogram is seen to degrade significantly towards the phosphor-coated end (at 14 and 18 mm). The primary reason for this is revealed by examining the pulse height spectra of all irradiated crystals at the five different depths (Figure 10). The photopeak position decreases with increasing interaction distance from the PMT because of the large light loss along the length of the unpolished crystal surface. Lower light collection leads to poorer flood histograms. The FWHM energy resolutions for a single crystal in the center of the array are 26.9%, 33.0%, 31.4%, 30.0%, and 29.0% for irradiation depths of 2, 6, 10, 14 and 18 mm respectively.

3.2.2 Pulse Discrimination Methods—Table 2 shows the FOM with optimal parameters for the five PSD methods evaluated. The DCI method was found to best distinguish the two data sets representing different depths with the largest FOM. Pulses recorded at each of the irradiation depths were then processed by the DCI method using the same optimal parameters ($W = 120$ ns and $D = 60$ ns).

3.2.3 DOI Resolution and Accuracy—The array was irradiated at 13 different depths in total. Pulses from events satisfying the energy criteria (375-775 keV) were processed by the DCI method to compute the PSD parameter related to the DOI. This DOI parameter was then histogrammed for depths corresponding to virtual binning of the LSO crystal into 2, 3, 4 and 5 bins (Figure 11). The histograms were formed with 1500 events at each depth. The peaks of the DOI histograms were plotted as a function of known irradiation depth (Figure 12) and demonstrated that this coating scheme gives a linear relationship between the DOI parameter and the actual known DOI. The DOI resolution (FWHM) of all irradiated crystals averaged along the whole crystal depth was estimated to be 8.0 ± 0.9 mm.

Using the linear calibration function in Figure 12, the DOI parameter estimated by the DCI method was calibrated into DOI (in mm) on an event-by-event basis. The fraction of events that were correctly assigned to a given depth bin are shown in Table 3 for different number of bins. For 2 bins (10 mm depth for each bin), the DOI accuracy is extremely good, with more than 80% of events assigned to the correct depth bin. For 3 bins (6.67 mm bin depth), more than 60% of the events are correctly assigned. For larger numbers of bins, significant fractions of events were mis-assigned. These results are consistent with the stated DOI resolution of 8 mm and match the performance of a traditional phoswich detector with 2 or 3 layers. The DOI

accuracy is better for depths closer to the PMT, presumably because more light is collected for these events.

3.3 Simulation to Compare Photodetectors

Figure 13(a) illustrates the averaged simulated pulses for PMT readout with different light conversion ratios. Figure 13(b) shows these pulses with the peak aligned in time to show differences in the decay time. It is found that when α is larger than 0.8, the decay time of the pulses show little change as the light conversion ratio (α) increases, for these high α values, the change is primarily in the rise time of the pulse. Figure 14 (a) shows the mean simulated pulse that would be detected by three different types of photodetectors receiving 50% direct LSO light and 50% YGG-converted light. The DCI value was calculated using the same parameters applied to the experimental data ($W = 120$ ns and $D = 60$ ns). The DCI value varies as the fraction of phosphor-converted light, α , is changed from 0 to 100% as shown in Figure 14(b). Using this plot, the conversion ratio for the experimental data is estimated and is included in Table 1. Table 1 shows that conversion ratio is estimated to vary in the range of 0.25 to 0.58 in the experiments with the “End + 1/2 Side” coatings configuration.

To compare the performance of different photodetectors for this DOI approach a FOM was defined as:

$$\text{FOM} = |\overline{\text{DOI}}_{\alpha=0.25} - \overline{\text{DOI}}_{\alpha=0.60}| / (\sigma(\text{DOI}_{\alpha=0.25}) + \sigma(\text{DOI}_{\alpha=0.60}))$$

where $\overline{\text{DOI}}_{\alpha=0.25}$ and $\overline{\text{DOI}}_{\alpha=0.60}$ are the mean values of DCI distribution as $\alpha = 25\%$ and 60% respectively, and σ is the standard deviation of those distributions. The α values were chosen again to represent values consistent with the range of the experimental data. The computed FOMs for PMT, MPPC, and APD were 4.0, 6.3 and 13.1 respectively. This result can be understood by examining Figure 7. For APDs, the QE is very high and changes little across the visible spectrum. An APD therefore can detect more YGG-converted photons than the other two photodetectors for any given conversion efficiency α , and this will lead to a slower pulse decay time and a smaller DCI value. The higher QE of APDs also produces better statistics, reducing the variance of the DCI estimation. For the PMTs used in the experimental studies here, the QE is lower and drops quickly beyond 450 nm. The QE for detecting the YGG-converted light is less than half of that for the direct LSO light, thus reducing the effect of the phosphor coating on the pulse shape. If α reaches a value of 100%, all the detected photons are phosphor converted and the pulses from different photodetectors will have different amplitudes but the same pulse shape. Therefore the DCI values for all three photodetectors are the same when α is 100%.

The simulation results within the experimental α range (0.25~0.60) indicate that a photodetector with higher QE in the green part of the spectrum should lead to a larger FOM and a better depth-decoding in this range. Thus Si-based detectors such as APDs and MPPCs should therefore also be studied. However, photodetector noise is not included in these simulations and the comparison is based solely on the spectral distribution of the light, the quantum efficiency of the photodetectors and statistical noise from the limited light production of LSO. Other photodetector properties such as photodetector noise, gain, stability etc. need to be considered and experimental studies will be required with these other photodetectors to determine if the enhanced green QE can be taken advantage of to improve DOI resolution with YGG-coated LSO crystals.

4. Discussion

We have proposed a novel scintillation detector for continuous DOI encoding. The key idea in this detector idea is to increase the original scintillation light decay time by adding a layer of phosphor to absorb and convert the scintillation light in a depth-dependent fashion. Continuous DOI information can then be acquired by evaluating pulse shape changes. Our preliminary experiments have shown that it is possible to create a ~19 ns change in decay time across a 2 cm long LSO crystal using a 0.25 mm thick coating of YGG phosphor on the end and along half the sides of the crystal. By using DCI, a common PSD method, a DOI resolution of ~8 mm was achieved for a 2 cm thick LSO array. Studies on a YGG-coated LSO array showed that if the 2 cm depth of the array is segmented into 3 bins, more than 60% events can be assigned into the correct bin.

These experimental results show the potential of this detector design for encoding DOI. The advantages are that the DOI information is continuous and the scintillator array has read out from a single end. At the present stage of development, this method provides DOI resolution that is roughly equivalent to a 2 or 3-layer phoswich detector. However, there are many opportunities to improve the performance of such a detector. First, better combinations of scintillator and phosphor may exist. Ideally, the scintillator should be fast and bright and the phosphor must have just the right decay time to provide clear depth-dependent changes without causing dead time problems. Most importantly, the emission spectrum of the scintillator must match well with the phosphor excitation spectrum for good conversion efficiency. While the spectral match between LSO and YGG is very good, it would be beneficial if there was a greater decay time difference between the two. Second, the surface treatment of the crystal and the application of reflectors need further optimization to get the best crystal identification and energy resolution while maintaining DOI performance. Third, the phosphor coating technique will be studied so that the coating process can be better controlled and the coating layer has better uniformity in terms of density of phosphor particles and thickness. Fourth, based on our simulations, photodetector with higher QE in the phosphor emission light range could help in the extraction of DOI information. These will be evaluated. Lastly, more sophisticated techniques to extract the depth information from the pulse shape can be studied – the present methods use only 1 or 2 measurements extracted from the pulse rather than the entire waveform in determining a pulse shape parameter that is related to DOI. Once all these studies are complete, we anticipate improvement in DOI resolution to a level that will be sufficient for significantly reducing parallax errors in applications using small diameter PET systems designed for animal and breast imaging.

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Figure 1.

Concept for a continuous DOI scintillation detector. The light reaching the photodetector is a mixture of direct scintillation light, and scintillation light that has been absorbed and re-emitted by the phosphor. The pulse-shape therefore depends on the relative contribution of the scintillation and phosphor light. If the fraction of phosphor-converted light can be made depth-dependent, pulse-shape analysis can yield information on the depth of interaction.

Figure 2.

(a) Measured excitation spectrum of YGG:Ce and emission spectrum of LSO:Ce; (b) Measured emission spectrum of YGG:Ce

Coating Scheme	End + Sides	End + 1/2 Sides	End Only	No Coating
Illustration				

Figure 3.

Illustration of four different schemes to coat a single LSO crystal with YGG:Ce phosphor. Phosphor coating is ~0.25 mm thick and is shown in green.

Figure 4.
Experimental set-up

Figure 5.

(a) and (b) pictures of 4 by 4 LSO array coated with YGG:Ce phosphor (End + $\frac{1}{2}$ Sides) and (c) a flood histogram by irradiating the LSO-YGG array uniformly. Outer layer of Teflon tape reflector has been removed to show phosphor coating.

Figure 6.
 Five PSD methods (a) Constant Fraction Discrimination (b) Rise Time Discrimination (c)
 Constant Time Discrimination (d) Charge Comparison (e) Delayed Charge Integration

Figure 7. Quantum efficiency spectra for three different photodetectors: MC-PMT H7546-M64, APD, and MPPC S10362-11-025. The MPPC data is expressed in terms of the photodetection efficiency, accounting for the non-unity fill factor of MPPC's as well as the quantum efficiency.

Figure 8. Averaged pulse shape at three different depths: 3, 10 and 17 mm with (a) “No Coating” (b) “End + 1/2 Sides” coating.

Figure 9.
Flood histograms of the LSO-YGG array for irradiation depths of 2, 6, 10, 14, and 18 mm

Figure 10.
Energy histograms obtained at five irradiation depths.

Figure 11.

Histograms of DOI parameter calculated by DCI method when 2 cm crystal length is segmented into 2, 3, 4 or 5 bins and array is irradiated with a ~2 mm wide beam at the center of each depth bin.

Figure 12.
Peak of DOI parameter histograms versus known irradiation depth with linear fit superimposed.

Figure 13.

(a) Simulated pulses detected by PMT with light conversion ratios of 0, 0.2, 0.4, 0.6, 0.8, 0.9 and 1.0. (b) Same data with peaks aligned in time to better illustrate changes in fall time of the pulses.

Figure 14.

(a) Simulated pulses detected by PMT, APD and MPPC (with QE taken from Figure 7) when there is 50% LSO light and 50% YGG-converted light; (b) Changes in DCI value as a function of the converted light ratio (DCI calculated with $W=120\text{ns}$, $D=60\text{ns}$).

Table 1
Decay times (τ), DCI values and estimated light conversion ratios (α) at three depths of interaction locations

	End + Sides			End + 1/2 Sides			End Only			No Coating		
	τ (ns)	DCI	α	τ (ns)	DCI	α	τ (ns)	DCI	α	τ (ns)	DCI	α
3 mm	51.8	3.12	0.420	44.4	3.65	0.247	43.6	3.75	0.215	41.7	4.04	0.123
10 mm	59.5	2.68	0.565	49.6	3.22	0.386	44.2	3.62	0.258	42.8	3.92	0.160
17 mm	67.2	2.49	0.628	64.0	2.64	0.580	48.1	3.37	0.340	42.6	3.87	0.177
diff	15.4	0.63	0.208	19.6	1.01	0.333	4.5	0.38	0.125	0.9	0.17	0.054

Table 2
Parameters for optimizing PSD methods and the resulted FOM

PSD methods	CFD	RTD	CTD	CC	DCI
Optimal Parameters	$\epsilon\% = 5\%$	$\epsilon_1\% = 95\%$ $\epsilon_2\% = 5\%$	D = 8 ns	W = 15 ns	W = 120 ns D = 60 ns
Maximum FOM	1.5506	1.5405	0.7485	0.7913	1.8657

Table 3 DOI accuracy for different number of virtual depth bins in the YGG-coated LSO array

# Bins	Fraction of Events Assigned to Correct Bin			
2	0.94		0.84	
3	0.81		0.64	0.64
4	0.75	0.51	0.52	0.58
5	0.73	0.42	0.41	0.46