Positioning Annihilation Photon Interactions in a Thin LSO Crystal Sheet with a Position-Sensitive Avalanche Photodiode

Angela M K Foudray, Student Member, IEEE, Frezghi Habte, Member, IEEE, Craig S Levin, Member, IEEE, Peter D Olcott, Member, IEEE

Abstract—Using scintillation crystal sheets instead of discrete crystal arrays in high-resolution PET has the advantage of reduced complexity. In order to evaluate the positioning capability of a position sensitive avalanche photodiode (PSAPD) using a sheet Lutetium Oxyorthosilicate (LSO) crystal scintillator, we need to understand the functional dependence of a detected event position on the known source position. We studied positioning with both collimated 57Co 122keV and coincidence-triggered 22Na 511keV sources, which were stepped across the face of an 8mm x 8mm LSO sheet crystal coupled to an 8mm x 8mm PSAPD at 160µm intervals using a voltage-driven mechanical stage with a LabVIEW controlled acquisition system. We analyze the energy resolution, sensitivity, photopeak position and energy gated full width at half maximum (FWHM) spread of the detected position for a particular known source position. We have observed a 10% variation in average energy from the center of the crystal to the edge with 57Co and <1% for 22Na and an average point spread function FWHM of 2.86mm and 1.12mm for 57Co and 22Na respectively. We investigated methods to create a 1-1 map between (1) the four positioning signals from the PSAPD and the recorded energy and (2) the true position of the annihilation photon interaction. We found the average energy change over the 1.2mm near the edge of the continuous LSO crystal to be ~5% - insufficient to resolve with the prototype PSAPD (energy resolution 12%) with an Anger-type logic positioning algorithm. Simulation using the annihilation photon interactions from GATE and scintillation photon transport from DETECT2000 have confirmed the effects observed in experiment.

I. INTRODUCTION

We are developing a high-sensitivity, high-resolution small animal positron emission tomography (PET) system for studying the kinetics and mechanisms of human disease in small laboratory animal models. Most high-resolution imaging systems in use and in development are incorporating increasingly smaller pixilated scintillation crystals to try to improve system resolution. Using a thin, continuous crystal may provide increased resolution while decreasing complexity and costs associated with crystal cutting, surface preparation and detector system assembly. Experimental and simulated results show comparable position resolution in the center 6mm of the device using a continuous crystal as compared to a 1mm pixellated array, with degeneracy at the edges using anger-logic type positioning.

Fig. 1. The acquisition setup for a) coincidence-collimated 22Na annihilation photon detection and b) lead collimated 57Co gamma photon detection.

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Angela M K Foudray is a graduate student at the University of California – San Diego, La Jolla, CA USA and is working at Stanford University, Palo Alto, CA USA (telephone: 650-736-2598, e-mail: afoudray@stanford.edu).

Frezghi Habte is with Stanford University, Palo Alto, CA USA (e-mail: fhabte@stanford.edu)

Craig S Levin is with Stanford University, Palo Alto, CA USA (e-mail: cslevin@stanford.edu)

Peter D Olcott is with Stanford University, Palo Alto, CA USA (e-mail: pdoc@stanford.edu)
II. EXPERIMENTAL STUDY

A. Setup

The PSAPD being characterized is a prototype developed by RMD, Inc. with an active region of 8mm x 8mm (see figure 2). A 8mm x 8mm x 1mm LSO sheet crystal is coupled to the PSAPD with silicone optical grease in each experiment. Seven layers of Teflon were wrapped around the crystal for a reflective coating. A LabView controlled, motorized MM-4M-EX-140 micro-stage from National Aperture was used to automate and accurately control the steps across the detector. Two sources were used to observe the point spread function and positioning linearity of the PSAPD: \textsuperscript{57}Co with gamma photon energies of 122 keV and \textsuperscript{22}Na with annihilation photon energies of 511 keV. To collimate the highly energetic 511 keV photons from the \textsuperscript{22}Na source, a coincidence setup was employed (see the top of figure 1). A Hamamatsu H3164 photomultiplier tube (PMT) was coupled to a Teflon-wrapped 5mm x 5mm x 10mm LSO crystal with silicone optical grease. The PMT was mechanically coupled to the source at a distance of 190mm and moved with the micro-stage in 160µm steps. The source-PSAPD distance was kept at a constant 1.5mm. The geometry of the setup resulted in a 540µm spot size on the face of the PSAPD. The coincidence circuit comprised of Fast Filter Amplifiers, Constant Fraction Discriminators, a TAC/SCA, and Gate and Delay Generator NIM modules to trigger the four-channel PSAPD event acquisition. The \textsuperscript{57}Co source was collimated using a 30mm x 30mm x 10mm block of lead with a 500µm hole (see the bottom of figure 1). Positions were calculated from the four digitized PSAPD channels using Anger-type logic. The units of position and therefore the point spread function full width at half maximum (psfFWHM), as well as the average energy, are all reported in a normalized form. Position is calculated from the four digitized voltages from the corner anodes of the PSAPD (see figure 3) in the following manner:

\[
x = \frac{(A + B) - (C + D)}{A + B + C + D}
\]

\[
y = \frac{(B + C) - (A + D)}{A + B + C + D}
\]

(range: [0,5] for A, B, C and D, range: [-1,1] for x and y).

The average energy is calculated from the sum A+B+C+D and has a range of [0 20]. The energies and counts plotted in figure 4 are shown at a fraction of their measured value to better visualize all data represented.

B. Tests and Results

Using the setups previously described, a 10µCi \textsuperscript{22}Na and a 10µCi \textsuperscript{57}Co were stepped in a line across the face of the PSAPD detector. Figure 4 shows the detected position spread for \textsuperscript{22}Na (left) and \textsuperscript{57}Co (right) at a particular source position. The log of the histogrammed counts are in part b) of figure 4 to show the relative size of the spread of events with respect to the size of the detection area. Data was gathered for 2000
Fig. 5. For a single source position, a) the histogrammed centroid of the light spread b) the log of the histogram values (enhance the visualization of the dynamic range). Top: $^{22}$Na and bottom: $^{57}$Co.

III. MONTE CARLO STUDY

To compare these results with theory, we utilized two standard simulation packages to model both the high and low energy interactions in the LSO scintillation crystal. The interaction mechanisms of the high-energy annihilation photon were simulated with the new medical imaging Monte Carlo add on package to the GEANT4 software, GATE. The subsequent scintillation photon transport and interaction mechanisms were carried out using the DETECT2000 package.

A. GATE

To simulate similar conditions as seen in the $^{22}$Na experimental coincidence study, GATE was used to obtain Compton scatter, Photoelectric and characteristic X-ray interaction positions in the LSO scintillation crystal. A 20µm radius sphere was placed 5mm from the surface of an 8mm x 8mm x 1mm single LSO crystal, which emitted 511keV photons normal to the surface of the crystal (see figure 6). Each interaction with the crystal is recorded by GATE into a "hits" file, which gives a great deal of information including the energy, three-dimensional position, and original annihilation event number. In order to probe the location-dependent response and light spread, the source sphere was stepped at 200µm increments at the locations of the face of the detector shown figure 7 in red. The position, energy and event number were passed, for each "hits" interaction to DETECT2000 to simulate optical transport within the crystal.

B. DETECT2000

The interactions determined by GATE were modeled as a point process, i.e., the scintillation photons modeled by DETECT2000 for a particular GATE interaction (“hit”) were all given the same initial location, the one listed in the “hits” file. DETECT2000 requires for input a location and number of...
photons to generate and outputs for each scintillation photon a location. The event number was passed through each step of the simulations to keep together all interactions and subsequent scintillation photons from the same event. The energy given in the GATE “hits” file was converted to a number of photons to generate for the DETECT2000 step using the average LSO value of 25 photons per keV. The two materials simulated are shown in figure 2: an 8mm x 8mm x 1mm LSO crystal, with index of refraction 1.82, and a 10µm deep optical grease layer with the same cross-section and an index of refraction of 1.465. The surface finish on the five faces of the scintillation crystal not in contact with the optical grease were considered ground, and the sixth connecting face, polished. These surface definitions were mirrored in the grease layer, except for the side considered in contact with the PSAPD which was defined as the detect layer. Scintillation photons that come in contact with this detect layer are considered detected and the position and location are automatically written out. The position reported is the mean of the centroids of the photons from an event. The PSAPD resistive surface was not modeled to simulate pincushion effects, which add non-linear distortions in these position estimates. These effects are small in this detector in the location that the experimental data were taken, i.e., the pincushion effect is not large where the experimental data was taken [1]. There is a larger region over which the calculated position for the 122keV $^{57}$Co data is non-linear due to the larger spot size and that more of the interactions happen closer to the top of the crystal (farther from the detector surface – see figure 8).

**IV. CONCLUSION**

Calculated positions from events whose centroid are in the first 1.5 mm near the edge of the sheet crystal are degenerate. This is due to a sizable portion of the scintillation photons reflecting off the surface of the crystal. Because of these reflections, some photons are lost, changing the average energy of events positioned at the edge as compared to events at the center of the detector. The percentage change of this energy in the first 1.5 mm is about 5%. The energy resolution of our characterized PSAPD is 10-12%. Even with a maximum likelihood estimation for positioning, for a high sensitivity, high-resolution PET system, using a single sheet crystal, we...
would need a detector with better than 5% energy resolution to out-perform position sensitive detectors coupled to single crystals using Anger-logic type positioning and energy information. Further efforts to utilize all the information collected from the four anode channels could involve maximum-likelihood estimation algorithms. Using Anger-type logic alone, this loss of resolution near the edge of the crystal is a price that may be considered since it drastically increases sensitivity due to higher packing fraction and more preferable crystal placement [5].

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VI. REFERENCES