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ALGORITHMS TO IDENTIFY DETECTOR COMPTON SCATTER IN PET MODULES*

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Abstract

Using Monte Carlo simulation, we investigate algorithms to identify and correct for detector Compton scatter in hypothetical PET modules with 3x3x30 mm BGO crystals coupled to individual photosensors. Rather than assume a particular design, we study three classes of detectors: (1) with energy resolution limited by counting statistics (such as conventional scintillator / PMT designs), (2) with energy resolution limited by electronic noise (such as PIN photodiode based designs), and (3) with depth of interaction measurement capability. For the first two classes, selecting the channel with the highest signal as the crystal of interaction yields a 24–28% misidentification fraction (MIF) for all reasonable noise fwhm to signal (N/S) ratios (*i.e.* <0.5 at 511 keV). Algorithms that attempt to correctly position events that undergo forward Compton scatter using only energy information can reduce the MIF to as low as 15%, and can be easily realized with counting statistics limited detectors but can only be achieved with very low noise values for noise limited detectors. When using position of interaction to identify forward scatter, a MIF of 7% is obtained with perfect position resolution, increasing smoothly as the position resolution degrades to 3 mm fwhm.

1. INTRODUCTION

The use of PET in medical research has stimulated development of detectors with improved spatial resolution. One factor that degrades the performance of these designs is crystal misidentification caused by detector Compton scatter. By examining the signature of Compton scatter events, we seek to identify and correct for detector scatter by improving the ability to determine the crystal of first interaction, and hence improve the accuracy of the reconstructed image.

Several recent proposals for high resolution PET detector modules incorporate small scintillation crystals that are individually coupled to photosensors [1–3]. Earlier work suggested that such designs may be able to identify and reject events that Compton scatter in the detector ring, thereby improving image accuracy [4], but this improvement comes at the expense of greatly reduced sensitivity. This paper extends the previous work by developing algorithms that identify detector Compton scatter and assign events to the detector element where the first interaction occurred, thereby improving the accuracy with no loss in sensitivity.

Rather than assume a particular design, we study three classes of detectors: those with energy resolution limited by counting statistics (such as conventional scintillator / PMT designs) [1, 3], those with energy resolution limited by electronic noise (such as PIN photodiode based designs) [2], and those capable of measuring the interaction depth in the crystal [5–7]. Most misidentified events are due to forward Compton scatter, where the kinematics require that the crystal of first interaction has the lesser energy deposit. Thus, the challenge is to develop an algorithm that first identifies events with energy deposit in multiple crystals with an energy threshold, then seeks to correctly identify the crystal of first interaction.

2. MONTE CARLO SIMULATION METHODS

Algorithms were investigated with Monte Carlo simulation. Individual detectors were modeled as 3x3x30 mm BGO scintillator crystals coupled to individual photosensors and arranged into a 60 cm diameter, 2.4 cm axial extent PET ring. The activity distribution simulated was a line source 1 cm from the ring's center, and energy dependent photoelectric and Compton cross sections were used to track the location and amount of energy deposit in each detector crystal until the gamma ray escaped from the PET ring or photoelectric absorption occurred. Events were rejected if the total energy deposited in an 8x8 element module was less than 200 keV. The detector modules with energy resolution limited by electronic noise and those capable of depth measurement also include an energy resolution contribution from counting statistics equivalent to 12% fwhm at 511 keV.

Algorithm performance was evaluated with two figures of merit: the MIF (misidentification fraction, defined as the fraction of those 511 keV photons that interacted in the detector ring, but whose interaction was assigned to a crystal element other than the element of first interaction) and a region of interest (ROI) analysis on the resulting reconstructed image. Like patient Compton scatter, detector Compton scatter does not significantly degrade spatial resolution, but it does affect quantitation. The ROI analysis, which plots the relative activity in circular regions of interest as a function of the region radius, investigates this effect by examining the relative spillover into regions close to the source.

3. ALGORITHM DEFINITIONS

A. Maximum Signal Algorithm

We evaluated the performance of four different algorithms to be used for detectors with energy resolution limited by counting statistics or by electronic noise. The simplest algorithm implemented was the *maximum signal* algorithm. This algorithm selected the channel with the largest signal as the crystal of first interaction, rejecting those events where the maximum signal was below an energy threshold. It set the standard by which we compared the results from all other

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algorithms investigated since it best models the techniques used to identify crystals which are individually coupled to photomultiplier tubes.

B. Reject Multiples Algorithm

The *reject multiples* algorithm attempted to eliminate Compton interaction events by rejecting events when at least two signals were above an energy threshold (otherwise the channel with the largest signal was selected).

C. Second Highest Signal Algorithm

The *second highest signal* algorithm attempted to maintain high detection efficiency by correctly positioning multiple interaction events. This algorithm selected the channel with the smallest signal of all those above an energy threshold (which is also the largest signal when only one signal was above threshold). Events were rejected only if the total energy deposited in a module was <200 keV, and hence the detection efficiency remained high independent of the N/S ratio.

D. Compton Weighted Algorithm

In attempt to further reduce the MIF without sacrificing detection efficiency, we developed the *Compton weighted* algorithm. Like the previous algorithm, events that result in energy deposit in more than one crystal were identified with a noise dependent energy threshold. If the event was identified as a multiple interaction event, an energy difference threshold was used to distinguish between forward Compton scatters and photoelectric events that were incorrectly labeled as multiple interaction events. The smaller signal was selected when the energy difference was less than a second threshold because in that case forward scatter is more likely than an incorrectly labeled photoelectric event.

4. DETECTORS LIMITED BY COUNTING STATISTICS

The performance of the algorithms described above with detectors with energy resolution limited by counting statistics is summarized in Figure 1, which plots the MIF as a function of energy resolution. These detectors are assumed to have no electronic noise. Hence, the optimal threshold on individual detectors for identifying events depositing energy in multiple crystals was 0 keV. For energy resolutions less than 100%, the MIFs remained fairly constant at 25% for the *maximum signal* algorithm, 15% for both the *Compton weighted* and the *second highest signal* algorithm, and 5% for the *reject multiples* algorithm. The *Compton weighted* and the *second highest signal* algorithm both improve upon the *maximum signal* algorithm because they correctly identify forward scatter events which the latter algorithm misidentified. The *reject multiples* algorithm further improved the MIF by rejecting multiple interaction events, which significantly lowers its detection efficiency.

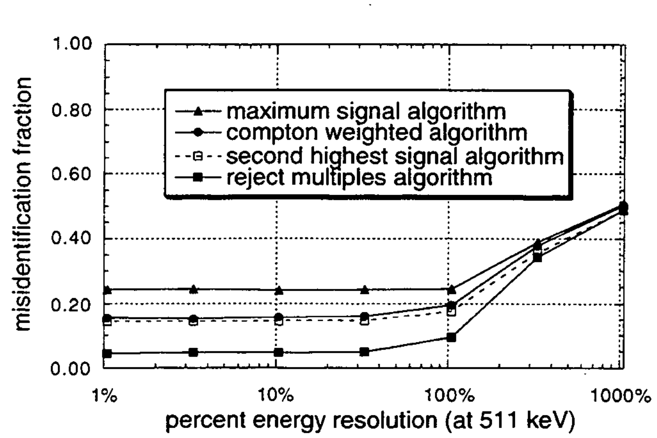

Figure 1: The MIFs obtained by each algorithm for detectors with energy resolution limited by counting statistics. Results are plotted as a function of energy resolution at 511 keV.

5. DETECTORS LIMITED BY ELECTRONIC NOISE

A. Maximum Signal Algorithm

For N/S ratios of 0.3 or lower and a 200 keV acceptance threshold, 25% of the events were misidentified when this algorithm was implemented (Figure 2a). Raising the threshold to 329 keV decreased this misidentification percentage to 19%; however, the coincidence detection efficiency became unacceptably low, dropping from 91% to 75% (Figure 2b).

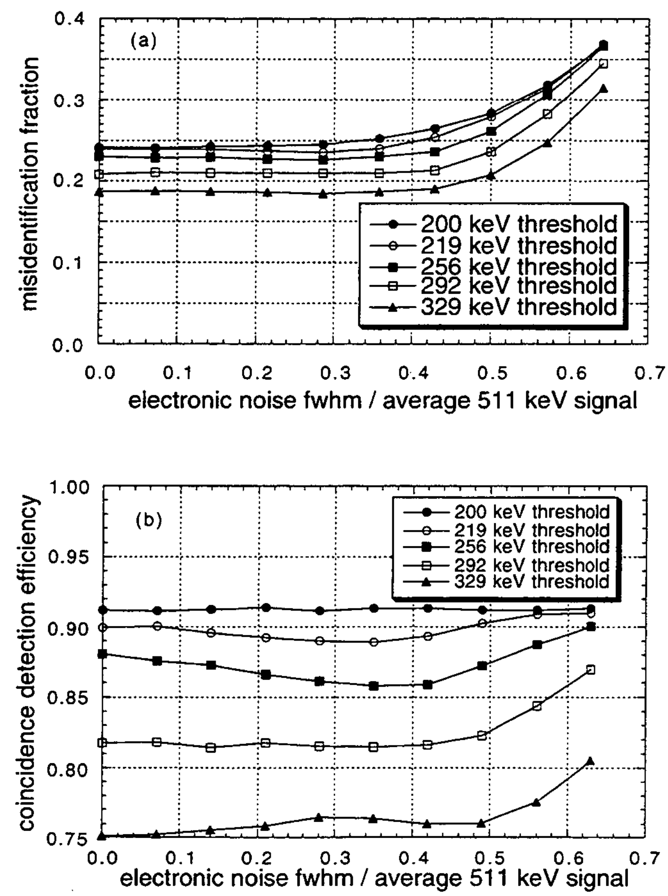

Figure 2: The (a) MIFs and (b) coincidence detection efficiencies obtained when the *maximum signal* algorithm was implemented in detectors with energy resolution dominated by electrical noise.

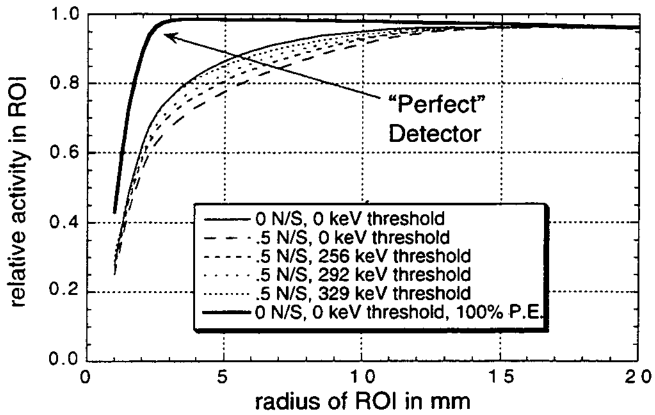

Figure 3: Relative activity in circular ROIs as a function of the region radius when the *maximum signal* algorithm is implemented in detectors with energy resolution dominated by electrical noise.

To examine the effects of spillover into regions close to the source, we plot the relative activity in circular region of interest (ROI) as a function of the region radius (Figure 3). While increasing the acceptance threshold decreases the detection efficiency, it also increases the activity in small ROIs and hence decreases the spillover into regions close to the source. The activities obtained when zero electronic noise and zero keV threshold were simulated are also shown in Figure 3, as is data from a "perfect" detector (zero electronic noise, zero keV threshold, and a scintillator with 100% photoelectric effect).

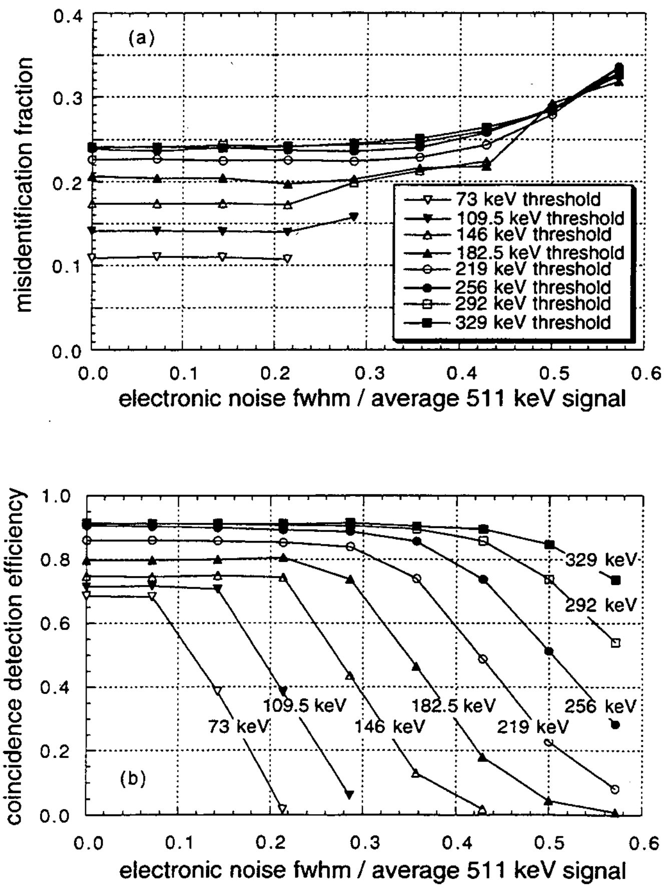

Figure 4: The (a) MIFs and (b) coincidence detection efficiencies obtained when the *reject multiples* algorithm was implemented in detectors with energy resolution dominated by electrical noise.

B. Reject Multiples Algorithm

With high thresholds, few events were rejected. Hence, the results from the *reject multiples* algorithm were the same as the results from the *maximum signal* algorithm without thresholding. With low thresholds, this algorithm decreased the MIF because it rejected a great majority of the events that had a possibility of being misidentified due to Compton scatter and/or noise (Figure 4a). While decreasing the threshold decreased the fraction of misidentified events, it also significantly degraded the detection efficiency (Figure 4b).

C. Second Highest Signal Algorithm

Because of the kinematics of forward scatter, which occurs a majority of the time, less energy is deposited in the first crystal of interaction than in subsequent crystals. Hence, choosing the crystal with the smaller energy deposit often results in correct identification. However, if the first interaction is photoelectric absorption, which happens 43% of the time in BGO, the crystal with the largest energy deposit is the only crystal of interaction and other signals are due to noise. In order for this algorithm to be effective, the threshold must be low enough to maximize the number of Compton scatters that are correctly identified but high enough to minimize the identification of photoelectric signals degraded by noise and misidentified as multiple interaction events.

Figure 5 compares the results of this algorithm to those obtained from the *maximum signal* algorithm when no threshold was applied. As expected, only with high thresholds was the *second highest signal* algorithm effective over a broad range of N/S ratios. With low thresholds the percentage of misidentified events significantly increased as the N/S ratio increased. However, with extremely low N/S ratios and low

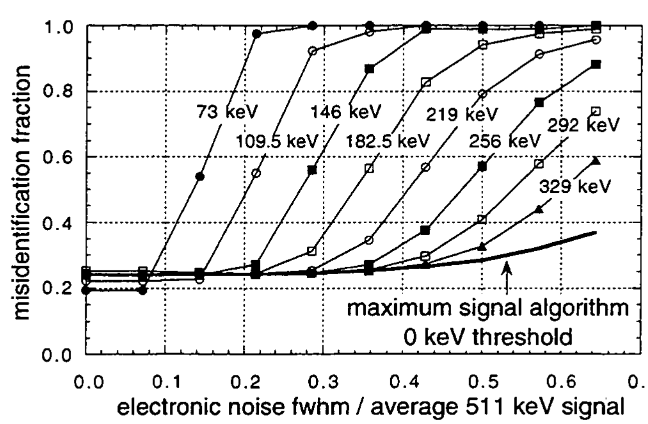

Figure 5: The MIFs obtained when the *second highest signal* algorithm with the indicated thresholds was implemented in detectors with energy resolution dominated by electrical noise.

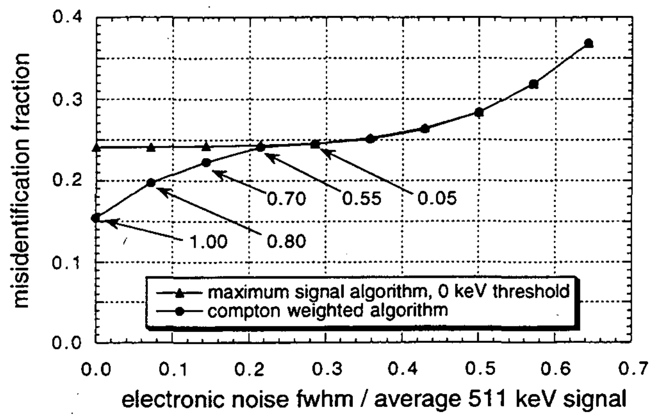

Figure 6: The MIFs obtained when the *Compton weighted* algorithm was implemented in detectors with energy resolution dominated by electrical noise. The energy difference thresholds normalized to 511 keV are indicated on the plot.

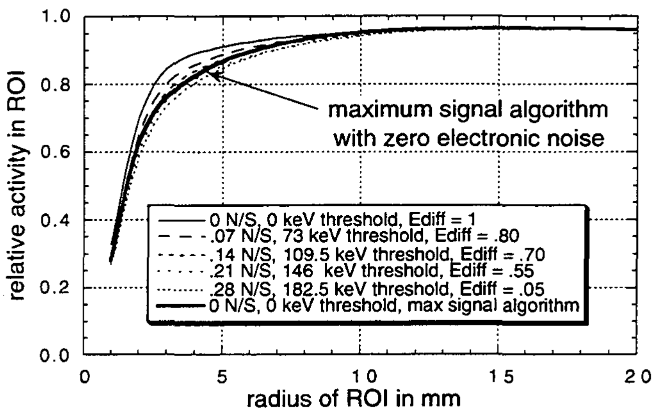

Figure 7: The ROI curves obtained when the *Compton weighted* algorithm at the specified noise and threshold were simulated in detectors with energy resolution dominated by electrical noise.

thresholds, the MIF was lower than the fraction obtained from the *maximum signal* algorithm.

D. Compton Weighted Algorithm

Not surprisingly, the performance of this algorithm was sensitive to the two thresholds used: the threshold to determine if a multiple interaction event occurred and the threshold to distinguish between forward scatters and photoelectric events incorrectly labeled as multiple interaction events. With larger N/S ratios, a smaller energy difference threshold was required to obtain the smallest MIF. With N/S ratios greater than 0.20, the MIFs were identical to those obtained from the *maximum signal* algorithm. However with zero electronic noise, the MIF was reduced to 15% (Figure 6).

The ROI curves obtained with the *Compton weighted* algorithm are shown in Figure 7. Since the MIF was lowered for small N/S ratios, the spillover into regions close to the source was also reduced for these low noise cases as compared to the results from the *maximum signal* algorithm.

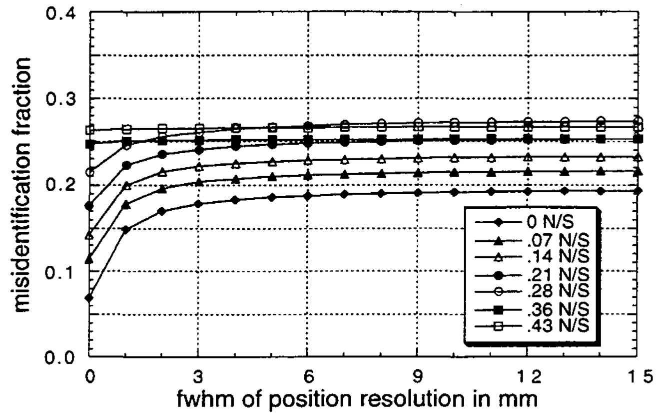

Figure 8: The MIFs with the *depth of interaction* algorithm.

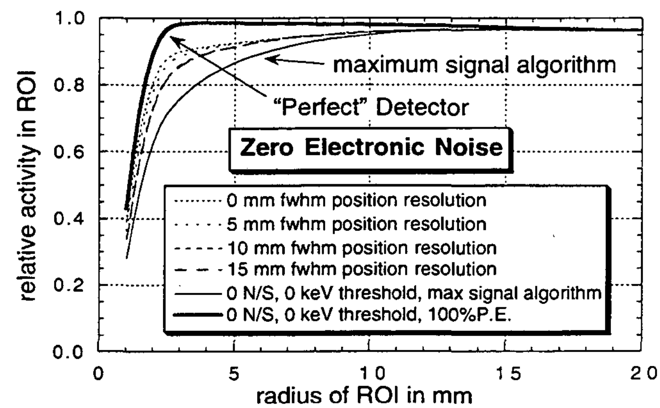

Figure 9: Relative activity in ROIs when the *depth of interaction* algorithm with zero electronic noise was implemented, as well as for the *maximum signal* algorithm and for a "perfect" detector.

6. DETECTORS WITH DEPTH OF INTERACTION

With detector modules that measure penetration distance, interaction position (rather than energy) can identify Compton scatter events. The *depth of interaction* algorithm labeled the "correct" channel as the channel with energy deposited at the smallest penetration distance when ≥2 signals were above an energy threshold and the channel with the largest signal otherwise. If either of the crystals had "signal" due only to electronic noise, a random interaction depth was assigned. With perfect energy and position resolution, this algorithm identifies the correct crystal unless backscatter occurs (the energy deposit topology is identical to a forward scatter event), or the gamma interacts in one module and then scatters into another module, or the gamma escapes the module before depositing at least 200 keV.

To determine if a multiple interaction event occurred, the same thresholds were implemented at each N/S ratio that were previously used in the *Compton weighted* algorithm. Figure 8 shows that when the fwhm of the position resolution was greater than 3 mm fwhm, the MIF did not decrease. However, with smaller resolutions, particularly less than 1 mm, the MIF decreased to as low as 7% with zero electronic noise and 15% with a N/S ratio of 0.14.

With perfect energy resolution and a position resolution as poor as 15 mm fwhm, we observed a considerable increase in the activity in small ROIs as compared to the results from the *maximum signal* algorithm without thresholding (Figure 9). We also examined ROIs at numerous N/S ratios for position resolutions of 0, 2, and 5 mm fwhm. As expected, we observed a decrease in the activity in small ROIs as the position and energy resolution increased.

7. Conclusions

We investigated algorithms to identify and correct for detector Compton scatter and thereby improve the accuracy of the reconstructed image. Algorithms that reject multiple interaction events decrease the MIF, but they prohibitively degrade the detection efficiency. The *maximum signal* algorithm obtained a MIF of approximately 25%, virtually independent of noise, for all detectors with a reasonable N/S ratio. This misidentification is due to forward Compton scatters that result in the majority of the 511 keV energy deposit in a crystal other than the one of first interaction. By identifying and attempting to correctly position these forward scatter events, the *Compton weighted* algorithm can reduce the MIF to 15%, limited by backscatter events that mimic forward scatters. This low fraction can be easily achieved with detectors with energy resolution limited by counting statistics (energy resolution <100% fwhm at 511 keV is required), but is difficult to achieve with detectors with energy resolution limited by electronic noise (≤25 keV fwhm noise is required). Finally, detectors with the ability to measure the position of interaction can reduce the MIF to 7%, but must be very accurate (<3 mm fwhm) to have any affect.

Acknowledgments

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References

[1] Lecomte R, Cadorette J, Richard P, et al. Design and engineering aspects of a high resolution positron tomograph for small animal imaging. *IEEE Trans. Nucl. Sci.* **NS–41:** pp. 1446–1452, 1994.

[2] Moses WW, Derenzo SE, Nutt R, et al. Performance of a PET detector module utilizing an array of silicon photodiodes to identify the crystal of interaction. *IEEE Trans. Nucl. Sci.* **NS-40:** pp. 1036–1040, 1993.

[3] Cherry SR, Shao Y, Tornai MP, et al. Collection of scintillation light from small BGO crystals. *IEEE Trans. Nucl. Sci.* **NS-42:** pp. 1058–1063, 1995.

[4] Cho ZH and Juh SC. Resolution and sensitivity improvement in positron emission tomography by the first interaction point determination. Proceedings of The IEEE 1991 Nuclear Science Symposium and Medical Imaging Conference, pp. 1623–1627, (Edited by G. Baldwin), Santa Fe, NM, 1991.

[5] Moses WW and Derenzo SE. Design studies for a PET detector module using a PIN photodiode to measure depth of interaction. *IEEE Trans. Nucl. Sci.* **NS–41:** pp. 1441–1445, 1994.

[6] Moisan C, Rogers JG, Buckley KR, et al. Design studies of a depth encoding large aperture PET camera. *IEEE Trans. Nucl. Sci.* **NS-42:** pp. 1041–1050, 1995.

[7] Moses WW, Derenzo SE, Melcher CL, et al. A room temperature LSO / PIN photodiode PET detector module that measures depth of interaction. *IEEE Trans. Nucl. Sci.* **NS-42:** pp. 1085–1089, 1995.