A Practical Block Detector for a Depth Encoding PET Camera

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Abstract

The depth-of-interaction effect in block detectors degrades the image resolution in commercial PET cameras and impedes the natural evolution of smaller, less expensive cameras. A method for correcting the measured position of each detected gamma ray by measuring its depth-of-interaction was tested and found to recover 38% of the lost resolution in a table-top 50 cm diameter camera. To obtain the desired depth sensitivity, standard commercial detectors were modified by a simple and practical process, which is suitable for mass production of the detectors. The impact of the detector modifications on central image resolution and on the ability of the camera to correct for object scatter were also measured.

I. INTRODUCTION

The latest commercial PET cameras operate in the volume imaging mode, without interplane septa. Such cameras incorporate BGO block detectors arranged in a ring around a cylindrical field of view (FOV). The diameter of the ring is an important factor in the cost of the camera, because the number of detectors required is proportional to the diameter of the ring. The smaller the ring, the fewer detectors are required, and therefore the cost of building the camera is lower.

Commercial cameras use a detector ring diameter substantially larger than the FOV diameter. With present commercial detector technology, it is not possible to make the ring diameter much smaller because the image resolution at the edges of the FOV is already limited by the depth-of-interaction (DOI) effect [1]. Gamma ray positions are miscoded by amounts which, on average, increase with the angle that the gamma ray line makes with the long axis of the long narrow crystals which make up the block. As the diameter of the ring is made smaller, gamma rays from the edges of the FOV make larger angles when they enter a block, which worsens the resolution. To avoid excessive loss of resolution, some form of correction for the DOI effect is required in small ring cameras.

A possible solution to the problem of DOI resolution loss was proposed recently by Rogers [2]. This method employs a modified gamma ray detector to evaluate the DOI of each gamma ray detected. When such a measure of DOI is incorporated into an appropriate algorithm [2], the loss of resolution at the edge of the FOV can be partially corrected, giving improved imaging from small-ring cameras. The work described in this article tests practical block detectors designed for implementing the method [2]. Because the new detectors were adapted from state-of-the-art PET detectors, with only minor modifications, the new blocks should cost about the same to manufacture as the conventional blocks, resulting in a significant saving in a small-ring camera due to its smaller number of blocks. The proposed method also offers the possibility of improving the performance of present day cameras in imaging large objects (e.g. the torso), again with little increase in the cost of the individual blocks.

The detectors tested were modified by hand from standard assembly-line detectors intended for the Siemens EXACT HR+ (hrplus) camera. Standard detectors have improved over the years from the original invention of Casey, Nutt, and Douglass [3, 4]. The main improvement has been an increase in the amount of usable scintillation light detected by the photomultiplier tubes (PMTs) which are coupled to the BGO block. The statistical noise in these photon signals is the crucial factor limiting the position resolution capability of the detectors. In the modified blocks, a portion of the available light was used for measuring the DOI and was, in the process, subtracted from that available for the normal transverse position measurement. As a result, the usual energy and position resolutions of the detector were somewhat degraded. This degradation, which showed up as a loss of resolution at the centre of the FOV, is an essential trade-off for an improvement in off-centre resolution by this method. To measure the amount of lost resolution was an essential goal of this work.

The hrplus block detector is shown schematically in Fig. 1. The BGO block is segmented into 64 small crystals which are optically separated from each other by narrow saw cuts filled with opaque material. In the unmodified blocks, the filling material is a white reflector, designed to direct as much of the scintillation light as possible to the back face where the optical photons are detected by an array of 4 PMTs. In the modified blocks, a small portion of the white reflector was replaced by inserting black modeling clay between the side walls of each small crystal, as indicated by the heavy black lines at the top end of each crystal in Fig. 1. The addition of the black absorbing material introduces a depth dependence to the number of
photons reaching the PMTs. The black material absorbs more photons from shallow penetrating gamma rays than from deep penetrating gamma rays, so that the number of detected photons was less for shallow penetrating events than for deep ones. The actual DOI was evaluated by analyzing the total pulse height produced by each gamma ray.

In such modified detectors, the loss of photons on the side walls encodes the DOI, but also reduces the performance of the detector in accurately measuring the transverse position, which remains its most important function. The accuracy of measuring the transverse position determines the image resolution throughout the FOV for cameras with large ring diameters. As the ratio of ring diameter to (fixed) FOV diameter shrinks, DOI errors degrade the resolution at the edges of the FOV, but only by a portion of the overall FOV resolution, which is still largely determined by the conventional transverse position measurement. Adding a correction to remove the depth effect would be pointless if the block modifications caused a large degradation of the transverse resolution, however this was fortunately found not to be the case.

II. EXPERIMENTAL METHOD

The experimental methods were aimed at accomplishing the following objectives:

1) To develop a practical technique for modifying the hprlus block detectors for depth correction,

2) to measure the performance of the modified hprlus detectors under conditions that duplicate the function-

ing of a small-ring PET camera, and,

3) to compare the performance of the modified camera with that of the unmodified camera to see if, or to what extent, the depth correction results in an overall improvement of image resolution.

To experiment with depth correction in a complete camera would require more than 100 detectors. Instead, we tested only two blocks at a time, moving them from place to place on a gantry designed to simulate a small-ring camera. A phantom consisting of a point positron emitter embedded in a Lucite cylinder was used to simulate the gamma ray scatter which would be present in a realistic scanning situation. The ability to reject scatter with an accurate energy threshold and to perform a scatter correction, such as that proposed by Lercher and Wienhard [5], is an important feature which must be maintained with the modified blocks.

Identical resolution measurements were made before and after modifying the detectors, by mounting them on a gantry table, and operating them in coincidence mode. The ring diameter for mounting the detectors was chosen to be 50 cm, one of the “future 3D PET systems” recently studied by Dahlbom et al. [6]. The 20 cm diameter Lucite cylinder was positioned at the centre of the table, so that a moving detector could be rotated about the cylinder’s axis. List-mode data was acquired [7] from a point source embedded at the centre of the cylinder, and also for the same point source embedded 75 mm off-axis in the same cylinder, as shown in Fig. 2. Four-dimensional (4D) pro-

COINCIDENCE-EVENT CORRECTION

Fig. 2. A plan view of the coincidence BGO detectors and scattering phantom, which contains an embedded point source at 75 mm from centre.
jections, normalized counts as a function of two lengths and two angles [8], were acquired in a technique similar to that used in [5]. Measuring the radial width of a point source peak in the projections was accomplished simply by rotating only one detector.

To assess the essential effects of uncorrected DOI broadening in the unmodified hrplus detectors, the projected width of the central point source (Rs=0) was compared with the width of the same source measured off-centre (Rs=75 mm). Then the blocks were modified and the same measurements repeated. The success of the correction technique was finally assessed by measuring the degree to which the resolution at Rs=75 mm could be restored to be the same as the central resolution measured before modification.

Calibration data, acquired beforehand, were used to correct the 4D projection arrays for transverse distortion, energy thresholding, crystal-to-crystal efficiency, and finally, depth distortion.

A. Block Modification Technique

The hrplus blocks were modified in two steps. First a shallow fill, 2.5 ± 0.5 mm deep, was done, and the depth sensitivity [10] measured using the fanbeam technique described in the next section. Next, a 5 mm deep filling was attempted. Because the outer saw cuts extend the full 30 mm depth (see Fig. 1), the outer rows of crystals were vulnerable to separating from the central 6 × 6 crystals of the block. The first attempt to push the black clay 5 mm deep into the saw cuts damaged the outer rows of crystals, which broke loose from the optical glue holding them to the faces of the PMTs. This damage degraded the light collection from the outer rows, but did not affect the functioning of the inner 6 × 6 crystals.

Successful filling of the second hrplus block was accomplished by cutting the metal can away from the front 8 mm of the block. Prior to filling the central part of the block, modeling clay was pushed into the saw cuts from the sides of the block, which avoided fracturing the outer rows.

B. Transverse Position Calibration

2D position calibration maps were measured and used to remove transverse position distortion. Fig. 3 (top) shows the position map of an unmodified hrplus block, determined with 511 keV gamma rays. A flood source was formed by placing a point source at a large distance from the detectors. To minimize possible counting rate effects, the pulse current from the PMTs was adjusted to be identical in the calibration runs as in the final projection measurements, i.e. the equivalent of 7000/6 511 keV gamma rays detected in each block. New maps were measured each time the blocks were modified or when the PMT voltages were changed to adjust the gains. Event-by-event data from the flood measurement was read by a histogramming program and formed into a 128 × 128 2D array of counts vs X_m and Y_m, where X_m and Y_m were the horizontal and vertical transverse positions calculated from the ratios of PMT pulse heights [7]. This 2D array showed peaks corresponding to each

Fig. 3. Typical crystal position maps (solid lines) overlaying 2D flood calibration data, used to determine maps. Top=unmodified hrplus, map and data from 66Ge. Middle=modified hrplus, map and data from 60Co. Bottom=modified hrplus, map from 60Co and data from 66Ge. of the to 64 crystals in the block. The position of each peak was located by a local-maximum search routine. The X_m and Y_m coordinates of the intersection points of the cuts segmenting the block were calculated by averaging the X_m and Y_m coordinates of the maxima in
the 4 crystals surrounding each intersection. The 128×128 coordinate space of the 2D array was divided into 64 regions of interest (ROI) by lines connecting the intersection points so determined.

Fig. 3 shows typical 2D calibration arrays with the ROI dividing lines determined by the above process. The validity of the maps was verified by noting that they followed the valleys between the peaks. When 511 keV gamma rays were used to calibrate the modified block (bottom panel), the peaks are not well enough resolved to use this data for determining the map, creating the need for higher energy gamma rays [9]. A Co$^{60}$ flood ($1.2 - 1.3$ MeV) gamma ray source was used to calibrate the modified blocks.

The transverse position response of the hrlpus block changes with DOI, an effect noted with earlier CTI blocks [7]. To determine if this effect would compromise the DOI correction, 2D position calibration data were acquired with a sideward going fanbeam (described in Section C) at a range of depths and compared with the map determined with the flood source described above. At depths up to 20 mm from the front face, the fanbeam peaks were well centred on the map boundaries, but at deeper depths the peaks representing some of the crystals were displaced so that they crossed map boundaries, resulting in significant crystal address miscoding. This miscoding at depth is believed to be a feature of all such partially-saw-cut block detectors, however it doesn’t cause much resolution loss because few 511 keV gamma rays penetrate beyond 20 mm, due to attenuation in the BGO [7].

C. Depth Sensitivity Calibration

A fanbeam was formed with the plane of its fan parallel to the table-top. Each detector was positioned with front face parallel to the plane of the fan, and then elevated step-by-step through the fanbeam, using a set of jacks and levels. The elevation of the detector was set with an accuracy of about 0.2 mm and the face was aligned parallel to the plane of the fan with an accuracy of about 1 mm.

The Z = 0 origin of the depth scale was determined by elevating the detector’s surface through the fanbeam, recording the fall-off of the counting rate at each step as the block surface moved out of the beam. The derivative of the counting rate with respect to depth was a measure of the beam width, a profile of 0.7 mm full-width-half-maximum (FWHM) and 1.8 mm full-width-tenth-maximum.

Fig. 4 shows typical pulse-height spectra in one quadrant of the second hrlpus block, at a fanbeam depth 12 mm from the front face. Gaussian fits to the photopeaks produced the peak positions and FWHM widths listed above each spectrum plot. Fig. 5 shows the variation of the fitted peak positions as a function of the depth of the fanbeam in the same quadrant. Three curves are shown for each crystal: before modification (top curves), after the 2.5 mm fill (middle curves), and after the final 5 mm fill (bottom curves).

The depth resolution was computed for each crystal as the product of the slope of its measured response function (Fig. 5) times its fitted photopeak FWHM. Fig. 6 shows the distribution of measured depth resolutions among the
64 crystals measured with the fanbeam at $Z = 12$ mm depth. The final (i.e. 5 mm) fill improved the average resolution at this depth from 10.5 to 8.3 mm FWHM. At a single depth, such as that shown, depth resolution varied from crystal to crystal according to photon statistics, being worst in the corner crystals, where the light collection was the poorest. Photon statistics also dominated the variation of depth resolution with depth in each crystal; depth resolution was best at the front face, where the absolute statistical uncertainty of the photopake pulse-height was the smallest.

### E. Crystal Efficiency, Normalization, and Threshold

The counts in each 4D projection bin were normalized to account for differences in the detection efficiencies of the two crystals defining the LOR. Individual crystal efficiencies were measured in separate data acquisition runs, using a $^{68}$Ge point source located at a large enough distance from the detector to flood it with a uniform flux of 511 keV gamma rays. To minimize scattering effects, an identical opposite trigger counter was operated in coincidence with the detector being calibrated, but at a smaller distance to the source so that only the uniform-efficiency central region of the trigger counter was effectively in coincidence with the detector being calibrated. The number of counts in the pulse-height spectrum of each crystal above a threshold channel was integrated and scaled to represent the crystal’s fraction of the flood counts detected in the entire block. In the h prolus blocks the threshold channel numbers were chosen as a fraction 200/511 or 350/511 of the flood spectrum’s photopake channel number. In the modified blocks, threshold channels were similarly chosen using depth-separated pulse-height spectra, measured with a fanbeam located at $Z = 2$ mm from the front face, as described in Section C above.

Detection efficiency also depends on the angle that the LOR makes with the normal to the block face. For projections acquired with the central source ($R_s=0$), this angle was nearly zero, while for projections acquired with the source at $R_s=75$ mm, the angle to the normal averaged about $16^\circ$. To account for efficiency variation with this angle, efficiency calibrations were done separately at $0^\circ$ and $16^\circ$ and were used to analyze the $R_s=0$ and $R_s=75$ mm projection data, respectively.

The flood source normalizations, described above, were applied event-by-event in forming the normalized projections. A table of threshold pulse-heights, along with the relative crystal efficiencies, was referenced for each detected gamma ray. If both gamma rays of an event were found to be above their respective thresholds, a normalized increment for the event was calculated as the reciprocal of the product of the two tabulated crystal efficiencies. This normalized increment was added to the projection to record the event. This procedure accounted for all crystal efficiency variations between the LOR values measured at a single angular position setting of the movable detector.

Other normalization effects, including solid-angle variation with the distance between the detectors, variation in run duration, and computer dead-time losses, were calculated and accounted for by a separate relative normal-

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**Fig. 6.** The distribution of measured FWHM depth resolution among the 64 crystals of the modified h prolus blocks: (A) after the 2.5 mm fill and (B) after the final 5 mm fill.
ization factor which multiplied the normalized projection values acquired at each angular setting of the movable detector. These relative normalization factors, one for each data run, were verified as correct by noting that the projection values varied continuously from one angular position to the next.

F. Depth Correction Technique

Fig. 2 shows the "measured" Z coordinates and calculated ΔX coordinates for a typical off-centre LOR detected in the two BGO detectors. As described in [2], the correction technique consisted of adding ΔX = Ztanθ to each gamma ray's measured horizontal (=radial) position, where Z is the most probable DOI for the event and θ is the gamma's angle of incidence at the face of the block. The angle θ was taken to be the central angle between the two blocks operated in coincidence, a simplifying approximation introducing negligible error for these small values of θ. The "measured" Z value for each gamma ray was extracted from a table formed as in [2], by interpolating the measured photopeak pulse-heights linearly between two calibration depths, 5 and 15 mm. The depth table contained interpolated depth values for all ADC pulse-heights which were above the threshold pulse-heights. For each gamma ray detected, its most probable Z coordinate was extracted from the table by using its measured pulse-height as an index to reference the table. The sum of two ΔX corrections, one for each block, was added to the sum of the two horizontal crystal addresses to determine the corrected Lr value. The normalized increment of the event was calculated from the uncorrected LORs and a normalized histogram of corrected Lr values was increment in memory.

Consideration was also given to implementing the joint-probability depth correction of Moses, Heusman, and Derenzo [11]. The method, however, produced negligible improvement in one test case, and therefore was not implemented in forming the projections presented here. This confirms the results of [11], which showed that the inclusion of joint probability had negligible effect if the depth resolution was better than 10 mm FWHM.

G. Design and Testing of an Automatic Depth Calibration Procedure

An automatic depth calibration procedure was developed which uses only 68Ge flood source data, acquired without moving the blocks from their normal positions on the gantry. The procedure tracks any drifts in the PMT gains, which might occur due to gradual PMT aging or even daily gantry temperature changes. Because the depth resolution would be spoiled by such drifts if not detected, calibrations must be done frequently, which is impractical with a fan-beam.

To simulate such drifts, flood energy spectra were acquired from a modified hrplus block with 1600 V and again with 1700 V applied to the PMTs. Fig. 7 shows the flood pulse-height spectra in crystals in one quadrant of the block. The vertical lines mark the positions of the most probable pulse-height in each spectrum, as determined by an automatic peak fitting procedure. The positions

Fig. 7. 68Ge coincidence flood spectra in one quadrant of the modified hrplus block, at PMT voltages 1600 V and 1700 V. Vertical lines indicate the positions of the maxima, the higher pulse-height for the 1700 V case.

Fig. 8. Comparison of the measured 1700 V depth response (solid lines) vs that predicted by scaling up the 1600V one (dashed lines) in the same quadrant of the modified hrplus block.
of these peaks shift with varying PMT gains by amounts which vary from crystal to crystal, depending on the 4 independent PMT gain changes and modulated by the light sharing among the PMTs. Since light sharing doesn't depend on PMT gains, it follows that the relative shift in the peaks of the flood spectra is the same as that for peaks of the fanbeam spectra. Hence measuring the fractional shift in the peaks of the flood spectra provided scaling factors for shifting the fanbeam peaks.

To validate this new method of depth calibration, the fanbeam peak positions at 1600 V were scaled up by the ratio of the maximum pulse-heights determined from the flood calibration shown in Fig. 7 and are compared to measured 1700 V fanbeam depth responses in Fig. 8. The disagreements between the flood and fanbeam curves in Fig. 8 were judged to be small enough to be safely ignored, considering that the gain shifts produced by the test 100 V change are much larger than those expected in normal camera operation. The remaining discrepancies appear to be due to statistics and could therefore have been reduced by smoothing the spectra prior to locating the peaks. An obvious example of such a statistical error is in the third down and third from the left panel in Fig. 7, in which the 1700 V peak-search failed due to a visible statistical anomaly.

Fig. 9 shows the measured projections of point sources with the unmodified (a-d) and modified (e-j) h-ppus block detectors. The top panel was acquired with a "low" energy threshold of 200 keV and the bottom panel with a "high" threshold of 350 keV. Only the non-overlapping central seven points of ea detector position are included in the projections; LOR values measured with the edge rows of crystals were omitted because of the more reliable efficiency calibration of the interior crystals. In the central projections, near Lz = 0, the Lz samples are plotted at 1/2 crystal intervals, 2.25 mm. Off-centre, the Lz samples are plotted at intervals foreshortened by the cosine of the angle between the block normals, i.e. at 2.25 × cos(16°) = 2.16 mm. The sum of two fitted Gaussians is shown with each projection by a solid line, which passes through the fitted points. Gaussians were fitted separately to five points in the narrow peaks, which measures point source spatial resolutions, and to the underlying backgrounds, which measures the scatter contamination from the 20 cm Lucite cylinder. The systematic uncertainty in the fitted FWHM values, due to the departure of the measured projections from true Gaussian shape, is estimated to be ±0.1 mm. The fitted FWHM values are 0.1 mm better in the higher-threshold projections than in their lower thres
terparts. The following analysis refers mainly to the higher threshold projections.

Curves (b) and (d), measured with the unmodified blocks, show that the point source FWHM resolution was 4.0 mm at FOV centre and 5.3 mm off-centre. This 33% degradation in off-centre resolution is due to the DOI effect which the modified detectors and new method [2] should correct. The corrected projection (j), shown on the right, is narrower than the uncorrected projection (d). Furthermore, with the modified blocks, the resolution was more nearly uniform across a 15 cm wide FOV; it varied from 4.4 to 4.8 mm FWHM instead of 4.0 to 5.3 mm with the unmodified blocks. As a percentage of the resolution loss, the block modification and correction method recovered 0.5/1.3=38% of the lost resolution.

The value indicated as “Contrast” in Fig. 9 was defined to be the ratio of the unscattered to scattered peak projection values, as determined by the Gaussian fits. This measure was adopted to quantify the capability of a PET camera, using such blocks, to separate the image of a point-like object from the undesired object-scattered background. The corrected projections have degraded contrast at each threshold level. The loss of contrast is small (9–12%) at the lower threshold and somewhat greater (13–19%) at the higher threshold.

IV. DISCUSSION AND CONCLUSIONS

Using the method of Rogers [2], 38% of the depth-of-interaction (DOI) degradation of image resolution was removed, to make the resolution more nearly uniform across the useful FOV of a typical small-ring camera. The detector modification and correction are both practical and cost effective in that they can be implemented in conventional PET cameras with little per-unit material expense. To routinely manufacture the new blocks on an assembly line should require only modest retooling of the process normally used to manufacture the detectors. Since the main cost of the detector is fabricating the uncut BGO block, the extra process step would only increase the fabrication cost by a small percentage.

The extra acquisition hardware and software required to process the DOI (i.e. Z) as a third parameter characterizing each detected gamma would be modest. In existing CTI cameras, energy analysis is done in real time by referring a memory containing calibration data for each detector [12]; for each detected gamma ray, the memory produces two digital bits which identify the pulse-height ADC value as lying in one of two programmable energy windows. DOI coding would require a few more such stored windows for energy analysis. Fig. 6 shows that the best DOI resolution obtained in any crystal is about 4 mm FWHM. An additional 3 bits of memory word-size would provide a digital depth resolution of \(30/2^3 = 3.75\) mm, which would be more than adequate to encode depth to within one resolution element, for any crystal. The expanded digital record describing each gamma-gamma coincidence would pass as usual from the blocks’ calibration memories to a programmable real time processor [13]. With minor reprogramming, this processor would compute a corrected LOR for each event. Incrementing the corrected projections would proceed as usual in a sinogram memory.

A new technique was designed and was verified to be capable of providing the required depth calibration data on a complete camera gantry. A table of photoprobe pulse-height vs fanbeam depth would be measured at the factory prior to mounting the block detectors on the gantry. The new technique uses this original characterization data, in conjunction with the usual flood calibration data, to adjust the depth data for variations in PMT gains. The required assumption to make the new calibration method work was that the light sharing among the four PMT’s was determined once and for all by the saw cuts and PMT mounting, and does not change once the detectors are mounted on the gantry. This would require dismounting blocks if, for example, the PMT coupling joints degrade with age.

The corrected projections have somewhat smaller scatter contrast values than their uncorrected counterparts, presumably due to the lower threshold for deeper penetrating events. However, the 9–19% change is much smaller than the necessary increase in scatter fraction inherent in any small ring camera [6], even without depth correction. The essential characteristic of the usual scatter background, that it is Gaussian in shape and much broader than the unscattered peak, is preserved with the modified detectors and depth correction method. It is therefore possible to correct for scatter [5], to the same accuracy as in any small-ring camera. The adoption of the “scatter contrast value” as a measure of overall tomograph performance in rejecting scatter is motivated by the work of Lercher and Wienhard [5], who argue very convincingly that the older line source scatter distributions are inappropriate as input for 3-D volume scatter correction. The crucial feature of point source scatter distributions that make 3D scatter correction practical are the Gaussian shape of the scatter profile and the weak dependence of the scatter profiles on position-in or size-of the scattering medium. A detailed study of the effects of depth encoding modifications on PET systems’ scatter rejection has also been studied by our group [14]. We are optimistic that scatter corrections, such as that of Lercher and Wienhard, will improve with time at a rate fast enough to compensate for the the increasing scatter fraction as ring diameters are made smaller.

The 38% improvement in edge resolution is at the cost of a 10% loss in resolution at the centre of the FOV. A perfect correction would be one that corrects 100% of the resolution loss and produces no loss of resolution at the centre. It is reasonable to ask what improvements in the detectors would be required to better approximate a perfect correction, using the same or similar correction method.

Making a more accurate depth-dependent correction would require measuring the depth with better depth resolution, which in our approach requires either increasing the slope of the depth sensitivity curves (Fig. 5) or decreasing the energy resolution width (Fig. 4). These factors were approximately optimized for the hirius detectors. Without increasing the amount of light output from the crystal block or photodetectors’ quantum efficiency, increasing the slope could only be accomplished at the expense of decreasing the number of detected photons, which would worsen the energy resolution and thereby cancel the advantage of
increased slope.

A promising method of getting more light out of the crystals is to replace the BGO by a brighter scintillator, such as LSO [15]. The rapid decrease in the bulk price of lutetium oxide [16], and the recent production of large, clear crystals of LSO [17], make such a DOI-correcting LSO block detector a real possibility for the next generation PET cameras.

Due to limited time and budget, this study was not extended to large distances from the centre of the FOV or to large scattering phantoms. Since our objective is to eventually utilize the entire ring diameter for imaging, additional measurements are needed in the future to investigate the performance of detectors and DOI correction algorithm for sources at large radii. For torso imaging, DOI correction in larger scattering phantoms should also be assessed.

V. REFERENCES


