CONF-951073--23

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

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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 ($R_s=0$) was compared with the width of the same source measured off-centre ($R_s=75$ 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 $R_s=75$ 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/s 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 ^{68}Ge . Middle=modified hrplus, map and data from ^{60}Co . Bottom=modified hrplus, map from ^{60}Co and data from ^{68}Ge .

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

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Fig. 6. The distribution of measured FWHM depth resolution among the 64 crystals of the modified hrplus blocks: (A) after the 2.5 mm fill and (B) after the final 5 mm fill.

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 photopeak pulse-height was the smallest.

D. Projections and Lines-of-Response

Projections were formed by binning events into arrays, indexed by lines-of-response (LORs). Fig. 2 shows a horizontal section of the apparatus with a typical event represented by its LOR. Without DOI correction, each such LOR was determined by the measured transverse positions of the two gamma rays detected by the two detectors operated in coincidence. For each event, previously acquired 2D maps were referenced by the X_m , Y_m words from the list-mode data file to fetch the column and row addresses, 0-7, of each gamma ray. Each end of the LOR was defined horizontally by the column address and vertically by the row address of a crystal. From pairs of horizontal and vertical addresses, 4 LOR descriptors were formed to record each event. The sum of the two horizontal indices is called L_x , the radial position of the LOR. The difference of the two horizontal indices is called ϕ , the azimuthal angle of the LOR. The sum of the two vertical indices is called slice, the axial position of the LOR. And finally, the difference of the two vertical indices is called θ , the polar angle of the

LOR [8].

Since, in this geometry, DOI degrades only the radial component of resolution, not the slice component, we analyzed only a one-dimensional section of the 4D projection, namely counts vs L_x for fixed values of slice, θ , and ϕ . Following [5], we integrated over a small range, i.e. 1.5° , in the angles about the direction perpendicular to L_x , which amounted to three bins in the units of the differences of crystal addresses. Three bins in slice were also summed over, to minimize the partial volume effect.

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 hrplus blocks the threshold channel numbers were chosen as a fraction 200/511 or 350/511 of the flood spectrum's photopeak 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° . To account for efficiency variation with this angle, efficiency calibrations were done separately at 0° and 16° 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-

Fig. 9. Radial point-source projections measured with energy threshold 200 keV (upper panel) and 350 keV (lower panel). Source, detector configurations were, from left to right, (a-b) central in FOV, unmodified blocks; (c-d) 75 mm off-centre radially, unmodified; (e-f) off-centre, uncorrected; (g-h) central, uncorrected; and (i-j) off-centre, corrected by the new method. FWHM = the width of the fitted Gaussian (solid curve). Contrast = the ratio of the unscattered to scattered peak amplitudes.

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.

III. RESULTS

Fig. 9 shows the measured projections of point sources with the unmodified (a-d) and modified (e-j) hrplus 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 each 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 $L_x = 0$, the L_x samples are plotted at 1/2 crystal intervals, 2.25 mm. Off-centre, the L_x samples are plotted at intervals foreshortened by the cosine of the angle between the block normals, i.e. at $2.25 \times \cos(16^\circ) = 2.16$ 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 threshold coun-

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.

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