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A Lower-Cost High-Resolution LYSO Detector Development for Positron Emission Mammography (PEM)

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Abstract

In photomultiplier-quadrant-sharing (PQS) geometry for positron emission tomography applications, each PMT is shared by four blocks and each detector block is optically coupled to four round PMTs. Although this design reduces the cost of high-resolution PET systems, when the camera consists of detector panels that are made up of square blocks, half of the PMT's sensitive window remains unused at the detector panel edge. Our goal was to develop a LYSO detector panel which minimizes the unused portion of the PMTs for a low-cost, high-resolution, and high-sensitivity positron emission mammography (PEM) camera. We modified the PQS design by using elongated blocks at panel edges and square blocks in the inner area. For elongated blocks, symmetric and asymmetrical reflector patterns were developed and PQS and PMT-half-sharing (PHS) arrangements were implemented in order to obtain a suitable decoding. The packing fraction was 96.3% for asymmetric block and 95.5% for symmetric block. Both of the blocks have excellent decoding capability with all crystals clearly identified, 156 for asymmetric and 144 for symmetric and peak-to-valley ratio of 3.0 and 2.3 respectively. The average energy resolution was 14.2% for the asymmetric block and 13.1% for the symmetric block. Using a modified PQS geometry and asymmetric block design, we reduced the unused PMT region at detector panel edges, thereby increased the field-of-view and the overall detection sensitivity and minimized the undetected breast region near the chest wall. This detector design and using regular round PMT allowed building a lower-cost, high-resolution and high-sensitivity PEM camera.

I. Introduction

In spite of the continuous radiographic advances in oncology, the diagnosis of breast cancer continues being uncertain. Of the annual 600 000 cases referred for biopsy by mammograms, 400 000 are unnecessary and increase the costs of the mammograms by \$2 billion annually [1]. To detect breast cancer in dense breasts is still difficult in x-ray, whether the density is a result of fibrocystic diseases or young age. Dynamic Enhanced MRI imaging has high sensitivity (90%) for lesions larger than 5 mm, but the average specificity is 40–60% [2], [3]. Accurate early cancer detection and diagnosis is essential to have the best survival and a good outcome for breast conservation, but this ideal diagnostic condition is still to be achieved in very small breast tumors (2 or 3 mm) and small metastases [4]. Positron emission mammography (PEM) has the potential to improve the accuracy of breast cancer detection [5], [31], [6], [7]. PET imaging is a highly effective imaging method for detecting, diagnosing, and managing a variety of breast diseases due to the capability of PET to discriminate between normal and abnormal tissue activity with very high sensitivity and specificity [8], [9], [32], [10]. This has encouraged our group to develop a breast PET camera that performs in a manner similar to or better than the current commercial systems but at a lower-cost. Table I shows some of the detector characterization of several PEM systems, (reported by the authors).

In recent years, our group has successfully developed several low cost and high-resolution PET cameras based on photomultiplier-quadrant-sharing (PQS) technology, including the MDAPET [19], the small animal PET (RRPET) [20] and the transformable PET (HOTPET) [21]. An important advantage of PQS technique is the near 1:1 ratio of the number of blocks to photomultiplier tubes (PMT) used in a system, as is shown in Fig. 1. The position of a gamma-hit is calculated using Anger logic with the signals from four photomultipliers, but each PMT is optically coupled to the detector block with only one quadrant of its photocathode. This technique represents a saving of up to 75% in the number of PMTs used, because the commercial PET cameras use four PMTs to decode just one block (Fig. 1) [22]. However when a PQS detector panel is made up exclusively of conventional square blocks, a section of the PMTs sensitive window (half of PMT) at the edge of the detector module is not used, thereby creating an undetected region, (shaded section in Fig. 2). For this study we developed two types of LYSO detector blocks to be used in a PEM detector panels: elongated blocks at the edge of the detector panel and square blocks in the inner area. This detector panel design, introduced by Wong, *et al.* in 1999 [23] and implemented in the HOTPET detector modules minimizes the unused section of the PMTs, while maintaining the low cost, high resolution, and high sensitivity of positron emission mammography camera. By implementing this design to the PEM detector panel it would be possible to expand substantially the axial field-of-view to improve detection sensitivity and image quality near the breast's pectoral region without losing position resolution.

II. Materials

Individual cerium-doped lutetium yttrium orthosilicate (LYSO) crystals from Crystal Photonics, Inc. (Sanford, Florida, USA), circular PMT with nominal dimension of 18.85 mm in diameter (XP1912) from Photonis imaging sensors (Beauregard, Bride Cedex, France) and reflector patterns made of 3 M Vikuiti™ ESR (enhanced spectral reflector) film placed on the crystal interfaces were used for the PEM detector development. The ESR film is a multilayered polymer film with high reflectance of 98% across the visible light spectrum and a thickness of 0.06 mm [24]. For the crystal finishing, 4 μm (roughness) on five crystal surfaces and polished smoothly (less than 1 μm) on one end was selected. This specific surface finish, together with the reflective patterns placed between adjacent crystals optimizes the light sharing in the detectors for PQS-PET system, [25].

In the first stage of the detector development and, to test the decoding capability of the light partition patterns, the blocks were assembled using optical coupling grease, RX-688 from Rexon Components, Inc (Beachwood, Ohio, USA), in order to be able to easily disassemble the blocks to refine the patterns design. But for the PEM production blocks, DYMAX Light Weld UV curing glass adhesive, from Dymax Corporation, USA (Torrington, CT, USA), was used. There is not any significant difference between the performances of the blocks using these two types of optical materials.

III. Methods

A. Detector-Blocks Design

For the detector design the scintillator material was extended to the PMTs unused sensitive window region by using elongated blocks at detector panel edges and square blocks in the inner area (Fig. 3). The unused PMTs sensitive window has a dimension of 8.43 mm calculated by subtracting the PMT wall dimension (1 mm) from the PMT area that is not cover by regular square detector blocks (9.43 mm = 1/2 PMTs diameter) (see Fig. 2). To assemble the elongate blocks, LYSO crystals with dimension of $1.93 \times 1.54 \times 10.0 \text{ mm}^3$ and light reflective patterns precisely placed between the adjacent crystals were used. These blocks were designed with 13 extended multi-crystal slices, with 12 crystals per slice. Each slice has a dimension of $1.93 \times 19.36 \times 10.0 \text{ mm}^3$. The slices and the reflector patterns were glued together into asymmetric blocks with dimension of $26.05 \times 19.36 \times 10.0 \text{ mm}^3 (\pm 1 \text{ mm})$ and 13×12 crystal array. This design creates an asymmetric block with respect to the center of the four PMTs. Therefore, to efficiently distribute the light in these blocks, symmetrical light partitions were placed between adjacent crystals of the multi-crystal-slices; whereas, between each adjacent multi-crystal-slice, the light partitions employed are asymmetrical. A multi-crystal slice is conformed of several individual crystals glued together using the slab-sandwich-slice detector production methodology [26], where only large slabs of crystals, and not individual pixels are processed. Fig. 4 shows an example of a multi-crystal slice used in our block detectors.

To assemble the square blocks, LYSO crystals with dimension of $1.54 \times 1.54 \times 10.00 \text{ mm}^3$ and light reflective patterns precisely placed between the adjacent crystals were used. These blocks were designed with 12 multi-crystal slices of 12 crystals per slice. Each slice has a dimension of $1.54 \times 19.36 \times 10.00 \text{ mm}^3$. The slices and reflector patterns were glued together into symmetric blocks with dimension of $19.36 \times 19.36 \times 10.00 \text{ mm}^3 (\pm 1 \text{ mm})$ and 12×12 crystal array. These blocks are symmetrically positioning on the center of the four PMTs. Hence, to efficiently distribute the light, symmetrical light partition patterns were employed between adjacent crystals of the multi-crystal-slices and between each adjacent multi-crystal-slice. Fig. 5 shows an example of asymmetric and symmetric light partitions.

B. Detector Panel Design

For the dedicated PEM camera, two detector panels with dimensions of $20 \times 12 \times 1 \text{ cm}^3$ (trans-axial, axial, and depth directions) were developed. Each panel has 6 detector-block-rows with 10 blocks each. Five of those rows are conformed by 50 symmetric blocks or 7 200 symmetric-crystal-detectors per panel. The 6th row is located in the edge of the panel, near the patient chest wall, and is conformed by 10 asymmetric blocks or 1 560 asymmetric-crystal-detectors. Each detector panel is optically coupled to 77 $\varnothing$ 19-mm PMTs. The gap between adjacent PMTs is 0.8 mm. Fig. 6 shows the geometries of the PEM detector panel design and the location of each type of block. In order to obtain a suitable decoding of the detectors, a conventional and a modified PQS coupling arrangement were employed for the asymmetric-elongated blocks, whereas for the square-symmetric blocks, the conventional PQS was employed. The modified PQS arrangement consists of a PMT half sharing (PHS) configuration (Fig. 7).

In Fig. 8, several possible data collecting modes of the PEM detector panel design are suggested, including a conventional X-ray mammography mode (the 2 modules are parallel and coaxial), a vertical mode (the 2 modules are parallel to the axillary region), and, a oblique mode (the 2 modules are in an oblique position with respect to the axillary region, covering the most difficult areas surrounding the breast pectoral region). The thickness of the panel shield case is proposed to be about 2 mm. Therefore, the distance between the crystal bank surface and the patient could be less than 2 mm when the camera is in a conventional X-ray mammography mode as is showed in Fig. 8. The distance from the edge of the crystal array to the external surface of the shield case could be less than 5 mm, because the distance from the edge of the LYSO blocks to the PMTs edge is less than 3 mm, (see Fig. 9).

C. Test and Data Processing

In order to test the crystal decoding capability and energy resolution of the detector production blocks presented in this study, each block were covered by mirror film over five of the external surfaces to improve light collection and optically coupled to $\varnothing$ 19-mm PMTs using optical coupling grease (Rexon 688). A film reflector was placed over the central gap between the four circular PMT's to enhance the light-collection efficiency for crystals in the central region of the blocks. The data were collected using Ga-68 source (511 keV) with our high yield pileup-event recovery (HYPER) electronics and data acquisition software [27], [28]. The high voltage bias was 1100 V.

The crystal-decoding maps were acquired with an energy threshold typically set to the Compton edge of the block-composite energy spectrum. From the crystal identifications a crystal look-up table of each block was created. Using the look-up table and list data, we extracted spectral information such as pulse height and energy resolution by fitting the individual crystal energy spectrum with Gaussian curves. From the decoding map we obtained profiles of each row and column of crystals (corner to corner). The profiles were fitted with Gaussian functions to obtain the heights and position of peaks and valleys. We use the Peak-to-valley ratio of the profiles to evaluate the decoding qualities of the detectors. The details of the block performance evaluation can also be found in [29].

IV. Results

The Asymmetric-elongated blocks have a high packing fraction of 96.3% and the square-symmetric block of 95.5% respectively. The effective dimensions of the PEM detector panels are the $19.7 \times 12.4 \times 1.0 \text{ cm}^3$ with a high packing fraction of 94.9%. In the elongated-asymmetric blocks, the scintillator material is extended by 6.7 mm to the PMT border (edge of the panel) with only 2.7 mm of distance between the border of the detector panel and the PMTs edge (see Fig. 3).

Fig. 10 shows the photography of the physical asymmetric and symmetric detector blocks and Fig. 11 shows the physical block coupled to the PMTs.

Fig. 12 shows the two-dimensional position-decoding maps of the 156 crystals in the extended-asymmetric block and of the 144 crystals in the square-symmetric block. Both of the blocks have excellent decoding capability with all crystals clearly identified, 156 for the asymmetric block and 144 for the symmetric block and peak-to-valley ratio of 3.0 and 2.3 respectively.

Examples of crystal profiles for a 12×13 asymmetric block are shown in Figs. 13 and 14. Fig. 13-left frame shows the profile of the last crystal row of the asymmetric block located at the external edge of the detector panel, (13th crystal row) and is decoded using PMT half sharing (PHS) configuration. The right frame of Fig. 13 shows the profile of the 6th crystal row with most of the crystals sitting in the middle of the four PMTs without any PMT coupling, (see

Fig. 3). Fig. 14-left frame shows the profile of the 1st crystal row of the asymmetric block located next to the symmetric block and is decoded using PQS configuration. The right frame of Fig. 14 shows the profile of the 5th crystal row (most of the crystals without any PMT coupling).

Fig. 15 shows the of crystal profiles of a symmetric block decoded using PQS configuration. The left frame shows the profile of the external crystal row (12th crystal row) and the right frame shows the profile of the central crystal row. The photo-peaks of all the crystals were normalized to the same standard pulse height and then by the counts of each crystal. The normalized pulse-heights for all the crystals were summed together as the normalized block-average energy spectra. Fig. 16 shows a comparison between the typical energy spectrum from the crystals located at the corner of the block, the crystals located at the block center and the normalized block-average energy spectra from asymmetric and symmetric blocks respectively. The average measured energy resolutions of the blocks were found to be 14.2% for the asymmetric (elongated) blocks (range between 11.0% and 24.46%) and 13.1% for the symmetric blocks (range between 10.4% and 19.7%).

V. Discussions

The asymmetric blocks design made it possible to increase the axial dimension of the PEM panels by 6.7 mm. Therefore the panel's effective area is extended by almost half of the PMT width, covering about 80% of the unused PMT sensitive window. This PEM panel design allows the scanning of breast pectoral region, breast surrounding tissues, and axillary's (underarm) areas. The area of our PEM detector panel is big enough for imaging the whole breast in most patients providing maximum visualization of breast anatomy and the signs of disease without subjecting the patient to unnecessary radiation. This design, not only increases the detection sensitivity of the system, but also allows to minimize the undetected breast region, near the chest wall. In addition, this design could have significant advantages in clinical applications, such as the early detection of cancer cells that have been spread to pectoral region (crossing the breast area to the surrounding tissues) and to the axillary's (underarm) lymph nodes.

In both of the decoding maps (Fig. 11) all the individual crystal detectors were clearly separated and also all of them were evenly positioned over the crystal-decoding maps with little pincushion distortions even for PHS asymmetric block that was positioned asymmetrically over four PMTs. The crystal profiles for the PQS-blocks (asymmetric and symmetric) show higher light-collection efficiency for the corner crystals because these crystals are coupled to the center of the photocathode.

Due to the light sharing in the PQS detector design, both of the tested blocks have a good light-collection efficiency and very good averaged energy resolutions, (14.2% and 13.1%), despite the fact that there was a large number of crystals in the central region of a block sitting down without any PMTs coupling (in the center gap between the 4 circular PMTs) and, that the asymmetric (elongated) block was sitting asymmetrically over the four PMTs.

The light-collection-efficiency could be higher in the asymmetric blocks than in the symmetric blocks, because the asymmetric-crystals have small light-partitions and bigger size. Therefore the crystal-optical-windows are bigger in the asymmetric blocks in order to reach the four PMTs.

Table II shows the performance comparison between the previous extended and square PQS detector blocks design for a HOTPET detector panel and the detector blocks from this study. In both design the detectors are using $\varnothing$ 19-mm PMTs with PQS and PHS configuration.

Comparing the results of this study with the ones obtained with the same panel design employed in the HOTPET detector panel; indicates an improvement over the previous detector blocks.

There may be some potential for slight degradation in the intrinsic spatial resolution due to the bigger size of the crystals used in the asymmetric blocks but in our PEM system, only one row of blocks out of six rows in each module are from the elongated type, which means only 16.7% of the total crystals. Therefore the resolution degradation arose from the 1.93-mm crystals should not be significant.

The PQS detector design allows building lower-cost PEM cameras, not only because the PQS technique, effectively, represents a saving of up to 75% in the number of PMTs used with respect to the commercial PET cameras, but also, because to build the detector array we use the slab-sandwich-slice production (SSS) methodology [30], that significantly reduces the detector production costs by itself. In the SSS cost effective methodology, only large slabs of crystals, and not individual pixels are processed, this advantage lowers the cutting and manufacturing costs reducing, significantly, the number of crystal surfaces to process in order to build the detector array.

VI. Conclusion

We developed two types of LYSO detector blocks, symmetric and asymmetric for a positron emission mammography camera. The detector blocks produced good light output and crystal-decoding performance. This cost effective design using regular round PMT can be used to build lower-cost, high-resolution and high-sensitivity PEM cameras.

With modified PQS geometry and using the asymmetric (elongated) block design, we can reclaim the unused PMT photocathode at detector panel edges, thereby increasing field-of-view and minimizing the undetected breast regions near the chest wall and the axillary's (underarm) lymph nodes, increasing the overall detection sensitivity.

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Fig. 1. Comparison between PMT-detector designs: (left) PMT-Quadrant-Sharing and (right) conventional-block design.

Fig. 2. Conventional PQS detectors panel design. The shaded section corresponds to the wasted PMT region.

Fig. 3. Modified PQS detectors design, the blocks are extended at detector panel edges (breast's pectoral region) and square blocks in inner area.

Fig. 4. Multi-crystal-slice: (left) physical slice from the production blocks and, (right) detector block designed with multi-crystal slices.

Fig. 5. Examples of light partition shapes (black section) of MDAPEM detector blocks where the PMTs are coupled to the bottom side. (a): the patterns for extended-asymmetric blocks and, (b): the patterns for square-symmetric blocks.

Fig. 6.
Design and dimensions of a PEM detector panel.

Fig. 7.

PEM blocks-to-PMTs coupling: (left) PMT half sharing (PHS) and PQS coupling for asymmetric blocks and, (right) PQS coupling for symmetric blocks.

Fig. 8. Proposed PEM collecting modes; (a) conventional X-ray mammography, (b) vertical and, (c) oblique mode.

Fig. 9.
Possible distance between the PEM-detector-bank surface and the patient, (conventional X-ray mammography mode).

Fig. 10. Physical LYSO blocks; left: asymmetric and right: symmetric blocks.

Fig. 11.
Side view of block-to-PMTs coupling: (left) PHS and PQS coupling for asymmetric blocks and (right) conventional PQS coupling for symmetric blocks.

Fig. 12. Two-dimensional position-decoding map of 156 crystals in an asymmetric detector block (left) and of 144 crystals in symmetric detector block (right) respectively.

Fig. 13.

Crystal profiles of asymmetric block: (left) external row at the panel edge and, (right) crystal row in the center of the four PMTs gap.

Fig. 14. Crystal profiles of asymmetric block: (left) external row near to the symmetric block and, (right) crystal row in the center of the four PMTs gap.

Fig. 15. Crystal profiles of the 12×12 symmetric block, (a) external crystal column and, (b) central crystal column.

Fig. 16.

Comparison of typical energy spectrums from corner and center crystals in the block and the normalized block average energy spectra; left: 12×13 asymmetric block and right: 12×12 symmetric block.

TABLE I

Characterization Of PEM Systems

Name	Detector Design	PMT	Resolution (mm)	Ref.
PEM-I	2-head BGO	PSPMT	2.6	[11]
PEM Flex	2-head LSO	PSPMT	1.5	[12]
LBNL PEM	4-head LSO	PSPMT/APD	2.1	[13]
PEM	2-head LGSO	PSPMT	4.1	[14]
Max PET	2-head LSO	PSPMT	2.3	[15]
PEImager	2-head BGO	PSPMT	2.9	[16]
Clear PEM	2-head LYSO	PSPMT	2.0	[17]
PET/CT	2-head LSO	PSPMT/APD	3.8	[18]

TABLE II

Comparison Between Extended and Square PQS Detector Blocks for A PET Detector Panel Applications

System	Block design	Crystals decoded	E. R.	Ref.
HOTPET	BGO 7×8 Extended	56	30.0%	[22,30]
HOTPET	BGO 7×7 Square	49	26.0%	[21,30]
MDAPEM	LYSO 12×13 Extended	156	14.2%	This study
MDAPEM	LYSO 12×12 Square	144	13.1%	This study

E.R: Energy Resolution