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Detector Position Estimation for PET Scanners

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Abstract

Physical positioning of scintillation crystal detector blocks in Positron Emission Tomography (PET) scanners is not always exact. We test a proof of concept methodology for the determination of the six degrees of freedom for detector block positioning errors by utilizing a rotating point source over stepped axial intervals. To test our method, we created computer simulations of seven Micro Crystal Element Scanner (MiCES) PET systems with randomized positioning errors. The computer simulations show that our positioning algorithm can estimate the positions of the block detectors to an average of one-seventh of the crystal pitch tangentially, and one-third of the crystal pitch axially. Virtual acquisitions of a point source grid and a distributed phantom show that our algorithm improves both the quantitative and qualitative accuracy of the reconstructed objects. We believe this estimation algorithm is a practical and accurate method for determining the spatial positions of scintillation detector blocks.

Keywords

Positron; Emission; Tomography; Alignment; mispositioning

1. Introduction

Accurate image reconstruction in Positron Emission Tomography (PET) requires precise knowledge of the position and orientation of each scintillation crystal within the scanner. In most implementations, the scintillation crystals are grouped into “detector blocks” throughout the PET scanner geometry, as is shown in Fig. 1.

Mis-positionings of the detector blocks within the scanner can lead to quantitative and qualitative artifacts in the reconstructed images ([1], [2]). For clinical PET scanners, this problem is mitigated by precise manufacturing of the PET scanner components.

Many prototype and small animal PET scanners suffer from detector block mis-positioning. The smaller geometries of small animal and high-resolution scanners demand a finer positioning tolerance and prototype scanners often need regular changes to the detector block positions during modifications of the system.

Several positioning algorithms have been proposed to address this issue. The method used by Stickel, *et. al.* [8] requires physically moving the detector blocks until counts from a

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point source occur in the correct opposing scintillation crystals. The methods used by Abella, *et.al.* [1] and Lee *et. al.* [2] attempt to compensate for detector mis-positioning algorithmically by matching measured sinograms to optimal sinograms. The method proposed by Sabet, *et.al.* [9] moves a point source along a line trajectory to compensate for block positioning errors. However, this method requires that the detectors are already nearly in alignment. All of these methods lack the ability to determine all six degrees of freedom possible in detector block positioning.

In this proof of principle paper, we propose a methodology to determine the position and orientation of detector blocks within a PET scanner. We have applied our method in a virtual simulation of the Micro Crystal Element Scanner (MiCES) PET system (currently under construction at the University of Washington) ([2]-[5]) with various detector positioning errors. We then tested our solution for accuracy in the position of the detector blocks. We also reconstructed several digital phantoms using our solution, and compared those reconstructions to the non-compensated and known-truth reconstructions. These simulations show that our algorithm produces qualitative and quantitative improvements in the image as compared to using an un-calibrated scanner.

2. Methods

2.1. Overview of calibration apparatus and positioning algorithm

Our detector positioning method utilizes a commercially available 1 mm diameter, 20 μCi ^{22}Na point source (Isotope Products Laboratories, Valencia, CA) that is rotated within the detector ring at stepped axial intervals. The radius of rotation and the axial offset is determined by the geometry of the scanner to be calibrated. For the MiCES scanner, we chose a rotational radius of rotation of 45 mm and an axial offset of 10 mm, as shown in Fig. 1.

2.1.1. Determination of Crystal Pairs within the Plane of Rotation—For each pair of opposing scintillation crystals (e.g. Fig. 2), we recorded a histogram of the number of events detected as a function of the angle of the point source (Fig. 3). For each crystal pair, the minimum and maximum angle of detection for the point source was recorded. If the difference from the minimum to the maximum angle was greater than 60° for a crystal pair, then each of those crystals was given a ‘vote’ as lying within the rotational plane of the point source. The crystals at the detector edges with the most votes were determined to lie within the plane of rotation. This was repeated for the second rotational path of the point source, yielding four scintillation crystals that were considered to lie within the two rotational planes.

2.1.2. Triangulation of Detector Edges—For each in-plane crystal pair (α , γ), the minimum and maximum angle of detection of the point source was used to determine the two points $P_{\min}(\alpha, \gamma)$ and $P_{\max}(\alpha, \gamma)$ by using the known angle and radius of rotation as shown in Fig. 2. These points are given in an absolute coordinate system independent of our scanner, and were then used to define the line $L(\alpha, \gamma)$ (Fig. 4).

We then computed the intersection of pairs of these lines to triangulate the corner of crystal α (Fig. 4). Four such triangulations were computed for each detector corner: $L(\alpha, \beta) \cap L(\alpha, \epsilon)$, $L(\alpha, \beta) \cap L(\alpha, \zeta)$, $L(\alpha, \gamma) \cap L(\alpha, \epsilon)$, and $L(\alpha, \gamma) \cap L(\alpha, \zeta)$.

These triangulations were performed for both axial positions of the point source phantom. Triangulations of the opposite edge of the detector block were performed symmetrically.

In this manner, we created 16 triangulation estimates of 4 points in each detector block. The least-squares best fit plane to these 16 points was then determined to be the plane in which the entrance face of the detector block lies.

2.1.3. Detector Z-positioning—For each in-plane crystal α , we examined the detected events in the opposing detector block when the point source was nearest α . By counting the opposing detector scintillation rows that had detected events with crystal α , we created similar triangles to determine the point in α which intersected the phantom plane of rotation (Fig. 5). Four such points were computed for each detector block, one for each combination of detector edge and axial position of the point source. These four points are given in detector coordinates on the entrance face of the detector.

To determine the position of the detector block in lab coordinates, the least-squares fit of these points to the triangulated lab-coordinate estimates was computed using the constraint that the detector-coordinate points lie within the entrance face plane determined in section 2.1.2.

2.2. Algorithm Evaluation

2.2.1. Description of MiCES Scanner Simulation—To evaluate our algorithm, we created a photon-tracking simulation in Matlab (The Mathworks, Inc. - Natick, MA) to model a single ring of the MiCES scanner [2]. This simulation modeled 18 detector blocks of a single ring of the MiCES scanner. Each detector block measured $19.7 \times 19.7 \times 10 \text{ mm}^3$ and was partitioned into 22×22 scintillation crystals. Our simulation modeled photon attenuation through the detector blocks ($\mu = 0.83 \text{ cm}^{-1}$ for LYSO at 511 keV), but did not incorporate scatter, positron range, photon acolinearity, or other physical properties. Coincidence photons were decoded to the exact crystal in which the photon event occurred.

Physical measurements of the MiCES scanner were made using a micrometer. Estimates of the MiCES detector block positioning errors were made using these measurements. These error estimates were then used to create seven randomized detector geometries in our simulation. Each of the randomized geometries had detector mis-positioning errors of up to 5 mm of translation and 5° of rotation about the x , y , and z axes, including combinations of all three rotations. These represent greater errors than were measured in the real scanner.

For each of the 7 randomized geometries, we simulated the rotation of a point source through two circular trajectories separated by 10 mm axially as shown in Fig. 1. Listmode data were recorded to obtain approximately 40 million coincidence events per axial position. The angle of the point source was recorded with an accuracy of one one-thousandth of a degree. The positioning algorithm was then applied to this listmode data to estimate the detector positions for each geometry.

2.2.2. Position and Reconstruction Error Metrics—For each corner of a detector block, we computed the Euclidean distance from the true position of that corner to the position estimated by our positioning algorithm. We then expressed the true and estimated corner positions in cylindrical coordinates, and measured the absolute differences in r , θ , and z . These errors were computed for 8 corners $\times$ 18 detector blocks $\times$ 7 randomized geometries, for a total of 1,008 error measurements. The mean, max, and standard deviation of these errors were then computed. This same process was then applied to the corners of the uncalibrated scanner geometry.

For the grid phantom reconstructions, we partitioned each of the three reconstruction volumes in order to localize the individual point sources. For each point source partition, we recorded the maximum voxel value within that partition. Using those voxels within the

partition that were at least half of the maximum value, we computed the voxel-value weighted centroid of the reconstructed point source. Using the reconstruction that utilized the true detector positions, we then computed the Root Mean Squared Error (RMSE) of the x , y , and z -coordinate errors of the non-calibrated and solution geometry reconstructions. The RMSE of the Euclidean distance was also computed, as well as the error in the maximum voxel value normalized by the maximum value of the reconstruction using the true detector positions (the %peak RMS).

Also for the grid phantom reconstruction, we summed axial slices 17-26 (the central grid of the point source phantom ± 4 slices) into a single image for each perceived geometry. A horizontal activity profile was then drawn through row 64 (just above the middle) of this summed image.

For the elliptical phantom reconstruction, we made difference images for the true minus uncalibrated and true minus calibrated images. Both difference images were scaled as a percentage of the mean voxel value within the analytical bounds of the phantom. We then drew a 4 mm radius cylindrical ROI centered within the phantom. Using the reconstruction from the true detector positions, the mean voxel value within this ROI was determined to be the background activity. We then drew an ROI using the elliptical bounds of the phantom. The voxel-value RMSE was computed for voxels within this ROI for the non-calibrated and solution geometry reconstructions. The RMSE was then normalized by the background activity (nRMSE).

2.2.3. Test Objects Simulated—We modeled two virtual phantoms for use within our simulation. These were continuously defined (not voxelized) in the simulation. The first was a layered grid of point sources, and the second was an elliptical phantom with four circular regions of varying activity.

The grid phantom consisted of three layers of point sources spaced in a square pattern. Each point source was a sphere of diameter 0.5 mm, with a grid separation of 9 mm. Each of the three grid layers were separated by 5 mm. A 2D drawing of this phantom is shown in Fig. 6.

The second phantom was an elliptical cylinder centered on the z -axis, with a x -diameter of 35 mm, and a y -diameter of 20 mm. Four circular regions of diameter 4 mm were placed within the ellipse with target-to-background ratios of 0.0, 0.5, 2.0, and 4.0. The axial extent of the ellipse and the four regions was 5 mm, centered half-way into the axial field of view. A drawing of this phantom is shown in Fig. 7.

Each of these was used to generate listmode data using randomized geometry 1 (shown in Fig. 8). The listmode data contained 11.7 million coincidence events for the grid phantom, and 15.5 million coincidence events for the elliptical phantom.

2.2.4. Reconstruction of Test Objects—For both of the virtual test phantoms, the listmode data was binned into stacks of 40 parallel-beam sinograms using Single-Slice Rebinning (SSRB, [6]) with a 10 mm axial acceptance, 196 angular bins and 128 radial bins over the 60mm reconstruction diameter. This was done three times, once for each of the perceived geometries: (a) using the theoretical detector positions (no compensation for mis-positioning), (b) using the known detector positions, and (c) using the estimated detector positions given by the positioning algorithm. Each sinogram was reconstructed using Ordered Subset Expectation Maximization (OSEM, [7]) with 7 subsets and 5 iterations, and post-filtered with a 3D Gaussian filter with a Full Width at Half Maximum (FWHM) of 3 pixels.

3. Results

3.1. Positioning Estimate Metrics

The results of the distances in cylindrical and Euclidean coordinates of the detector corners are given in Table 1. A visualization of the positioning estimate for randomized geometry 1 is shown in Fig. 8.

3.2. Reconstruction Error Metrics

The results of the errors in the positions of the reconstructed grid phantom centroids are shown in Table 2. Reconstructed images of the grid phantom are shown in Fig. 10, and the profiles drawn from those reconstructions are shown in Fig. 9.

For the elliptical phantom reconstruction error measurements, the nRMSE of the uncalibrated and calibrated voxel values are shown in Table 3. Reconstructed images of the elliptical phantom are shown in Fig. 11.

4. Discussion

Fig. 8 and Table 1 show that the proposed method accurately estimates for the positions of the detector blocks and compensates for six degrees of freedom of the positioning errors.

Fig. 9 and Fig. 12 as well as Table 2, indicate that this method improves the quantitative accuracy of the reconstructed image. In particular, Fig. 12 shows that the quantitative accuracy of the calibrated reconstruction is an order of magnitude improvement over the uncalibrated reconstruction.

Fig. 10 and Fig. 11 illustrate that the qualitative accuracy of the phantom scans is improved by using our algorithm to estimate the geometry of the scanner. These figures show that our algorithm eliminates several significant artifacts and deformities that are present in the uncalibrated reconstructions.

Our first attempts to determine the positions of the MiCES block detectors (in 2-dimensions) used optimization algorithms on measured sinograms. We found that we could achieve excellent matching of measured to ideal sinograms, even when the estimated detector block positions were as much as 10 mm from the true positions. In those studies, we found that certain types of positioning errors had larger impacts than others. We found that moving a detector block radially away from the center of the scanner had little effect on the sinograms and reconstructed images. However, positioning errors tangential to the ring of the scanner had noticeably larger errors. These observations led us to the decision to measure detector positioning errors in cylindrical coordinates. The mean radial error for our solution was 0.483 mm, which is half of the width of a scintillation crystal. However, since this error is in the radial direction, there is little impact on the reconstructed images. Of greater importance is the tangential mean error of 0.119° , which represents approximately one-seventh of the crystal pitch.

Our proposed method is not restricted to the geometry of the MiCES scanner, and can be adapted to different scanner geometries. Also, any number of phantom rotational planes can be used, making this algorithm highly customizable for different scanner geometries.

This method also address all six degrees of freedom of possible detector mis-positioning. For a scanner with such positioning errors, the methods described in [1], [2], [8], and [9], would not be comparable to our method, especially in this simulated environment.

This method will require a minimum number of coincidence events from each axial position of the rotating point source in order to get a good position estimate. A rough estimate of the scan time needed to generate the 40 million counts that were used in the simulation (including scattered events, solid angle, detector efficiency, etc.) is 30 – 60 minutes per axial position, using a 20 μCi point source.

Although there is some time required for acquisition and processing of the detector alignment data, this should only need to be performed when detector modules are installed. The detector block position estimates were computed from the listmode data on a MacBook Pro with a single 2.66 GHz Intel Core i7 processor and 4GB of RAM. It took approximately 30 minutes to generate each position estimate.

5. Future Work

While the proposed method accurately determines the detector block positions in simulation, positron range, photon acolinearity, scatter, random events, and detector block decoding errors could degrade the performance of the method. Since we know the position of the point source at the time of each coincidence event, we have the ability to reject many of the random and scattered events, as well as some of those events where the detector block decoding was inaccurate. To compensate for photon acolinearity and positron range, a statistical method will be necessary that places the points $P_{min}(\alpha, \beta)$ and $P_{max}(\alpha, \beta)$ somewhere on the trailing edges of the separated peaks shown in Fig. 3. The exact method of this positioning will be determined by actual measurements taken from the MiCES detector modules. Our method relies on a least-squares fitting to the triangulated points. Using more triangulation points and an iterative examination of the tightness of the triangulations can be used as an indication of the confidence level of our position estimate. Our proposed method could also be used to generate an initial position estimate, that could then be fine-tuned by using the method proposed by Sabet, *et.al.*, [9] applied to the rotating point source data.

6. Conclusions

We have tested a proof of concept methodology for determining the spacial positions of block detectors in PET scanners with mis-alignment errors. We have tested our method in seven simulations of the MiCES PET scanner with random positioning errors. We have shown that our position estimation method has the ability to accurately determine the positions of the detector blocks, resulting in increased quantitative accuracy and image fidelity.

Acknowledgments

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Figure 1.

A side view of the detector ring with no positioning errors, illustrating two axially-stepped rotational paths of the point source. The detector block inner diameter is 125 mm, and the diameter of the rotating point source is 90 mm. The distance between the two circular paths is 10 mm.

Figure 2.

A phantom plane cross section of the MiCES scanner. The circle represents the path of the point source. Two coincident scintillator crystals, α and γ , are outlined in two of the detector blocks. The field of view between the two crystals is shown in dotted black lines. The positions where the point source phantom enters and leaves the field of view are labelled $P_{\min}(\alpha, \gamma)$ and $P_{\max}(\alpha, \gamma)$, and define the line $L(\alpha, \gamma)$.

Figure 3.

A histogram of the point source phantom angle versus the number of coincidence events detected for the crystal pair α and γ shown in Fig. 2. If this curve exhibits two distinct and separated peaks (as this curve does), then that pair is given a vote to lie within the rotational plane of the point source. The points $P_{\min}(\alpha, \gamma)$ and $P_{\max}(\alpha, \gamma)$ are determined by the first and last angles represented.

Figure 4.

By computing the intersection point of lines $L(\alpha, \gamma)$, and $L(\alpha, \zeta)$, we get a position estimate of the corner of crystal α . Our algorithm uses four different triangulations to improve the positioning estimate.

Figure 5.

Determining the z -coordinates of scintillator crystals in detector coordinates. The rotational plane of the point source is shown by the dotted line, and the in-plane crystals are colored in gray. The two solid lines represent the field of view of the in-plane crystal α with the opposing detector. By counting the number of scintillator crystals above and below crystal β , we determine the similar triangles to the left and right of the point source. These similar triangles are used to determine the point in α which intersects the plane of rotation.

Figure 6. Representation of one layer of the grid phantom. Each sphere is 0.5mm in diameter, and the grid spacing is 9mm. The 3 layers are separated by 5mm gaps. The circle represents the field of view of the scanner.

Figure 7.
Representation of the elliptical phantom showing the relative intensities of each area within the phantom. The circle represents the field of view of the scanner.

Figure 8. Randomized detector geometry 1 (one of seven randomized geometries). This geometry was used for all of the reconstructions. The true detector positions are in solid gray, and the positions estimated by our algorithm are in dashed black.

Figure 9.

A horizontal profile through the center of the sum of slices 17-26 for the grid phantom. The profile obtained by using the true detector positions is in gray, the estimated model is in dashed black, and the uncalibrated model is in solid black.

Figure 10.

Reconstructions of the grid phantom. Top row: axial views through the central slice. Bottom Row: sagittal view through the center. Left column: reconstruction using no compensation, middle: true geometry, and right: compensation using the solution geometry.

Figure 11.

Reconstructions of the elliptical phantom. Top row: axial views through the central slice. Middle Row: sagittal view through the centers of the upper two circular regions. Bottom Row: sagittal view through the centers of the lower two circular regions. Left column: reconstruction using no compensation, middle: true geometry, and right: compensation using the solution geometry.

Figure 12.

Difference image of the reconstructions shown in Fig. 11. The color scale values are given as a percent of the mean voxel value within the phantom. (a): Uncalibrated percent error; (b): Calibrated percent error

Ensemble Statistics for the $n=7$ randomized geometries with 8×18 detector corners. Absolute errors are given in Euclidean distance (d) and cylindrical coordinates.

Table 1

	d (mm)	r (mm)	θ°	z (mm)
Uncalibrated	Mean	1.94	1.06	0.38
	STD	1.19	0.99	0.33
	MAX	4.99	3.99	1.41
Calibrated	Mean	0.62	0.48	0.12
	STD	0.35	0.34	0.09
	MAX	2.17	1.78	0.63

RMS difference for grid phantom centroids in the x , y , and z -directions. The Euclidean distance is given by d . The %peak RMS in the peak voxel value is also given.

Table 2

	x	y	z	d	%peak RMS
Uncalibrated	0.20	0.14	0.51	0.50	46.46 %
Calibrated	0.08	0.09	0.19	0.22	4.04 %

Table 3

nRMSE for elliptical phantom normalized by background activity

Uncalibrated	Calibrated
24.10%	7.60%