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Simulation Study of Spatial Resolution and Sensitivity for Tapered Depth of Interaction PET Detectors for Small Animal Imaging

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Abstract

Improvements to current small animal PET scanners can be made by improving the sensitivity and the spatial resolution of the scanner. In the past, efforts have been made to minimize the crystal dimensions in the axial and transaxial directions to improve the spatial resolution and to increase the crystal length to improve the sensitivity of the scanner. We have designed tapered PET detectors with the purpose of reducing the gaps between detector modules and optimizing the sensitivity of a future generation small animal PET scanner. In this work, we investigate spatial resolution and sensitivity of a scanner based on tapered detector elements using Monte Carlo simulations. For tapered detector elements more scintillation material is used per detector resulting in a higher sensitivity of the scanner. However, since the detector elements are not uniform in size, degradation in spatial resolution is also expected. To investigate characteristics of tapered PET detectors the spatial resolution and sensitivity of a one-ring scanner were simulated for a system based on traditional cuboid detectors and a scanner based on tapered detectors. Additionally, the effect of depth of interaction (DOI) resolution on the spatial resolution for the traditional and tapered detectors was evaluated.

All simulations were performed using the Monte Carlo simulation package GATE. Using the tapered arrays a 64 % improvement in the sensitivity across the field of view was found compared with traditional detectors for the same ring diameter. The level of DOI encoding was found to be the dominating factor in determining the radial spatial resolution and not the detector shape. For all levels of DOI encoding, no significant difference was found for the spatial resolution when comparing the tapered and the cuboid detectors. Detectors employing the tapered crystal design along with excellent DOI resolution will lead to PET scanners with higher sensitivity and uniform spatial resolution across the field of view.

1. INTRODUCTION

For small animal PET, like human imaging, improving the sensitivity of the PET scanner may allow for the duration of the scan to decrease or the injected amount of radionuclide to be reduced without sacrificing image quality. When the same subject is used for multiple studies, minimizing the injected activity is particularly important. Previous studies have shown that the average whole body dose to a mouse is in the range of 6–17 cGy for an imaging study using 9.6 MBq of ¹⁸FDG (Funk *et al.*, 2004). In addition to the dose to the organs, the tumour was found to receive a dose of 22.3 cGy for an imaging study using 7.4 MBq of ¹⁸FDG (Taschereau and Chatzioannou, 2007).

For a given detector material, the sensitivity of a scanner may be increased by using longer detector elements, by increasing the amount of material in which the 511 keV photons may

interact, or by increasing the solid angle coverage by decreasing the ring diameter. With increasing crystal length and a decreasing detector ring diameter parallax errors will be larger, resulting in the degradation of spatial resolution away from the center of the field of view. One way to correct for this parallax error without compromising sensitivity of the scanner is to use depth of interaction (DOI) encoding detectors. Previous experiments have shown that continuous DOI resolution of 2 mm or better can be achieved using dual ended read out detectors, in which the array of scintillation crystals are read out by a position sensitive avalanche photodiode (PSAPD) at the front and back ends of the detectors (Yang *et al.*, 2006). The depth of interaction is determined by taking the ratio of the signals from the two PSAPDs, and a continuous measure of depth of interaction is determined for each recorded event. Other groups have focused on phoswich DOI detectors (Saoudi *et al.*, 1999; Tsuda *et al.*, 2004; Ziemons *et al.*, 2005) or discrete DOI detectors with offset crystals (Zhang *et al.*, 2002).

In addition, the sensitivity of the scanner may be increased by decreasing the gaps between the detectors in the ring geometry. In small diameter animal scanners, based on a ring geometry, these gaps can be a significant factor in limiting the sensitivity. Other groups have explored, through simulation, novel system geometries that reduce the gaps between detector blocks (Habte *et al.*, 2007). Another way to improve the sensitivity of the scanner through minimizing crystal gaps may be to move towards monolithic detectors (van der Laan *et al.*, 2007; Maas *et al.*, 2009), however all such detectors to date have been cuboid in shape and thus have not eliminated the large gaps between detector modules, only the smaller gaps due to reflector material between individual detector elements in an array.

In the past, efforts have been made to decrease the scintillation crystal element size in the axial and transaxial directions to improve the spatial resolution of the scanner (Stickel *et al.*, 2007). This is not without its challenges, as common scintillator crystals are brittle and often difficult to cut. Other detector designs may be employed to improve spatial resolution. One example is the use of semiconductor detectors that may be finely pixelated or read out in strips. Recently, both human (Shiga *et al.*, 2009) and small animal (Cesca *et al.*, 2007; Ishii *et al.*, 2007) PET scanners using semiconductor detectors have been introduced. However, semiconductor detectors do not have the same potential to improve the sensitivity of the scanner because of the low stopping power of materials such as CdTe compared with common PET scintillators like LSO and BGO.

In this work we take a different approach and propose the use of LSO scintillator arrays in which each element, instead of being cuboid, is tapered in the transverse direction. The resulting scintillator array is wedge-shaped, allowing tight packing of detector modules in a ring geometry. Because the PSAPDs used in our prior work (Shah *et al.*, 2004) can be manufactured in any desired size, it will still be possible to read out these arrays at both ends for DOI encoding. By significantly reducing the gaps between detector modules, we hypothesize that there will be a large increase in system sensitivity with this design. We also hypothesize that although the detector elements are tapered, leading to some loss of spatial resolution for events occurring towards the back of the detector, that this effect will be negligible for a realistic field of view and DOI resolution. The aim of this work therefore is to characterize through Monte Carlo simulation the sensitivity and spatial resolution of a small animal PET scanner based on tapered depth of interaction (DOI) detectors and compare the results to a scanner based on traditional cuboid detectors. The small inner ring diameter (60 mm) proposed presents the possibility that these scanner designs may be employed in a future generation PET-MR insert or as a stand-alone small animal PET scanner.

2. MATERIALS AND METHODS

2.1 Monte Carlo Simulation of the Evaluated Scanner Geometries

All of the simulations were performed using GATE (Jan *et al.*, 2004), a Monte Carlo simulation package based upon the well validated, multipurpose Monte Carlo package Geant4.

The simulated small animal PET scanner has an inner diameter of 6 cm and an outer diameter of 10 cm, and is composed of 20 detectors in a ring. This is a design that could be used for a small animal PET scanner or as a PET insert for a small animal MRI scanner. The two simulated scanners are shown in Figure 1, illustrating the tapered geometry of the novel PET detectors compared with the traditional cuboid detectors used to date.

The simulated detectors are based on continuous depth of interaction (DOI) detectors developed in our laboratory that are read out at both ends of the crystal array by position sensitive avalanche photodiodes (PSAPDs) (Yang *et al.*, 2006; Yang *et al.*, 2008). The depth of interaction is determined by the ratio of the summed signals from the two PSAPDs. The traditional cuboid detector simulated was a 14 X 14 array of 0.5 X 0.5 X 20 mm³ LSO crystals with a crystal pitch of 0.57 mm allowing for reflectors between the individual crystals. This traditional detector design is similar to detectors that have been previously characterized experimentally (St. James *et al.*, 2009). The novel detectors had a 14 X 14 array of crystals, with the crystal elements uniform in the axial direction and tapered in the transaxial dimension. The crystal pitch and crystal dimensions at the entrance face of the detector were identical for the traditional and tapered arrays. The dimension of the crystals at the far end of the tapered arrays in the simulation studies was set to 0.5 X 0.875 mm² with the pitch being 0.57 mm in the axial direction and 0.945 mm in the transverse direction. The angle of taper was chosen to reduce the gaps as much as possible while still accounting for the small dead space (1 mm) surrounding the PSAPD photodetectors. Though this is a simulation study, tapered arrays have been manufactured to ensure that it is possible to fabricate LSO arrays in this geometry. These arrays are currently being evaluated in our lab. A photograph of a tapered array of LSO crystals next to a cuboid array of LSO crystals is shown in Figure 2, along with an illustration of the crystal dimensions. The tapered arrays are easily manufactured using minor modifications to the technology used for fabricating cuboid arrays (Stickel *et al.*, 2007).

2.2 Sensitivity of the Scanner

A point source with activity 1.11 MBq was simulated in the center of the field of view (FOV) emitting mono-energetic back-to-back 511 keV photons. In the simulation, the coincidence window was set to 20 ns, the energy resolution was set to 25 % and the energy window was 250 keV– 650 keV. The simulated energy resolution was based on the reported energy resolution for similar detectors (St. James *et al.*, 2009; Yang *et al.*, 2008). The timing window was chosen to be twice the reported timing resolution of similar detectors (Yang *et al.*, 2008), with the PSAPDs being the dominating factor in the timing resolution of these detectors (Wu *et al.*, 2009). The sensitivity was taken to be the percentage of total events that were recorded as coincidence events. The duration of the simulation was 15 seconds, resulting in more than 16 million simulated back-to-back photon pairs. To compare the simulated sensitivity results to that of a known scanner the same simulation was performed for the microPET II scanner (Tai *et al.*, 2003). The reported sensitivity of microPET II is 2.3 % at the center of the field of view for a 10 ns timing window and a lower level discriminator setting of 250 keV.

The sensitivity across the field of view was evaluated by simulating a line source extending from a radial offset of –16 mm to a radial offset of + 16 mm - the approximate width of a

mouse. The integrated sensitivity (weighted by radial offset) was then computed for the two simulated scanners to evaluate the sensitivity gain over the entire field of view.

Additionally, to evaluate the effect of scatter, the sensitivity for the scanner designs was also evaluated at the center of the field of view for varying lower level discriminator (LLD) settings from 250 keV to 425 keV in increments of 25 keV.

2.3 Spatial Resolution

A small (1 μm) point source emitting mono-energetic back-to-back 511 keV photons with activity 1.11 MBq was simulated for 15 seconds, resulting in more than 16 million simulated pairs of back-to-back 511 keV photons. These simulations were repeated, varying the radial offset of the point source to demonstrate the spatial resolution at different locations across the field of view.

From the simulations, the center of mass location of the interaction of the annihilation photons in the scintillator detector was recorded. To model the effect of finite depth of interaction (DOI) resolution, the depth of interaction of the events was blurred by adding a Gaussian random variable to the depth of interaction. The use of a Gaussian function is justified based on measurements of DOI distributions from experimental detectors (St. James *et al.*, 2009; Yang *et al.*, 2006). For an actual depth of interaction Z in the crystal, the blurred depth Z' is given by:

$$Z' = Z + \Delta Z \quad (1)$$

where ΔZ is taken from a normal distribution of mean 0 and standard deviation σ , where

$$\sigma = \frac{\text{DOI Resolution (mm)}}{2 \sqrt{2 \ln 2}} \quad (2)$$

The resulting estimated depth in the detector, Z' , is limited to the physical length of the scintillation crystals (20 mm), thus events that after DOI blurring would be located outside of the crystal, are placed at 0 or 20 mm depth as appropriate. For the tapered arrays, the crystals are not perpendicular to the face of the detector. The DOI blurring was performed along the individual crystal axes accounting for the crystal orientations. The physical scintillator arrays are not continuous detectors, and the location of interaction in a physical detector can only be localized to the crystal element in which the interaction occurred. To model the discrete nature of the crystal elements, yet also produce lines of response with relatively uniform efficiencies, the events were randomly positioned across the transverse width of the crystal. To improve the quality of the sinograms, a bootstrapping method was used whereby this random blurring of the position of interaction with respect to the crystal length and width was repeated 10 times per event. Sinograms were created using the blurred positions of the coincident events in the detectors for DOI resolutions of 10 mm, 5 mm, 2 mm and 1 mm. Events were binned into 300 angles and 1400 radial positions, with a radial sampling distance of 0.04 mm.

Normalization sinograms were created by simulating more than 5 million detected events for the scanners based on tapered and cuboid scintillator arrays. The source for the normalization sinograms was a non-attenuating cylinder of diameter 5.0 cm, emitting back-to-back 511 keV photons. A path-length correction was applied to account for the differences in the intersection of a line of response with the cylinder. Normalization sinograms were formed for each DOI resolution by binning the data according to the DOI

resolution, in the same manner described above. To ensure that no significant additional noise is added to the sinograms through the normalization process, it is desirable to simulate many more events for the normalization sinograms than for the emission sinograms. To increase counting statistics, we used twenty-fold rotational symmetry arguments to give a total of ~100 million detected events in the normalization sinograms. All of the sinograms were normalized by dividing the raw sinogram by the normalization sinogram and the images were then reconstructed using filtered backprojection (FBP) with a Shepp-Logan filter with a frequency cutoff at the Nyquist frequency. The spatial resolution was taken to be the full-width at half maximum (FWHM) of the profile of the point source, following the NEMA protocol for small animal PET scanners (NEMA, 2008). The tangential and radial spatial resolutions were calculated from the reconstructed images. The error on the FWHM measurement was taken to be a measurement error of one pixel (0.04 mm). The average reconstructed resolution across a mouse-sized field of view (32 mm diameter) was also computed.

3. RESULTS

3.1 Sensitivity of the Scanner

The sensitivity at the center of the field of view for the scanner with the cuboid arrays was found to be 3.0 %. For the scanner based on the tapered arrays, the sensitivity at the center of the field of view was found to be 4.2 %. Both of these values are for lower level discriminator settings of 250 keV. The simulated sensitivity of the microPET II scanner was 2.2 %, comparable with the experimentally measured value of 2.3 %. This suggests that the simulations are a good guide to the sensitivity that would be realized in a real scanner.

When varying the lower level discriminator settings, the sensitivity of the scanner based on the tapered arrays was always greater than for the scanner based on cuboid detector arrays. This is shown in Figure 3. The sensitivity profiles across the field of view are shown in Figure 4. The comparison of the sensitivity profiles shows that the sensitivity of the scanner based on tapered arrays is greater than the sensitivity of the scanner based on cuboid arrays, across the entire field of view. Additionally, it shows that for the scanner based on cuboid scintillator arrays the sensitivity at the center of the field of view is peaked. At the center of the field of view of the scanner with the cuboid detectors, all of the gaps between the scintillators align and the maximum number of back-to-back photon pairs will be detected. For a solid detector ring (annulus) the sensitivity profile across the field of view would be a cusp with the maximum number of photon pairs detected being for sources at the periphery of the field of view. The estimated sensitivity profile for the scanner based on the tapered arrays is closer to the ideal case of the solid annulus of scintillator material. The true gain in sensitivity achieved by developing scanners with tapered arrays is greater than a sensitivity comparison made solely at the center of the field of view would suggest. Integrating across the entire field of view, a sensitivity gain of 64 % is achieved with tapered arrays for the same axial field of view and ring diameter.

3.2 Spatial Resolution

The spatial resolution for the two scanner designs, across the field of view and for varying DOI resolutions, are shown in Figure 5. As would be expected, the tangential spatial resolution does not change significantly with source position and DOI resolution. The radial spatial resolution does however depend largely on the source position and DOI resolution. To demonstrate the effect of DOI binning, reconstructed images of the point source located at a radial offset of 10 mm from the center of the field of view are shown. The reconstructed images from the two scanner designs, employing the four different DOI resolutions are shown in Figure 6. The spatial resolution for all reconstructions and source locations is

reported in Table 1. The average spatial resolution across a mouse-sized field of view (32 mm diameter) is also given. To compare the spatial resolution of the cuboid and tapered detectors (of the same DOI resolution) a paired t-test was performed. For all of the DOI resolutions examined the differences in the spatial resolution measurements between the cuboid and tapered detectors for the same DOI resolution are not statistically significant ($p < 0.05$).

4. DISCUSSION AND CONCLUSIONS

The simulation results show the sensitivity gain achieved by designing small animal PET scanners using tapered arrays is significant. Using 37.5 % more LSO and the same number of electronics channels results in a gain in sensitivity of 64 % for a mouse-sized object. However, the most interesting result is that by changing to tapered detector arrays the spatial resolution is not significantly degraded for any given level of DOI encoding. As expected radial resolution improves rapidly with improving DOI resolution.

With iterative reconstruction techniques differences in spatial resolution between cuboid and tapered detectors may become more apparent, however much will depend on the accuracy of the system model. We decided to use an analytic reconstruction technique such as filtered backprojection to ensure that any differences seen in the reconstructed spatial resolution are due to the crystal shape rather than differences or approximations in the system model.

Overall, these results show that the accuracy of the DOI encoding, and not the proposed crystal geometry, is the most important factor in determining the spatial resolution across the appropriate field of view for mouse imaging. However, for detectors with a larger taper than those evaluated here, the influence of the shape of the detector may be more significant. The Monte Carlo simulations and the framework presented here for evaluating the spatial resolution achieved with DOI detectors could be used for other novel detector geometries. These same techniques can also be used to evaluate future generation scanners based on discrete DOI detectors (such as the phoswich detectors).

Factors that were not included in these Monte Carlo simulations include the non-collinearity of the two annihilation photons, the positron range, additional components of the scanners that may introduce scatter and optical light transport in the scintillation crystals. These factors will additionally blur the resulting images. These effects were intentionally left out of the study to evaluate the effect of continuous DOI resolution and the differences between tapered and cuboid detectors without additional blurring factors that might mask the geometrical effects of interest.

The results of this simulation study shows that images acquired with a small animal PET scanner with a diameter of 60 mm and 20 mm long scintillator crystals will be quite uniform across the FOV providing that the DOI resolution of the detectors is better than 2 mm. Combining the tapered crystal design with excellent DOI resolution provides a pathway to PET scanners that exhibit very high sensitivity and spatial resolution.

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Figure 1.
Left: Scanner based on cuboid LSO elements. Right: Scanner based on tapered LSO elements.

Figure 2.

A photograph of a tapered LSO array next to a cuboid LSO array (left) and an illustration of the dimensions of the simulated tapered LSO array.

Sensitivity as a Function of Lower Level Discriminator Setting

Figure 3. The sensitivity of both scanner designs as a function of changing lower level discriminator settings.

Figure 4. The number of coincidence counts for a line source positioned across the transverse field of view.

Figure 5.
The radial and tangential spatial resolution as a function of source position for varying DOI resolutions.

Figure 6. Reconstructed images of the point source at a radial offset of 10 mm for the cuboid arrays (left), the tapered arrays (right) and varying DOI resolutions.

Table 1

The radial and tangential spatial resolution across the field of view for different DOI resolutions and the two evaluated detector designs. Estimated error on these measurements is ± 0.04 mm. The average spatial resolution from 0 mm to 16 mm is also reported. For DOI resolution of 5 mm and 10 mm the spatial resolution was not reported for source offsets past 14 mm, as the fits to the reconstructed images were poor. This is also reflected in the average spatial resolution.

	DOI Resolution (mm)	1 mm		2 mm		5 mm		10 mm	
		Radial	Tangential	Radial	Tangential	Radial	Tangential	Radial	Tangential
Tapered Arrays	0	0.29	0.25	0.29	0.29	0.39	0.46	0.39	0.46
	2	0.46	0.39	0.43	0.46	0.46	0.46	0.46	0.50
	4	0.43	0.46	0.50	0.50	0.54	0.50	0.64	0.54
	6	0.46	0.46	0.50	0.50	0.64	0.50	0.86	0.50
	8	0.46	0.50	0.50	0.54	0.79	0.43	1.00	0.54
	10	0.50	0.50	0.57	0.50	0.86	0.54	1.18	0.50
	12	0.46	0.54	0.61	0.54	0.86	0.46	1.39	0.50
	14	0.46	0.54	0.64	0.54	0.90	0.54	1.57	0.50
Cuboid Arrays	16	0.50	0.57	0.68	0.61	-	-	-	-
	Average	0.45	0.47	0.52	0.50	0.68	0.49	0.94	0.50
	0	0.39	0.39	0.36	0.36	0.43	0.43	0.39	0.43
	2	0.39	0.39	0.46	0.39	0.43	0.46	0.46	0.46
	4	0.43	0.50	0.50	0.43	0.57	0.46	0.57	0.46
	6	0.43	0.50	0.54	0.46	0.71	0.43	0.86	0.54
	8	0.39	0.46	0.46	0.50	0.71	0.43	1.07	0.46
	10	0.09	0.50	0.50	0.54	0.79	0.50	1.14	0.40
	12	0.43	0.43	0.61	0.50	0.79	0.46	1.25	0.43
	14	0.43	0.54	0.57	0.50	0.96	0.57	1.64	0.57
	16	0.46	0.50	0.64	0.50				
	Average	0.42	0.47	0.51	0.46	0.68	0.47	0.93	0.48