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W. J Ryder
Portsmouth Hospital NHS Trust (United Kingdom)

I. N Wienberg
Weinberg Medical Physics (USA)

P. S Stepanov
Weinberg Medical Physics (USA)

A Reznik
Lakehead Univ. (Canada)

M Urdaneta
Weinberg Medical Physics (USA)

See next page for additional authors

Authors
W. J Ryder, I. N Wienberg, P. S Stepanov, A Reznik, M Urdaneta, E Anashkin, M. A Masoomi, and Anatoly B. Rosenfeld

Simulation of Low Dose Positron Emission Mammography Scanner for Global Breast Health Applications

Ryder W.J[a], Weinberg I.N.[b], Stepanov P.S.[b], Reznik A[c], Urdaneta M[b], Anashkin E[b], Masoomi M.A[a], Rozenfeld A[d]

a Nuclear Medicine Physics, Portsmouth Hospital NHS Trust, Portsmouth. UK
b Weinberg Medical Physics, Bethesda, Maryland, USA
c Thunder Bay Regional Research Center and Lakehead University, Thunder Bay, Ontario, Canada
d Medical Radiation Physics, University of Wollongong , NSW 2522, Australia

ABSTRACT

Positron emission mammography ("PEM") is a breast imaging modality that typically involves the administration of relatively high doses of radiotracer. In order to reduce tracer costs and consider PEM for global screening applications, it would be helpful to reduce the required amount of administered radiotracer so that patient dose would be comparable to conventional x-ray mammograms.

We performed GATE Monte Carlo investigations of several possible camera configurations. Increasing the detector thickness from 10 to 30 mm, increasing the camera surface area from $5x20cm^2$ to $20x20cm^2$, and applying depth-of-interaction information to increase the acceptance angle, increased the overall efficiency to radiation emitted from a breast cancer by a factor of 24 as compared to existing commercial systems.

Keywords: Keywords: PEM, Monte Carlo, Scintillators, Breast imaging, Global Healthcare

1. INTRODUCTION

Positron emission mammography (PEM) is a highly accurate breast imaging modality[i], which typically involves the administration of relatively high doses of radiotracer.

The purpose of this research was to increase count sensitivity of a PEM imaging system, by optimizing detector characteristics. With such increased count sensitivity, high-accuracy devices could potentially be used as primary screening tools in countries with access to positron-emitting radiotracers. For example, if a 740 MBq supplied unit dose was available to a clinic for a price of $100, and it was possible to reduce the per-patient administration to the 37MBq level by increasing camera efficiency, then the cost per patient could be less than $10.

In order to consider PEM for global screening applications, the required amount of administered radiotracer would need to be reduced hence that patient absorbed dose would be comparable to conventional x-ray mammograms and this can be achieved by increasing the sensitivity of the PEM imaging system.

1.1 Design of Commercially available PEM Scanner

The design of a commercially available PEM scanner has two parallel detectors mounted on a compression pedals. The detectors are $20x5cm^2$ with LSO (7.4 g/cm^3) scintillator with a crystal thickness of 10mm and a limited acceptance angle. For image acquisition detectors are translated along these compression pedals to acquire an image of an entire breast. A comparison between the existing design and new configurations is proposed. The PEM detector characteristics were calculated using analytical techniques and the GATE[ii] Monte Carlo package was used to investigate PEM imaging system designs.

*wjryder@ieee.org; phone +44 2392 286000 ext 4014

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2. ANALYTICAL CALCULATIONS

2.1 LSO Sensitivity

Using XCOM[iii] software it is possible to calculate the Total Attenuation and Photoelectric Absorption for LSO. The increase in sensitivity of LSO was predicted by analysing the attenuation coefficients for LSO (Lu_2SiO_5), the output from XCOM is plotted in figure 1.

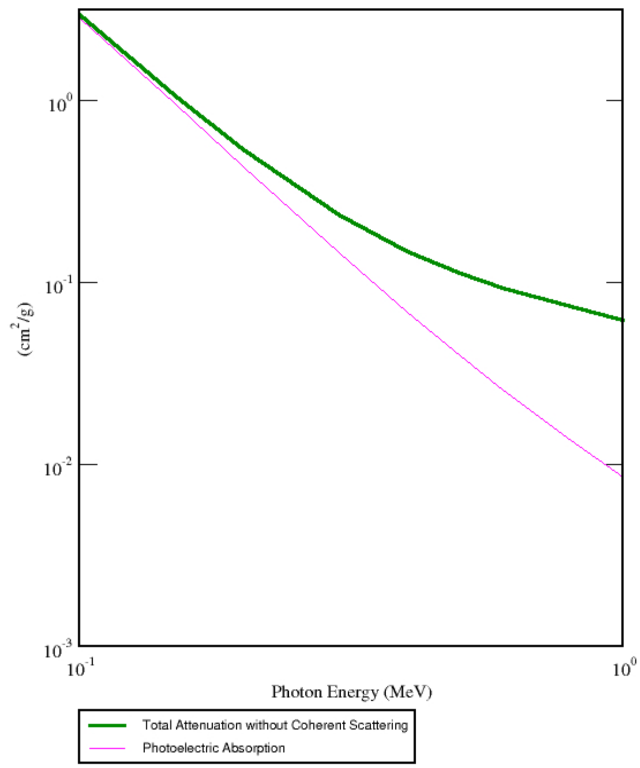

Figure 1: XCOM generated LSO Total Attenuation and Photoelectric Absorption

Using a density for LSO of 7.4 g/cm^3 the probability of interaction was calculated for a 511 keV photon being absorbed in a 10mm, and 30mm thick crystals, see table 1.

Table 1: Probability of interaction in LSO crystal for 511 keV photons entering crystal surface at 90º

Thickness (mm)	Probability of total absorption (Compton and Photoelectric effect)		Relative Sensitivity of Coincidence absorption
	Single absorption	Coincidence absorption	
10	0.58	0.34	1.0
20	0.82	0.68	2.0
30	0.93	0.85	2.6

A relative increase in absorption of 2.6 times was predicted for an increased crystal thickness from 10mm to 30mm for a co-incidence event of two photons at 511keV entering crystal surface at 90º.

2.2 Increased Acceptance Angle and Detector Size

The commercially available scanner has a limited acceptance angle, which is dependent on compression distance. It is proposed to model 20x5 cm^2 detector with an acceptance angle at 22.5º to normal of the detector; this results in some good events being discarded. This will be compared with a detector 20x20 cm^2 with an unlimited acceptance angle.

The increase in detection sensitivity can be analytically predicted by comparing the spherical cap areas determined by the acceptance angle and the detector size and intra-detector distance. Figure 2 and 3 show the geometry for the two detector configurations, equation 1 is used to calculate the area. The area of the spherical cap[iv] can be calculated by using the following formula:

$$S_{area} = 2\pi hR \qquad (1)$$

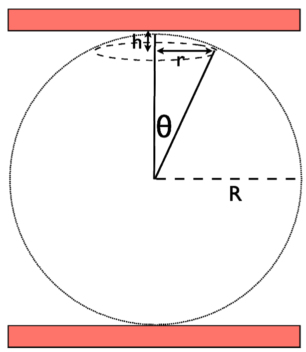

Figure 2: Geometry for calculating the areas of the spherical cap for a 20x5cm^2 detector with the acceptance angle limited (θ) to 22.5º and R= 2.5 cm

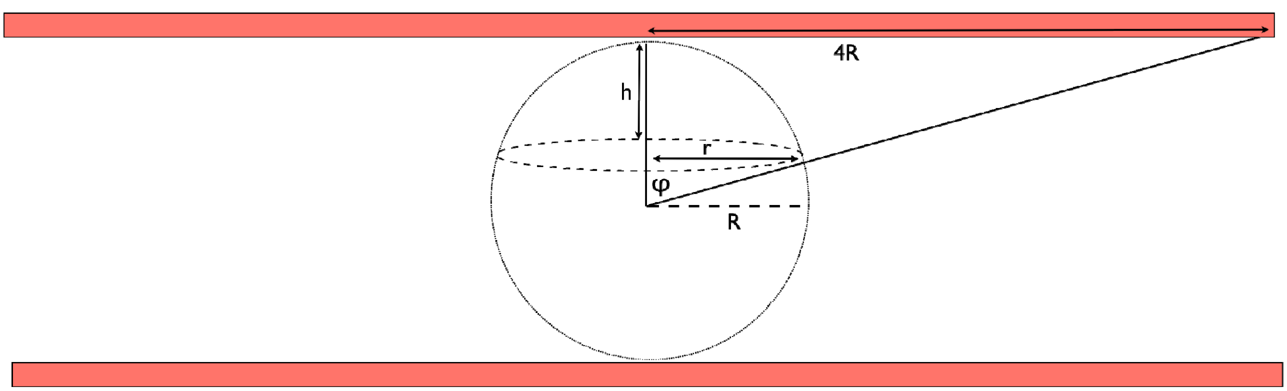

Figure 3: Geometry for calculating the areas of the spherical cap for a 20x20cm^2 detector with unlimited acceptance angle (φ) and R = 2.5 cm

Table 2: Sensitivity of detectors to radiation from the center of the field-of-view for limited and non-limited acceptance angle.

Limited acceptance angle of 22.5º , R=2.5cm	Non-limited with $20x20cm^2$ detector and R= 2.5cm Using similar triangles, see figure 1b
$h = R.(1-\cos(\pi/8))$ $S_a = 2\pi.R.R(1-\cos(\pi/8))$ $S_a = 2\pi.R^2(0.0761)$	$h = R.((\sqrt{17}-1)/\sqrt{17})$ $S_b = 2\pi.R.R.((\sqrt{17}-1)/\sqrt{17})$ $S_b = 2\pi.R^2.(0.757)$

In table 2 it has been shown that the increase in detector sensitivity could give a factor of ~10 times gain in detection efficiency and the maximum angle that would be detected as 80º. By changing the detector configuration to two $20x20cm^2$ LSO detectors and not limiting the acceptance angle, it should be possible to increase the detection efficiency of the system.

3. MONTE CARLO SIMULATIONS

GATE Monte Carlo simulations have been used to compare detector size, acceptance angle and crystal thickness. For all simulations a point source was positioned at the centre of the field of view with an intra-detector space of 5cm containing breast tissue; this is specified in GATE as being made up of 8 elements: Oxygen (52%), Carbon (33%), Hydrogen (10%), Nitrogen (3%), Sulfur (0.2%), Sodium (0.1%), Phosphor (0.1%), Chlorine (0.1%) and a density of $1.020g/cm^3$. The output of the GATE simulation was in the list-mode ASCII format.

3.1 Simulation of commercially available PEM Scanner

For the Monte Carlo simulations of commercially available PEM Scanner, two $20x5cm^2$ LSO detectors spaced 5 cm apart were simulated, with an acceptance angle of 22.5 degrees to detector face normal.

3.2 Increased Scintillator Thickness

In section 2.1 and table 2 it can be seen that by increasing the thickness of scintillator from 10mm to 30mm may result in an increased detection efficiency for a single detector by a factor 1.6. As the PET events are detected in co-incidence this results in a total increase in sensitivity by 2.6. By increasing the thickness of the crystals, the reconstructed image resolution may be decreased; hence methods for depth of interaction correction in crystal need to be applied to maintain system resolution.

3.3 Increased Detector Size

It has been proposed to increase the size of the detector to $20x20cm^2$ as this should increase the detection efficiency of the system by up to 10 times as calculated in section 2.2. The Monte Carlo simulation of the system was modeled for $20x20cm^2$ area detector with 10 and 30 mm crystal thickness; the output of the GATE visualization is shown in figure 4.

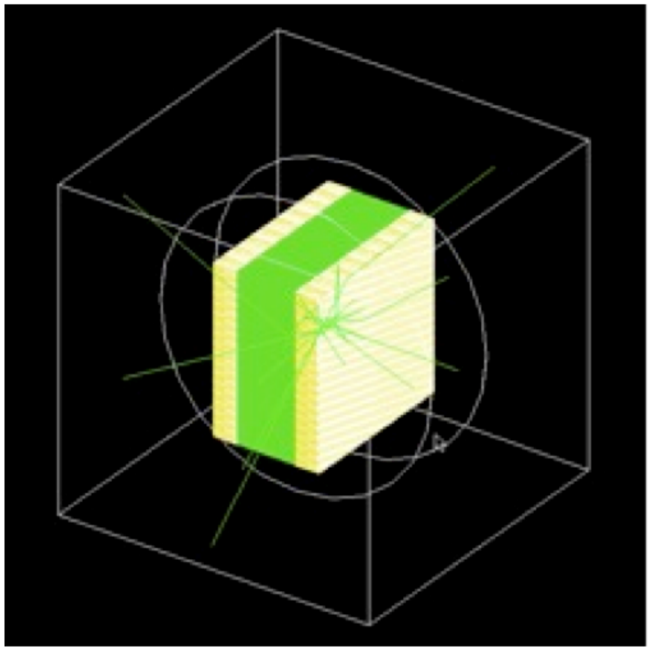

Figure 4: GATE visualization of PEM detector system

The visualization shows the two 20x20cm^2 detectors (yellow) with a thickness of 10mm. The breast tissue is colored green and green lines are photons produced by annihilation events

4. RESULTS

The list-mode ASCII outputs of GATE were processed using an in-house code written using Visual Studio 2003 in C# (*Microsoft, Redmond, WA*), figure 5 shows GUI running on Debian 5 Linux using Mono framework.

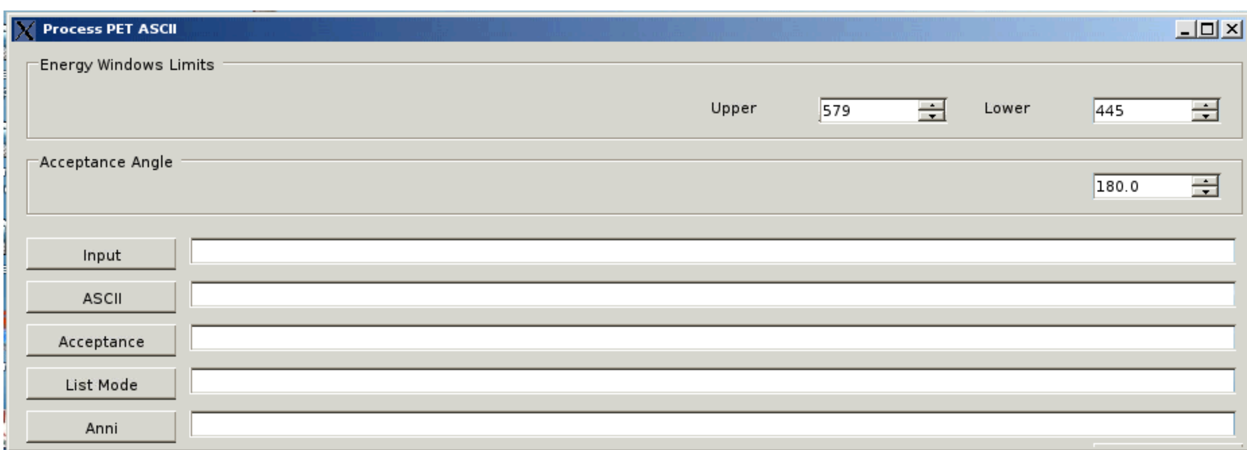

Figure 5: Process PET ASCII (PPA)

PPA was developed to process the ASCII list mode data; it is shown here running under Mono Framework on Debian 5.

For all simulations the energy window was set to be between 445 keV to 579 keV. The results of the processing of the raw list-mode data are shown in tables 3 and 4.

Table 3: Detector co-incidence events for detectors with 10mm thick LSO crystal with limited acceptance angle

Detector	$20x5cm^2$ x10mm	$20x20cm^2$ x10mm
Acceptance angle 22.5º	1430	1435

Table 4: Detector co-incidence events for detector configurations without limitation on acceptance angle

Detector	$20x5cm^2$ x10mm	$20x5cm^2$ x30mm	$20x20cm^2$ x10mm	$20x20cm^2$ x30mm
All events	5625	15158	13088	34504
Relative sensitivity of 10 mm and 30 mm LSO	1	2.7	1	2.63

Table 3 shows that as the size of the detector is increased from $20x5cm^2$ to $20x20xm^2$ and the acceptance angle is limited, that there is not increase in sensitivity. Table 4 shows that for all events without any limit on the acceptance angle, the sensitivity gain of ~2.6 is in good agreement with value calculated in section 2.1.

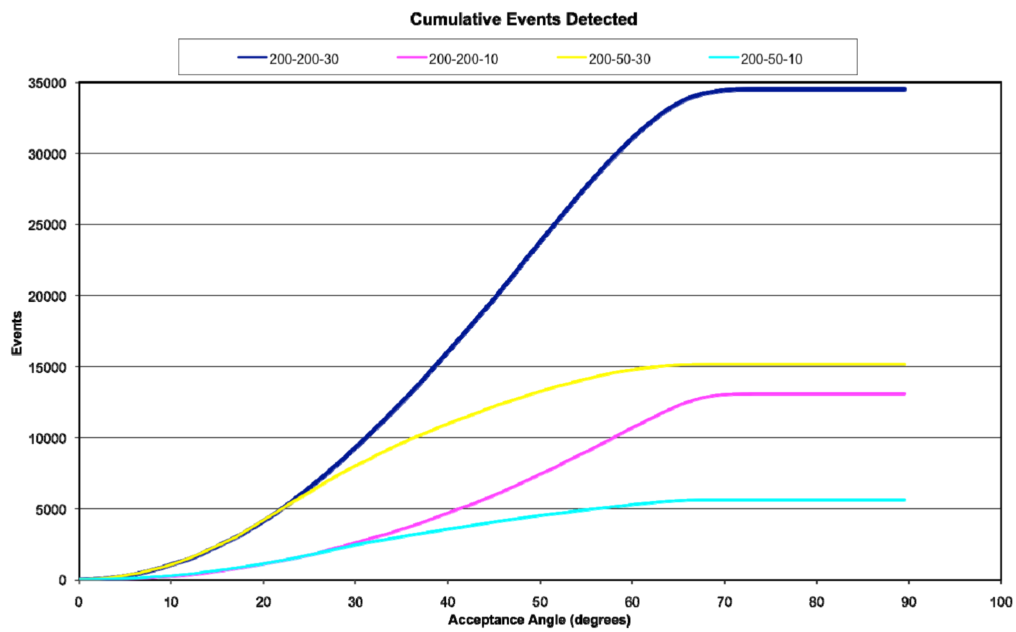

Figure 6: Integrated coincidence events over acceptance angle

Figure 6 shows the integrated coincidence events over acceptance angle, it can be seen that the increase in total counts stops at ~74º which is in agreement with the value calculated in section 2.3. Figure 7 shows that large proportion of the detected events are in the 22.5 to 60 degrees acceptance angle, therefore for increased sensitivity it is important not to limit the acceptance angle of the detector.

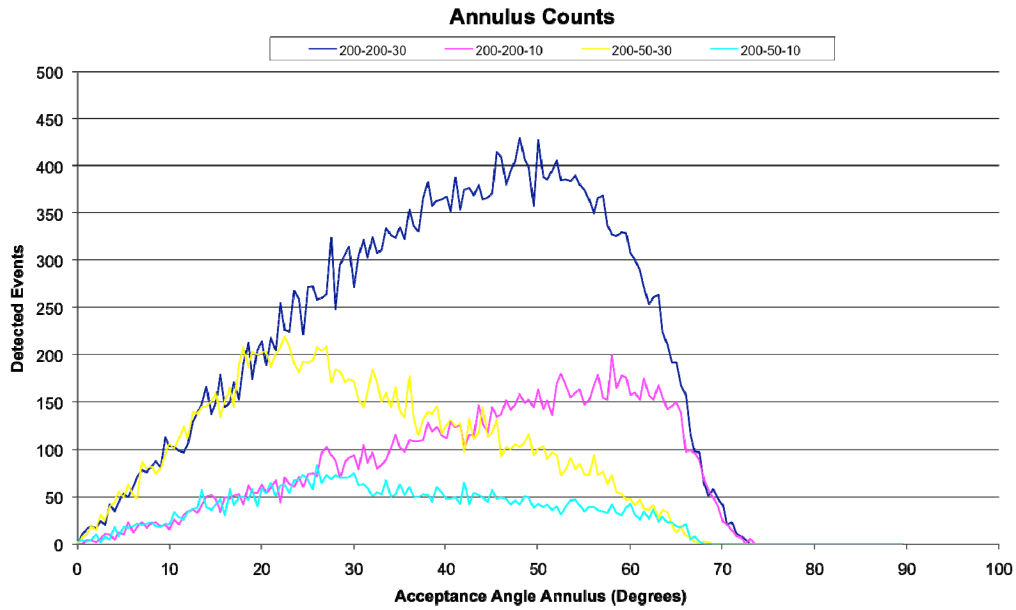

Figure 7: Counts detected in half degree annulus steps

Table 5 shows the all events for detector configurations normalised to the limited acceptance angle of $20x5cm^2x10mm$ crystal. It can be seen that when the detector size is increased to $20x20cm^2$ the total number of counts increases by a factor of 9.15. This is in good agreement with the analytical estimate in section 2.2.

Table 5: All Events for detector configurations normalised to the limited acceptance angle of $20x5cm^2x10mm$ crystal

Crystal thickness	$20x5cm^2$	$20x20cm^2$
10mm	3.93	9.15
30mm	10.6	24.1

When the $20x5cm^2$ x 10mm crystal configuration with limited acceptance angle is compared to $20x20cm^2$ x30mm without limit on acceptance angle, there is an increase from 1430 to 34504 detected co-incidence events; which is a gain in sensitivity of 24 times. This can be explained by an increase of a factor ~2.6 from the detector sensitivity due to the increase in thickness of LSO from 10 to 30mm and a factor of ~9 increase due to a larger detector without limits on acceptance angle. The combination of increasing the crystal size and thickness, without limiting the acceptance angle results in a greatly increased sensitivity of 24 times.

5. CONCLUSIONS

The GATE simulation of PEM has shown it is possible to increase sensitivity of the imaging system by increasing the thickness of the crystal, detector size, considering interaction depth and not limiting the acceptance angle. The increase of LSO crystal thickness from 10mm to 30mm resulted in a sensitivity gain of 2.6 times for 511 keV photons entering the crystal surface at 90º.

Increasing the detector area from 5x20 cm^2 to 20x20 cm^2, and applying depth-of-interaction information to increase the acceptance angle would increase the overall efficiency to radiation emitted from a breast cancer by ~ 9.1 as compared to existing commercial systems restricted to a 22.5 degree angular acceptance. The results have shown the combined effects may increase sensitivity by ~24 times, which could lead to reduced patient absorbed radiation doses for PEM imaging.

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