Maximizing Detection Efficiency of CZT and Scintillator Detectors - A Monte Carlo Study

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***Abstract*— This study investigates the potential advantages of a Compton Positron Emission Tomography (PET) system utilizing Cadmium Zinc Telluride (CZT) detectors, in comparison with conventional PET systems based on scintillator materials such as Lutetium Yttrium Oxyortho-Silicate (LYSO) and Lutetium Gadolinium Oxyortho-Silicate (LGSO). The CZT-based system uses the detection of both photoelectric and Compton scattering events, leading to enhanced spatial resolution and more effective event utilization. Given that Compton scattering dominates at 511 keV, the system achieves a marked improvement in detection efficiency. Through Monte Carlo simulation studies using various detector materials, Compton PET demonstrated superior performance over traditional PET, with the CZT-based system exhibiting the highest spatial resolution and the LGSO-based system achieving the greatest detection efficiency.**

Keywords-CZT; LYSO; LGSO; Compton PET; GATE

I. Introduction

Monte Carlo simulation is a probabilistic method that uses random sampling to model physical processes. In radiation transport, it follows particle trajectories and their interactions with matter based on probability distributions. This allows accurate analysis even in complex geometries and diverse materials [1].

Genat4 Application for Tomographic Emission (GATE) is an open-source toolkit built on the Geant4 platform. It is widely used in nuclear medicine imaging such as PET and Single Photon Emission Computed Tomography (SPECT), as well as in radiotherapy [2], [3]. PET, in particular, is commonly applied in clinical practice for tumor detection, neurological disorder evaluation, and cardiovascular studies. GATE enables simulation of medical imaging systems and dynamic behavior of radiation sources, making it valuable for both research and clinical applications.

Most PET systems used in clinics today are based on lutetium-based scintillators, such as Lutetium Oxyortho-Silicate (LSO), LYSO, or LGSO. These materials have high atomic numbers and densities, which lead to good detection efficiency. However, in scintillator-based PET systems, the z-axis information of detected radiation cannot be distinguished. In addition, the resolution of these systems is limited by the size of the scintillator pixels and the connected photodetectors. This can reduce the accuracy of PET images, which is important for medical diagnosis. Although combining PET with high-resolution Computed Tomography (CT) or Magnetic Resonance Imaging (MRI) images can help provide better anatomical detail [4], improving the resolution of PET itself is still an important goal.

Semiconductor materials such as CZT show lower detection efficiency than scintillators but provide much higher resolution. They can also identify z-axis information accurately. As a result, Compton scattering events, which are regarded as invalid data, can be used as valid data and improve detection efficiency. In this study, a micro-PET system using pixelated CZT detectors was tested as an alternative. CZT has lower atomic number and density compared to common scintillators, so its basic detection efficiency is lower. However, it offers much better energy and position resolution. Also, pixelated CZT can detect both photoelectric and Compton scattering events by identifying the interaction point inside the detector. This makes it possible to improve overall detection efficiency [5]. Monte Carlo simulation results showed that the CZT-based Compton PET had about three times higher efficiency than a conventional PET with the same setup. The performance of this system was compared with LYSO and LGSO PET systems, focusing on detection efficiency and image quality.

The Materials and Methods section describes the scintillator PET and semiconductor PET systems simulated using GATE. The Results and Conclusion sections present the improved detection efficiency achieved through the use of Compton scattering and the resolution of the semiconductor PET system.

II. Materials And Methods

Monte Carlo simulations were conducted using GATE 9.0. LYSO and LGSO scintillators had compositions of $Lu_{0.4}Y_{1.6}SiO_5$ and $Lu_{1.9}Gd_{0.1}SiO_5$ respectively [6], and were voxelized into 7 mm × 1.5 mm × 1.5 mm elements. A cylindrical water phantom (radius: 10.39 mm, height: 1.5 mm) was placed at the center and surrounded by 40 scintillator detectors. For the CZT PET system, 100 detector modules (20 mm × 0.5 mm × 1 mm) were used, each consisting of 1 mm × 0.5 mm × 1 mm voxels (Figure 1).

Scintillators require photodetectors at the backend, which makes the detector size larger compared to CZT. In addition, since semiconductors can identify z-axis information, a

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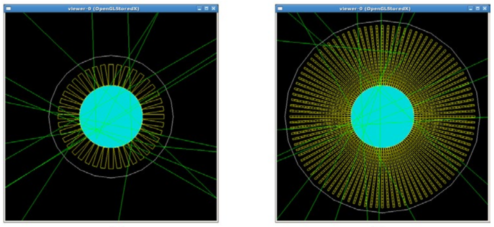
single detector module was divided into several parts for the simulation.



(a) (b)

Figure 1. Geometry of PET system (a) LYSO and LGSO PET (b) CZT PET

Eight disk-shaped positron sources with radii from 0.3 mm to 2.05 mm, in 0.25 mm steps, were simulated (Figure 2).

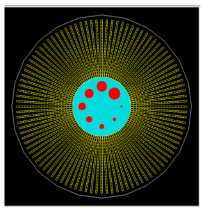


Figure 2. Position and size of positron sources

Image reconstruction was performed using the Filtered Back-Projection (FBP) method. Evaluations included: (1) comparison between images using photoelectric-only vs. photoelectric plus Compton events, (2) visual inspection based on varying source sizes, and (3) calculation of Relative Standard Deviation (RSD) for the largest sources to assess noise.

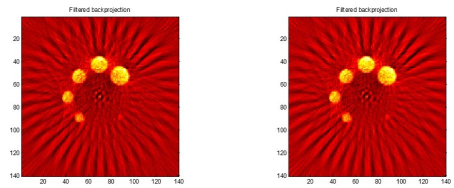
III. Results

Table I showed the detected counts for LYSO, LGSO, CZT PET.

TABLE I. Detected Counts for Each PET System

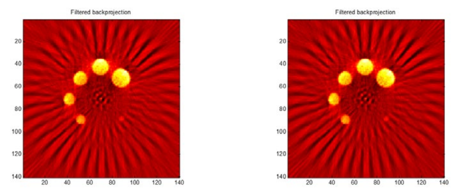
	LYSO PET	LGSO PET	CZT PET
Photoelectric events only	311,078	1,499,760	311,325
Photoelectric and Compton scattering	354,345	1,665,079	369,375

More than 10% of detection efficiency increased in all PET systems when both photoelectric and Compton scattering events were considered in the reconstruction process. Among the three systems, LGSO PET showed the highest efficiency—approximately five times greater than the others—due to its high concentration of lutetium, which has the highest atomic number and density among the materials used. The lutetium content in LGSO is roughly four times that of LYSO, which explains the significant difference. In contrast, the efficiency of the CZT-based PET was comparable to that of LYSO. The gain from including Compton events in CZT PET was lower than reported in earlier studies [5], likely because the design used in this work had relatively large gaps between adjacent CZT detector modules.



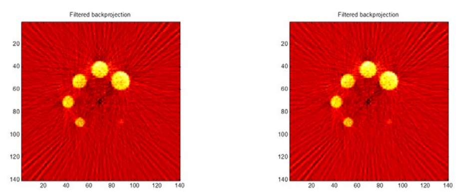
(a) (b)

Figure 3. Filtered backprcjection images for LYSO PET
(a) photoelectric events only (b) photoelectric and Compton scattering



(a) (b)

Figure 4. Filtered backprcjection images for LGSO PET
(a) photoelectric events only (b) photoelectric and Compton scattering



(a) (b)

Figure 5. Filtered backprcjection images for CZT PET
(a) photoelectric events only (b) photoelectric and Compton scattering

As shown in Figure 3-5, images reconstructed using both photoelectric and Compton events had lower noise than those using photoelectric events only, as expected. LGSO PET showed less noise compared to LYSO PET, which can be explained by its higher detection efficiency. In terms of spatial resolution, the CZT PET system successfully visualized all sources, including the smallest one, unlike the other systems. This result highlights the advantage of CZT in resolving fine details. However, the bottom source was not reconstructed by any of the PET systems, even though it was larger than some others. This may be due to limitations in the reconstruction algorithm.

TABLE II. RSD of Each PET System

	LYSO PET	LGSO PET	CZT PET
Photoelectric events only	0.0687	0.0683	0.0706
Photoelectric and Compton scattering	0.0678	0.0677	0.0701

Table II shows the relative standard deviation (RSD) measured over a 10×10 pixel area for the largest source in each system. In all cases, the RSD values of Compton PET were lower than those of conventional PET. These findings indicate that Compton PET provides improved image quality compared to conventional PET systems.

IV. CONCLUSION

Three evaluation methods were applied to assess both Compton and conventional PET systems using LYSO, LGSO, and CZT detectors. In all cases, Compton PET showed higher detection efficiency than conventional PET, leading to improved image quality. Among the systems tested, CZT PET provided the highest spatial resolution, while LGSO PET achieved the best detection efficiency, resulting in the lowest image noise. Overall, Compton PET technology proved effective for all detector types. Most commercial PET systems currently in use are made only with scintillators. Since they treat only the photoelectric effect as valid data, a large amount of information is discarded. However, by applying the semiconductor-based Compton PET technology proposed in this study, both higher resolution and improved detection efficiency can be expected.

Future research will focus on developing methods to maximize the use of Compton scattering, which occurs more than three times as often as the photoelectric effect at 0.511MeV, as valid data. In addition, simulations with smaller sources will be conducted to analyze in greater detail the advantages of semiconductor detectors.

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