IJBBE International Journal of Biophotonics & Biomedical Engineering Vol. 4, No. 1, Spring-Summer, 2024

Research Article

Comparative analysis of PET image characteristics using two types of crystals BGO and LYSO with GEANT4 simulation

M. Golshanipour [a] and Sh. Shahi [*b]

a Department of Biomedical Engineering, Isfahan (Khorasgan) branch Islamic Azad University, Isfahan, Iran.
b Department of Biomedical Engineering, Laser and Biophotonics in Biotechnologies Research Center, Isfahan (Khorasgan) branch, Islamic Azad University, Isfahan, Iran

***Corresponding author:** shahilaser@khuisf.ac.ir

DOI: 10.71498/ijbbe.2024.1128184

ABSTRACT

Received: Aug. 4, 2024, Revised: Jan. 3, 2025, Accepted: Jan. 4, 2025, Available Online: Jan. 27, 2025

Positron emission tomography is a nuclear imaging technique that uses radiotracers to observe the body's metabolic activities in real time. Key to PET systems are the scintillation crystals in detectors, which impact image quality. This study examines BGO and LYSO crystals, analyzing optical yield, decay time, energy resolution, and contrast using GEANT4 simulations. In this simulation, G4EmStandardPhysics was employed as the primary physics model Results show distinct performance patterns between the crystals that the BGO recorded an average of 499 energy deposition events, slightly higher than LYSO's 485.9. The BGO also achieved a higher patient dose score of 3.06126 versus 3.04326 for LYSO. Both crystals show similar behavior in energy depositions per crystal block, with BGO at 13.14 and LYSO at 13.02, but LYSO had a more concentrated energy distribution and better resolution. The findings indicate the BGO's strengths in interaction rates, cost, and durability, while the LYSO offers enhanced resolution due to more focused energy distribution. This study highlights the trade-offs between the BGO's affordability and higher interaction rate in comparison with the LYSO's superior image resolution based on specific imaging and priorities. This study, as an innovative approach and in contrast to previous studies, directly and simultaneously compared the characteristics of these two types of crystals. Enhancing the accuracy of disease diagnosis and improving the performance of PET systems are among the outcomes of this study.

KEYWORDS

PET imaging, GEANT4 simulation, BGO and LYSO crystals, Energy deposition, Dosimetry.

I. INTRODUCTION

PET is a nuclear medical imaging method used to study the metabolic and molecular functions of the human body. In this technique, positron-emitting radioisotopes, such as Fluorine-18, are used to label biologically active molecules. PET detectors identify these photons and record their positions. This information is then used to reconstruct three-dimensional images of the radioisotope distribution in the body [1,2]. Artificial intelligence and deep learning in enhancing positron emission tomography image reconstruction stating that these technologies significantly improve image quality and diagnostic performance compared to traditional methods [25,26,27].

Total-body imaging modalities provide advantages such as higher sensitivity and low-dose imaging, but high construction costs limit their global use [28].

This paper compares two widely used scintillation crystals, BGO and LYSO, which are essential components in PET imaging systems. Their distinct physical properties, including energy resolution, light yield, and decay time, affect their performance and are evaluated using GEANT4 simulations.

The choice of PET detector crystal type is a key factor in determining image quality. BGO and LYSO are two common crystals that are used in PET imaging, each with its advantages and disadvantages. BGO is less expensive and more durable, but it has lower image resolution compared to LYSO. LYSO offers higher image resolution but is more expensive and more prone to breakage [3,4].

GEANT4 simulation is a powerful tool for simulating PET systems. This tool can simulate the paths of particles and their interactions with matter. GEANT4 simulations can be used to compare the performance of BGO and LYSO in PET systems under different geometries and conditions [5].

PET detectors are key components of PET systems that are used to detect gamma photons emitted from radiopharmaceuticals. These photons are then used to generate three-dimensional images of the distribution of radiopharmaceuticals in the patient's body [6].

BGO is an inorganic crystal with the chemical formula Bi3Ge4O12. Due to its unique physical properties, BGO finds applications in a wide spectrum of uses including nuclear medical imaging, particle detection, and nonlinear optics [7].

With a density of 7.13 g/cm³, BGO is known as one of the densest crystals. This high density makes BGO a highly efficient detector for ionizing radiation such as gamma rays and X-rays. BGO has a high light output capability, meaning it can produce a significant amount of light when stimulated by ionizing particles. This property makes BGO an ideal material for light detectors in nuclear medical imaging and particle detection. BGO has high thermal stability and can operate without degradation at high temperatures. This property makes BGO suitable for applications that require performance in harsh environments, such as particle detection in space. BGO is widely available and can be easily obtained in various shapes and sizes [8].

LYSO is a type of scintillator crystal that is increasingly used in PET imaging due to its superior physical properties compared to traditional crystals like BGO [9].

BGO and LYSO are two popular crystals used for photon detection in PET imaging. Each crystal has its advantages and disadvantages, which should be considered when selecting the appropriate crystal for a specific application.

Density: BGO has a density of 7.13 g/cm³, while LYSO has a density of 7.1 g/cm³. The higher density of BGO allows it to detect higher energy photons more effectively.

Attenuation Length: BGO has a shorter attenuation length for 511 keV (1cm) compared to LYSO (1.2 cm). This means that BGO more effectively absorbs the light produced by positron particles, resulting in PET images with better spatial resolution.

Light Yield: BGO has a higher light yield (30,000 photons/MeV) compared to LYSO (8,000–10,000 photons/MeV). This means that BGO produces more light for each detected positron particle, leading to PET images with less noise.

Dead Time: BGO has a longer dead time (300 ns) compared to LYSO (37–45 ns). This means that BGO requires more time to reset after detecting a positron particle before it can detect the next particle. This can affect the speed of PET imaging.

Durability: BGO is more durable compared to LYSO, making it more resistant to mechanical and chemical damage.

Sensitivity: BGO generally has higher sensitivity than LYSO due to its higher density, which allows it to absorb more photons.

Cost: LYSO is generally more expensive than BGO due to the rarer materials used in LYSO.

Applications: LYSO is popular for applications requiring high spatial resolution, such as imaging small tumors (Table 1).

Energy Deposition in Detector Materials:

Energy Deposition in Detector Materials is the process by which incoming particles, like gamma rays in PET imaging, transfer energy to a detector material (e.g., BGO or LYSO crystals). According to equation 1, the energy transfer produces light photons, which are converted into electrical signals for image reconstruction.

$$E_{dep}=E_{initial}\cdot e^{-\mu . x} \quad (1)$$

Where $E_{initial}$ is the initial photon energy, μ is the attenuation coefficient of the material, and x is the depth of interaction within the crystal. This relation can help quantify how material properties influence energy retention.

Spatial Resolution and Image Quality:

The resolution of PET images can be impacted by detector design and material. Equation 2 shows the spatial resolution based on detector size and geometry.

$$\text{Resolution}=\frac{\boldsymbol{K}}{\boldsymbol{D}} \quad (2)$$

Where k is a constant determined by detector properties, and D represents detector dimensions or separation distance

Detection Efficiency:

A formula 3 relating the detection efficiency to the crystal material and thickness could be helpful in the methodology section to show how these parameters affect sensitivity.

$$\eta=1-e^{-\mu . d} \quad (3)$$

Where η is the detection efficiency, μ the material's linear attenuation coefficient, and d the thickness of the crystal.

Noise and Signal-to-Noise Ratio (SNR):

The signal-to-noise ratio in terms of count rate and noise factors may help readers understand how different energy thresholds impact image clarity as shown in equation 4:

$$SNR=\frac{C}{\sqrt{C+N}} \quad (4)$$

Where C is the count rate (signal), and N is the noise or background counts.

Table 1 Comparison between the BGO and LYSO for PET Imaging [10].

Feature	BGO	LYSO
Density (g/cm³)	7.13	7.1
Attenuation Length for 511 keV (cm)	1	1.2 mm
Effective Atomic Number (Zeff)	74	60
Light Yield (photons MeV^{-1})	30000	8000-10000
Dead Time (ns)	300	37-45
Peak Wavelength (nm)	480	420
Durability	High	Medium
Cost	Low	High

GEANT4 is an open-source software framework used for simulating the passage of particles through matter. GEANT4 is a complex tool that requires knowledge of programming and physics to use effectively. This powerful tool is utilized by physicists and engineers worldwide for simulating a wide range of applications [11].

Nuclear medicine systems utilize radioisotopes for both diagnosis and treatment of diseases.

Simulating these systems using tools like GEANT4 can lead to a better understanding of their performance, optimization of their design, and development of new therapeutic methods. In such simulations, various parameters can be studied, including absorbed dose in different tissue parts, dose distribution within tissues, distribution of alpha, beta, gamma, and neutron particles within tissues, production of radionuclides, and tracking their trajectories within the body, among others. This information enhances the understanding of radiation effects on cells and biological tissues, ultimately facilitating improvements in therapeutic methods. [12].

This research focused on several key performance parameters that influence the efficiency and precision of the crystals in PET systems. These include:

- Energy Deposition
- Decay Time
- Light Yield
- Energy Resolution
- Timing Resolution
- Detection Efficiency
- Photon Absorption and Light Yield Distribution

While energy deposition and decay time are essential in evaluating the basic performance of scintillation crystals, the inclusion of energy resolution, timing resolution, and detection efficiency allows for a more comprehensive comparison between BGO and LYSO

In this simulation, G4EmStandardPhysics was employed as the primary physics model to handle electromagnetic interactions, including processes such as ionization, excitation, and photon interactions. Additionally, G4DecayPhysics and G4RadioactiveDecayPhysics were utilized to accurately simulate particle decays, which are critical to this simulation due to the inclusion of decay processes.

The cutoff energy was set to the default value in Geant4, which corresponds to a range cutoff of 0.7 mm. This default cutoff ensures a balance between computational efficiency and the accuracy of the particle tracking.

II. MATERIAL AND METHODS

Both BGO and LYSO were modeled using the same simulation parameters (as shown in Table 2), where the homogeneous cylinder of brain tissue represented the patient. A total of 1000 events were simulated for each crystal type.

Table 2 Simulation specifications for the BGO and LYSO Crystals

Parameter	BGO ($Bi_4Ge_3O_{12}$)	LYSO ($Lu_1.^8Yb_0.^2SiO_5$)
Dimensions	Length (dx) = 6 cm Width (dy) = 6 cm Thickness (dz) = 3 cm	Length (dx) = 6 cm Width (dy) = 6 cm Thickness (dz) = 3 cm
Number of Crystal Blocks	-	-
Density (g/cm³)	7.13	7.1
Zeff	74	60
Decay Time (ns)	300	37-45
Patient Representation	Homogeneous cylinder of brain tissue	Homogeneous cylinder of brain tissue
Patient Position	Center of the complete detector	Center of the complete detector
Total Number of Simulated Events	1000	1000

The crystal_edep_event_Id chart examines the amount of energy deposited in each crystal for each simulated event. This chart facilitates the comparison of energy deposition patterns and distributions in PET images obtained with BGO and LYSO crystals. This information can be useful in improving the algorithms and methods for image reconstruction in PET imaging (Fig. 1 & Fig. 2).

The crystal_edep_event_cell chart shows the distribution of energy deposition in each crystal cell for each simulated event. This chart aids in identifying the points within each crystal that receive higher energy deposition. This information can be used to improve the accuracy and quality of PET images.

The crystal_edep_score chart assigns a score to each simulated event in the BGO and LYSO crystals based on specific criteria. These criteria can reflect the quality and performance of the crystals in PET imaging. The information obtained from this chart can be used to select the best crystal for use in PET imaging systems and to improve the quality and accuracy of the images.

III. RESULT

The results for the BGO and LYSO crystals have been obtained for 1000 events. These results include the following:

Crystal_edep_eventId shows the distribution of the number of energy depositions in the crystal based on the event ID (eventId). In other words, it indicates how many energy depositions occur in a particular crystal for different events.

For the LYSO crystal, the average number of events is 485.9 with a standard deviation of 287.7. This means that, on average, about 485.9 times energy is deposited in the LYSO crystal among various events, and this distribution has a relatively large spread with a standard deviation of 287.7.

Similarly, for the BGO crystal, the average number of events is 499.0 with a standard deviation of 288.1. This means that about 499.0 times energy is deposited in the BGO crystal among various events average, and this distribution also has a relatively large spread with a standard deviation of 288.1.

Based on these results, it can be concluded that the distribution of energy depositions in the BGO and LYSO crystals is on average close to each other. However, there are variations in their values which are reflected in their standard deviations.

Crystal_edep_cell indicates the distribution of the number of energy depositions in each individual crystal block within the PET detector crystal array. This chart visually shows which crystal blocks are more involved in the energy deposition process (Fig. 3 & Fig. 4).

For the BGO crystal, the average number of events in the crystal blocks is 13.14 with a standard deviation of 9.72. This means that for different blocks of the BGO crystal, on average, about 13.14 times energy is deposited in each block, and this distribution has a relatively large spread with a standard deviation of 9.72.

Similarly, for the LYSO crystal, the average number of events in the crystal blocks is 13.02 with a standard deviation of 9.873. This means that for different blocks of the LYSO crystal, on average, about 13.02 times energy is deposited in each block, and this distribution also has a relatively large spread with a standard deviation of 9.873.

Based on these results, it can be concluded that the distribution of energy depositions in the blocks of BGO and LYSO crystals is on average close to each other. However, there are variations in their values. This indicates that the energy deposition process in crystals is not random and depends on various factors such as crystal geometry, particle type, and energy.

Crystal_edep_score shows the distribution of energy deposition events based on energy levels (MeV). This chart indicates how many of the energy depositions have different energy levels (Fig. 5 & Fig. 6).

For the BGO crystal, the average number of energy deposition events is 0.3887 with a standard deviation of 0.1592. This means that for energy depositions in the BGO crystal, the average number of events is about 0.3887 times, and this distribution has a relatively large spread with a standard deviation of 0.1592.

Similarly, for the LYSO crystal, the average number of energy deposition events is 0.3929 with a standard deviation of 0.1578. This means that for energy depositions in the LYSO crystal, the average number of events is about 0.3929 times, and this distribution also has a relatively small spread with a standard deviation of 0.1578.

Based on these results, it can be concluded that the distribution of energy deposition in the BGO and LYSO crystals differs at various energy levels. Additionally, the LYSO crystal has less dispersion in the number of events compared to the BGO crystal, suggesting that its distribution is more concentrated and less scattered.

This table summarizes the findings from the GEANT4 simulation for LYSO over 1000 events (table 3 & table 4).

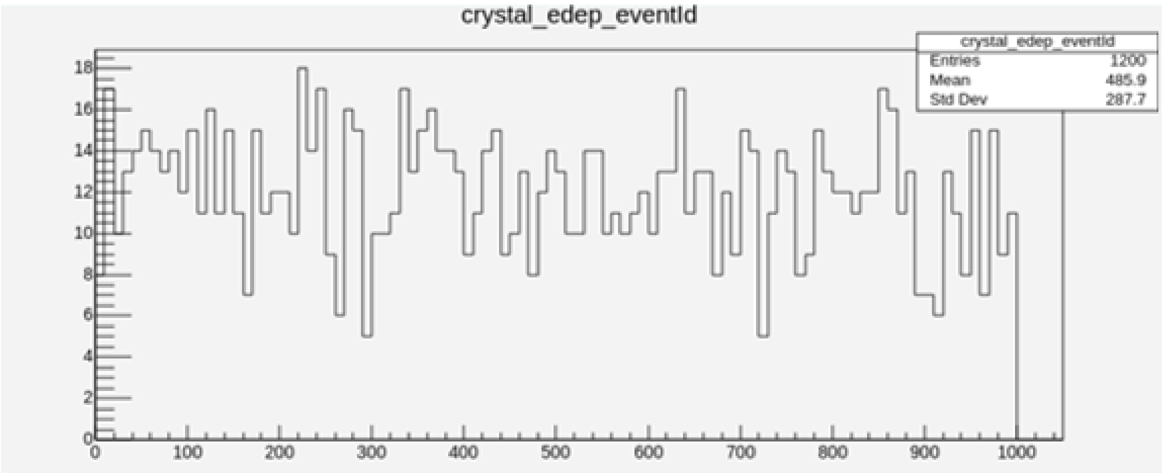

Fig. 1 Crystal_edep_eventId related to LYSO crystal

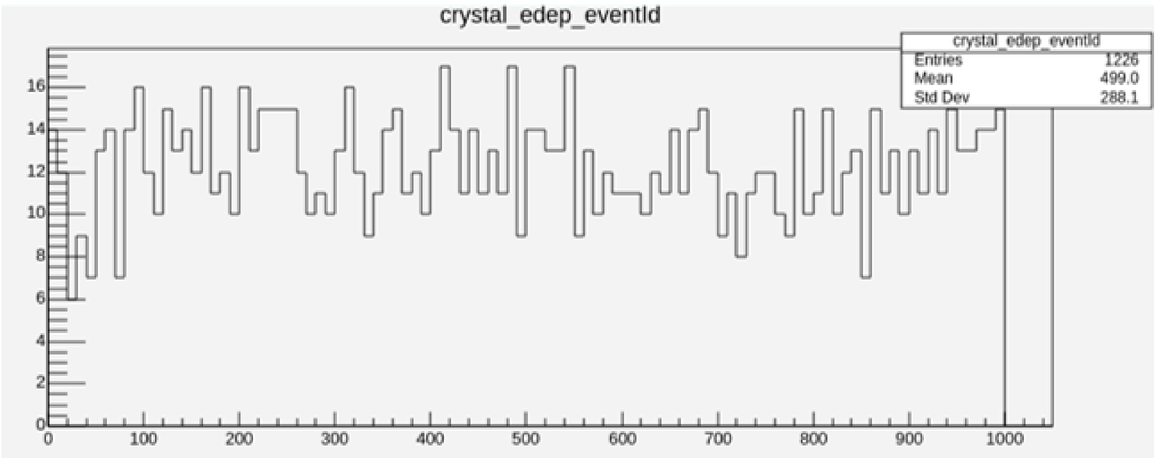

Fig. 2 Crystal_edep_eventId related to BGO crystal

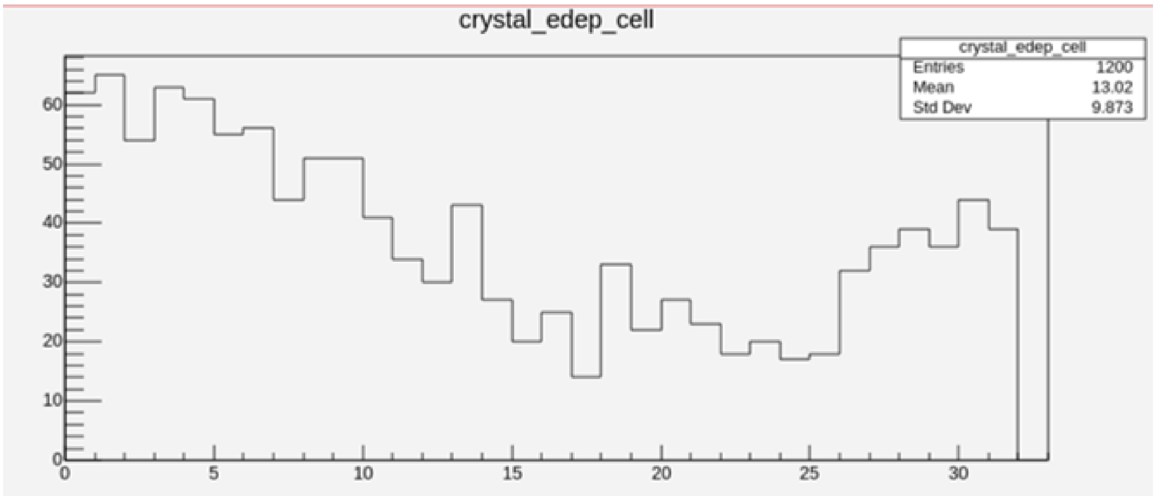

Fig. 3 Crystal_edep_ cell related to LYSO crystal

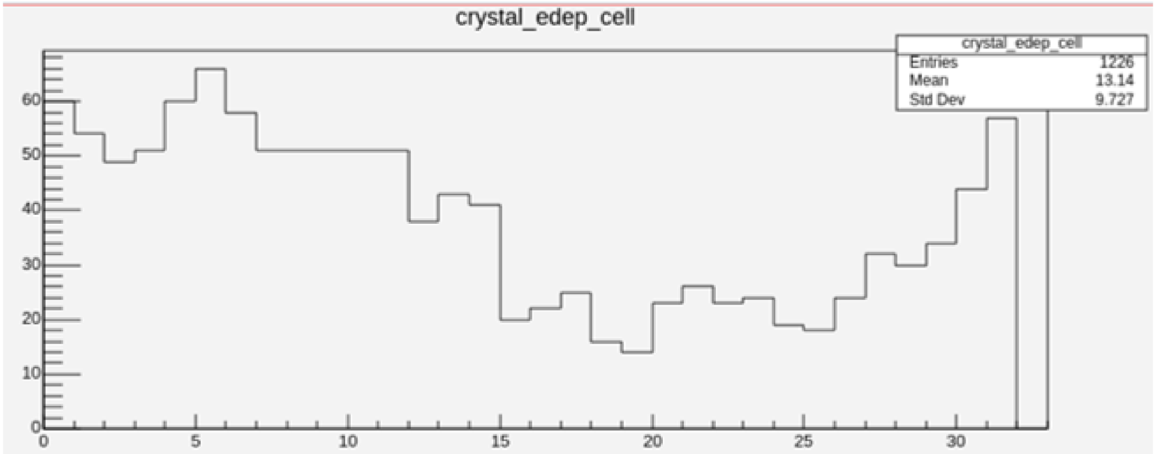

Fig. 4 Crystal_edep_ cell related to BGO crystal

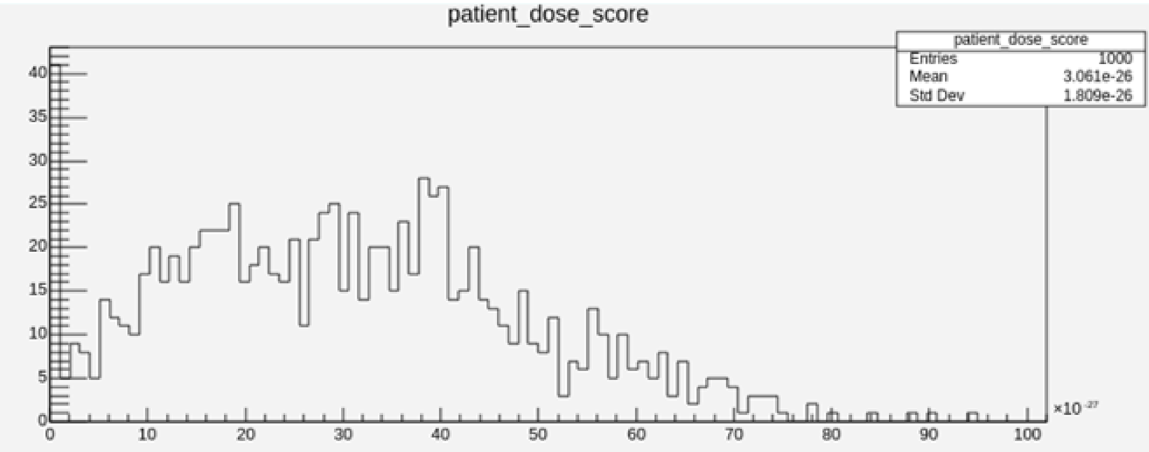

Fig. 5 Patient_dose_score related to BGO crystal

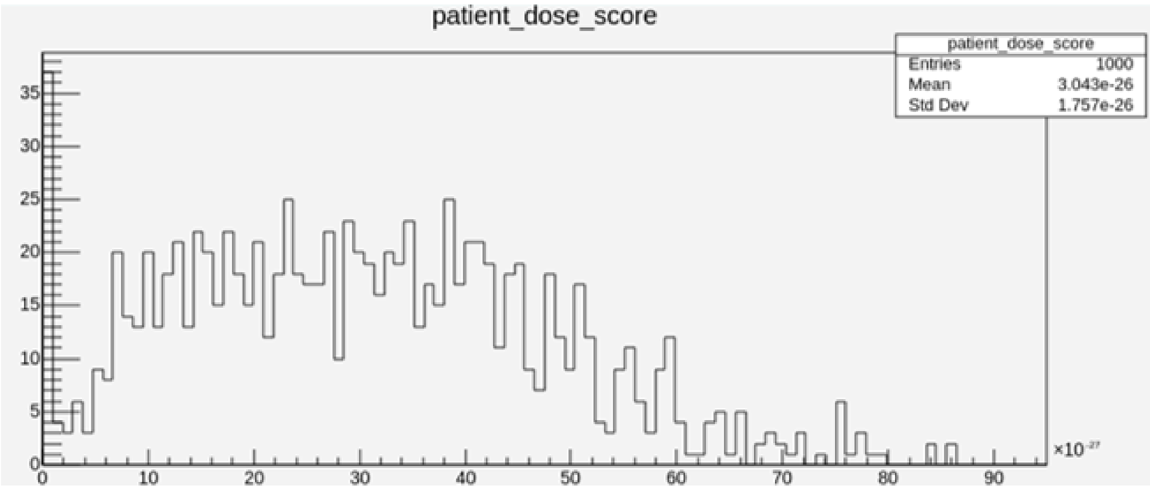

Fig. 6 Patient_dose_score related to LYSO crystal

TABLE 3 THE FINDINGS RESULT FROM THE GEANT4 SIMULATION FOR LYSO FOR 1000 EVENTS

	Crystal_edep eventId	
	Entries	1200
	Mean	485.9
	Std. Dev	287.7
	Crystal_edep cell	
	Entries	1200
	Mean	13.02
	Std. Dev	9.873
	Crystal_edep score	
	Entries	1200
	Mean	0.3929
LYSO	Std. Dev	0.1578
	Patient Dose_score	
	Entries	1000
	Mean	3.04326
	Std. Dev	1.75726

TABLE 4 THE FINDINGS RESULT FROM THE GEANT4 SIMULATION FOR BGO FOR 1000 EVENTS

	Crystal_edep eventId	
	Entries	1226
	Mean	499
	Std. Dev	288.1
	Crystal_edep cell	
	Entries	1226
	Mean	13.14
	Std. Dev	9.727
	Crystal_edep score	
BGO	Entries	1226
	Mean	0.3887
	Std. Dev	0.1592
	Patient Dose_score	
	Entries	1000
	Mean	3.06126
	Std. Dev	1.80926

IV. DISCUSSION

Several studies have discussed the benefits of using different crystals in detectors employed for radiation measurement. Additionally, some studies, due to the dependence of tomography on the characteristics of detector materials, are actively exploring the potential of innovative phosphors (scintillating materials). Therefore, it appears that most efforts are focused on the properties of materials with high density and high atomic number, such as their decay time.

However, some studies have failed to find useful experimental materials for PET phosphors [13]. Recently, some studies have discussed the modeling of materials for PET [14, 15], hoping that improving physical knowledge about scintillation processes can lead to the prediction of new phosphor material properties that may be useful for their modeling. Although the materials used for scintillation are slightly affected by temperature, they have wide applications in the field of radiation detection and protection in medicine [15, 16].

Moreover, some studies have combined known phosphors with new methods, such as phoswich detectors, which are made of two dissimilar phosphors in one detector to create new detectors [21]. Dahlbom and colleagues have researched LSO and NaI(Tl) layers for PET and SPECT, respectively [24]. The scintillation crystals used in PET are made of inorganic materials that can convert high-energy photon beams (511 keV) into a number of fluorescent photons [20]. In this study, the physical properties of two scintillation detectors, including BGO and LYSO, were examined using GEANT4 Monte Carlo simulation.

The comparison of BGO and LYSO in terms of energy deposition shows trade-offs between BGO's higher atomic number and LYSO's superior energy resolution. While BGO absorbs more gamma-ray energy through the photoelectric effect, LYSO's improved resolution offers more precise energy measurements.

In this study, the performance of BGO and LYSO was compared by using GEANT4 simulations, focusing on key parameters such as energy deposition, decay time, energy resolution, and patient dose score. These findings indicate that although both crystals show similar energy deposition behaviors, they offer distinct advantages depending on the specific needs of the PET system.

Energy resolution was one of the key differences between the two crystals. LYSO outperformed BGO in energy resolution, as seen from its narrower distribution of energy deposition events. This improved resolution in LYSO is crucial for enhancing image quality and precision in PET imaging, making it an ideal choice for applications that require high spatial resolution, such as imaging small tumors or detecting fine details in the body.

BGO, on the other hand, demonstrated a higher energy deposition average, reflecting its higher light yield. This property makes BGO advantageous in terms of photon absorption and sensitivity, which can be useful for detecting weaker signals in high-energy environments. However, BGO's wider energy distribution resulted in a less clear distinction between energy levels, potentially leading to more noise in the resulting images compared to LYSO.

In GEANT4 simulations, which is a toolkit for modeling the passage of particles through matter, the number of events has a profound impact on the energy deposition in a PET system, reflecting real-world scenarios. GEANT4 facilitates the representation of particle interactions and energy deposition, where the number of events plays a pivotal role. In GEANT4 simulations for PET systems, the number of events is crucial in determining the accuracy, precision, and reliability of the simulated results. Increasing the number of events generally leads to more robust and informative simulations, which are essential for understanding system behavior and accurately interpreting simulated data.

V. CONCLUSION

This study compares the performance of BGO and LYSO scintillator crystals in PET imaging, using GEANT4 simulations. BGO showed higher energy deposition but lower energy resolution compared to LYSO. LYSO, with its better spatial resolution and shorter decay time, is advantageous for applications requiring high precision. The study's findings align with previous research, which has shown BGO's superior photon absorption but lower spatial resolution compared to LYSO. The choice between these crystals depends on the specific requirements of the PET system, including resolution, sensitivity, and cost. Further experimental studies are needed to validate these simulation results and optimize PET systems for improved diagnostic performance.

The PET system with LYSO shows effective performance, characterized by smoother shapes, a significant number of entries corresponding to the 511 keV energy level, and highly comparable absorbed dose values. However, BGO emerges as a stronger option, offering smoother shapes like LYSO, a notable distribution of interactions across different blocks, and clear superiority in terms of the number of interactions, mean values, and entries around 511 keV. Notably, BGO's superiority is further confirmed by its better performance in the number of entries, mean values, and interactions, indicating its potential as a more effective choice for PET imaging under simulated conditions

However, choosing between LYSO and BGO in PET systems involves trade-offs that encompass factors such as atomic number, density, decay time, light output, and cost. This decision depends on the unique needs of the PET system and takes into account factors such as energy resolution, sensitivity, cost, and overall performance. Evaluating priorities, whether emphasizing energy resolution, superior timing, cost-effectiveness, or other application-specific factors, is crucial. In practice, determining the "better" crystal involves aligning the choice with the specific needs and priorities of the PET system while considering the inherent strengths and trade-offs of each type of crystal.

Acknowledgment

This study does not involve any experiments or interventions on humans. Therefore, there is no need for informed consent from human participants. This study was conducted with the permission and support of Isfahan Islamic Azad University, Iran.

References

[1] TOWNSEND D. W. et al. "Physical principles and technology of clinical PET imaging," Annals-Academy of Medicine Singapore, vol. 33, pp. 133-145, 2004.

[2] BASU Sandip, et al. "Fundamentals of PET and PET/CT imaging," Annals of the New York Academy of Sciences, vol. 1228, pp. 1-18, 2011.

[3] GUNDACKER S. et al. "Time resolution deterioration with increasing crystal length in a TOF-PET system," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 737, pp. 92-100, 2014.

[4] MELCHER Charles L. "Scintillation crystals for PET," Journal of Nuclear Medicine, vol. 41, pp. 1051-1055, 2000.

[5] AHMED Abdella M., et al. "A validated Geant4 model of a whole-body PET scanner with four-layer DOI detectors," Physics in Medicine & Biology, vol. 65, pp. 235051, 2020.

[6] MARSDEN Paul K. "Detector technology challenges for nuclear medicine and PET," Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, vol. 513, pp. 1-7, 2003.

[7] TOWNSEND, David W., et al. A rotating PET scanner using BGO block detectors: design, performance and applications. Journal of Nuclear Medicine, 1993, 34.8: 1367-1376.

[8] TURKINGTON Timothy G. et al. "Performance of a BGO PET/CT with higher resolution PET detectors," In: IEEE Nuclear Science Symposium Conference Record, IEEE, vol. 4, pp.-1894, 2005.

[9] D.U. Junwei, et al. "Physical properties of LYSO scintillator for NN-PET detectors," In: 2009 2nd international conference on biomedical engineering and informatics. IEEE, pp. 1-5, 2009.

[10] D.U. Junwei, et al. "Performance comparison of dual-ended readout depth-encoding PET detectors based on BGO and LYSO crystals," Physics in Medicine & Biology, vol. 65, pp. 235030, 2020.

[11] BHATNAGAR Sonali, SIRISHAS. N. L. "GEANT4 & GAMOS—A particle implementation of high energy simulation toolkit to oncology therapy," In: Proceedings of the IEEE Students'

Technology Symposium. IEEE, pp. 25-30, 2014.

[12] MCNAMARA A. L. et al. "Towards optimal imaging with PET: an in silico feasibility study," Physics in Medicine & Biology, vol. 59, pp. 7587, 2014.

[13] STEINBERG Jeffrey. "MRI-Based Attenuation Correction for PET Reconstruction," PhD Thesis. The Ohio State University, 2008.

[14] ANDRIESSEN J. DORENBOS P. VAN EIJK C. W. E. "Calculation of energy levels of cerium in inorganic scintillator crystals," MRS Online Proceedings Library (OPL), vol. 348, pp. 355, 1994.

[15] DERENZO Stephen E. KLINTENBERG Mattias, WEBER Marvin J. "Ab-initio cluster calculations of hole formation and trapping in PbF/sub 2/and PbF/sub 4," In: 1998 IEEE Nuclear Science Symposium Conference Record. 1998 IEEE Nuclear Science Symposium and Medical Imaging Conference (Cat. No. 98CH36255). IEEE, pp. 163-167, 1998.

[16] ARIÑO-ESTRADA Gerard, et al. "Study of Čerenkov light emission in the semiconductors TlBr and TlCl for TOF-PET," IEEE transactions on radiation and plasma medical sciences, vol. 5, pp. 630-637, 2020.

[17] BERGER M. J. et al. "Stopping-power and range tables for electrons, protons, and helium ions, NIST Standard Reference Database 124," National Institute of Standards and Technology (NIST), Physical Measurement Laboratory (PML), 2017.

[18] BRUNNER S. E. SCHAART D. R. "BGO as a hybrid scintillator/Cherenkov radiator for cost-effective time-of-flight PET," Physics in Medicine & Biology, vol. 62, pp. 4421, 2017.

[19] CATES Joshua W. et al. "Improved single photon time resolution for analog SiPMs with front end readout that reduces influence of electronic noise," Physics in Medicine & Biology, vol. 63, pp. 185022, 2018.

[20] EFTHIMIOU Nikos, et al. "TOF-PET image reconstruction with multiple timing kernels applied on Cherenkov radiation in BGO," IEEE transactions on radiation and plasma medical sciences, vol. 5, pp. 703-711, 2020.

[21] PAGANO Fiammetta, et al. "Advances in heterostructured scintillators: toward a new generation of detectors for TOF-PET," Physics in Medicine & Biology, vol. 67, pp. 135010, 2022.

[22] ENOCH S. et al. "Design considerations for a new generation of SiPMs with unprecedented timing resolution," Journal of Instrumentation, vol. 16, pp. P02019, 2021.

[23] GOLA Alberto, et al. "NUV-sensitive silicon photomultiplier technologies developed at Fondazione Bruno Kessler," Sensors, vol. 19, pp. 308, 2019.

[24] KRATOCHWIL Nicolaus, GUNDACKER Stefan, AUFFRAY Etiennette," A roadmap for sole Cherenkov radiators with SiPMs in TOF-PET," Physics in Medicine & Biology, vol. 66, pp. 195001, 2021.

[25] Dirk Hellwig, N. C, S. B, et al. Artificial Intelligence and Deep learning for advance PET image reconstruction : state-of-the-art and future directions, 2023, 62.6:334-342

[26] Stephen Adler J.D, et al. "Advances in preclinical PET," vol. 52, pp. 308-402, 2022 .

[27] Fumio Hashimoto K.O , et al. 4D deep image prior: dynamic PET image denoising using an unsupervised four-dimensional branch convolutional neural network: vol. 66, pp. 015006, 2021.

[28] M.Dagar S.Parzych, et al. Comparative studies of sensitivities of space and full geometries of Total-Body PET scanners built from crystals and plastic scintillators, vol. 10 , pp 62, 2023.

THIS PAGE IS INTENTIONALLY LEFT BLANK.