Nuclear Engineering and Technology 55 (2023) 2567–2571

Contents lists available at ScienceDirect

Nuclear Engineering and Technology

journal homepage: www.elsevier.com/locate/net

Original Article

Spatial resolution and natural image quality assessment evaluation of gamma camera image using pinhole collimator in lutetium-yttrium oxyorthosilicate scintillation detector

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A R T I C L E I N F O

Article history:
Received 1 March 2023
Received in revised form
22 March 2023
Accepted 17 April 2023
Available online 25 April 2023

Keywords:
Gamma camera imaging
Pinhole collimator
Lutetium-yttrium oxyorthosilicate (LYSO) scintillation detector
Spatial resolution evaluations

A B S T R A C T

Scintillator materials are widely used in the medical and industrial fields for imaging systems using gamma cameras. In this study, image evaluation is performed by modeling a gamma camera system based on a lutetium-yttrium oxyorthosilicate (LYSO) scintillation detector using a pinhole collimator that can improve the spatial resolution. A LYSO detector-based gamma camera system is modeled using a Monte Carlo simulation tool. The geometric concept of the pinhole collimator is designed using various magnification factors, and the spatial resolution is measured using the acquired source image. To evaluate the resolution, the full width at half maximum (FWHM) and natural image quality assessment (NIQE), a no-reference-based parameter, are used. We confirm that the FWHM and NIQE values decrease simultaneously when the diameter of the pinhole collimator increases. Additionally, we confirm that the spatial resolution improves as the magnification factor increases under the same pinhole diameter condition. Particularly, a 0.57 mm FWHM value is obtained using the modeled gamma camera system with a LYSO scintillation detector. In conclusion, our results demonstrate that a pinhole collimator with a LYSO scintillation detector is a promising gamma camera imaging system.

1. Introduction

The gamma camera is mainly used as a nuclear medicine device for obtaining functional information of the human body in the medical field and is widely used for detecting radiation in the industrial field [1–4]. Particularly, contamination measurement in nuclear facilities is significant in terms of safety management, and a gamma camera system for measuring the degree of environmental contamination of radioactive materials is being actively researched and developed [5].

To acquire gamma-camera images, a source capable of emitting gamma rays and a detector capable of detecting beams are required. Among the components of the gamma cameras, the scintillator is the most commonly used detector material. The NaI(Tl) scintillator is a representative inorganic crystal detector and has the advantage of obtaining an appropriate gamma ray image at a low price. In 1964, Anger developed a NaI scintillation detector with a diameter of 11.5 inches and a thickness of 0.5 inches and analyzed the characteristics of various sensitivities and resolutions [6]. Various studies have been conducted based on the type of gamma camera developed by Anger, and research on developing a detector that expands the range of detectable energy has also been conducted [7].

The NaI(Tl) scintillation detector has an appropriate density (3.67 g/cm^3), but recently, the detection efficiency has been improved by scintillators with higher densities [8]. Lutetium-yttrium oxyorthosilicate (LYSO) material is a scintillator with a high atomic number and is non-hygroscopic; which are very efficient characteristics for gamma-ray detection [9,10]. According to Lee et al., the 2-mm thick LYSO scintillation detector can obtain higher photoelectric and detection efficiency than the 5-mm thick NaI(Tl) type [9]. Moreover, the LYSO scintillation detector outperforms the NaI(Tl) type with respect to the full width at half maximum (FWHM) [10]. The research results of LYSO, which can simultaneously improve the detection efficiency and spatial resolution, indicate that the efficiency of the gamma-ray detection is high.

The role of the collimator is significant in all gamma cameras,

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https://doi.org/10.1016/j.net.2023.04.027

including LYSO scintillation detector-based gamma ray imaging systems. A pixel-matched parallel-hole collimator was proposed by Lee et al. [9] in a system configured in a pixelated form, such as the LYSO detector. According to the above study, the spatial resolution of the gamma camera system based on the LYSO scintillation detector using a pixel-matched parallel-hole collimator is approximately 3.88 mm. However, in terms of the parallel-hole collimator, the above resolution may be appropriate; however, the application of a pinhole collimator may be considered to observe a more detailed structure. Particularly, because the detection efficiency of the LYSO detector is relatively high compared to the general crystal system, an environment that can consider the spatial resolution aspect slightly more than the sensitivity aspect can be established. In addition, it is very important to determine the geometry when modeling the pinhole collimator, and the theory that spatial resolution decreases and sensitivity increases as the size of the hole increases must be considered.

Thus, this study aimed to evaluate the resolution characteristics of images by modeling a LYSO scintillation detector system using a pinhole collimator. The resolution is evaluated by changing the geometric structure of the pinhole collimator, and the image quality is analyzed using FWHM and no-reference-based evaluation parameters.

2. Materials and methods

2.1. LYSO scintillation detector system using pinhole collimator modeling

For system modeling for gamma-ray imaging, the Geant4 Application for Tomographic Emission (GATE) platform, a representative type of Monte Carlo simulation method, was used. The GATE simulation platform has been successfully demonstrated in many studies for the validation of gamma-ray imaging. Lee et al. succeeded in imaging by modeling LYSO on a simulation [9]. A LYSO scintillation detector consisting of a total active area of 44.8 × 44.8 mm2 and a thickness of 3 mm was modeled using GATE simulation.

The pinhole collimators were modeled at increments of 0.2 mm from a diameter of 0.2 mm to a diameter of 2.0 mm. The distance from the source to the detector was adjusted such that the magnification factor could be designed as 2, 3, and 6. The angle of the pinhole was set to 51°, and the effective pinhole diameter ($d_{effective}$) based on tungsten was calculated using the following formula [11]:

$$d_{effective} = \sqrt{d\left(d + \frac{2}{\mu}\tan\frac{\alpha}{2}\right)} \tag{1}$$

where d is the diameter of the pinhole collimator, μ is the linear attenuation coefficient, and α is the full acceptance angle of the pinhole collimator.

In the pinhole collimator system, the geometrical efficiency (ε_g) and object resolution (R_o) of the collimator are defined as follows [11,12]:

$$\varepsilon_g = \frac{{d_{effective}}^2 \sin^3\theta}{16(x+h)^2} \tag{2}$$

$$R_o = \sqrt{{R_i}^2 + \left[\frac{d_{effective}\left(a_{effective} + x + c\right)}{a_{effective}}\right]^2} \tag{3}$$

where a is the distance from the source to the collimator along the central axis of the collimator, h is the focal length, θ is the angle from the central axis, R_i is the intrinsic resolution, $a_{effective}$ is the effective hole length, and c is the distance from the detector surface to the collimator end.

2.2. Source and phantom modeling

The source modeled 99mTc with 140 keV, the most widely used energy in gamma camera images, was used for the GATE simulation. The 99mTc source was inserted into a water phantom with a diameter of 44 mm. The diameter of the hole in the phantom ranges from 1.0 mm to 7.0 mm and was designed to evaluate spatial resolution by visual assessment (Fig. 1).

2.3. Methods for spatial resolution evaluation

In this study, two parameters were used to evaluate the spatial resolution of the phantom images using the acquired gamma camera. The FWHM, which is most widely used to evaluate the spatial resolution of nuclear medicine images, was used as the first parameter. To evaluate the FWHM, a 99mTc point source was modeled in the GATE simulation, and the final value was derived after obtaining the profile. Second, to evaluate the overall spatial resolution, no-reference-based result values of the acquired phantom images were derived. Among the no-reference-based evaluation methods, natural image quality assessment (NIQE), which is the most representative and highly accurate, has been used [13–15]. The formula for calculating the distance value used to evaluate NIQE is as follows [13]:

$$D(A_1, A_2, \Sigma_1, \Sigma_2) = \sqrt{\left[(A_1 - A_2)^T \left(\frac{\Sigma_1 + \Sigma_2}{2}\right)^{-1} (A_1 - A_2)\right]} \tag{4}$$

where A_1 and A_2 are the mean vectors of the natural multivariate

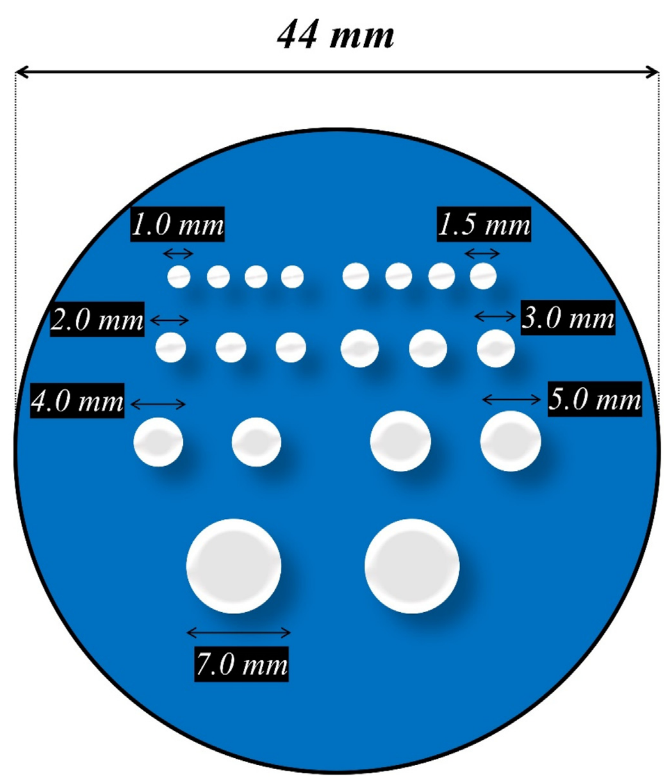

Fig. 1. Schematic diagram on the GATE simulation of a phantom with a^{99m}Tc source composed of a total of 7 hole diameters. The diameters of the hole were designed differently to enable the visual assessment of spatial resolution.

Gaussian (MVG) model and the MVG model of the distorted image, respectively, and Σ_1 and Σ_2 are the covariance matrices.

3. Results and discussion

Fig. 2 shows the phantom images acquired using the LYSO detector system with various pinhole collimator geometries. The resulting phantom images were displayed according to the magnification factors using 0.2-, 1.0, and 1.8 mm pinhole diameters. Relatively smaller holes were observed as the magnification factor of the LYSO detector system using the pinhole collimator increased. Particularly, all hole sizes of 1.0 mm were clearly observed when a magnification factor of 6 was used.

Fig. 3 shows the FWHM result graph with respect to the pinhole diameter using various magnification factors. We confirmed that the FWHM value increased linearly as the pinhole diameter increased for all magnification factors. Particularly, the FWHM obtained using a magnification factor of 6 showed the best value of approximately 0.57 among all the geometries used. Additionally, when the pinhole diameter was set to 2.0 mm using a magnification factor of 6, an FWHM value of approximately 2.41 was derived. The results of the comparative analysis of the FWHM value in the system using magnification factors of 2 and 6 show a difference from approximately 1.40 to 2.71 times, and the difference decreased as the pinhole diameter increased. These results indicate that the effect of the magnitude factor increases when a relatively small diameter is set in the design of the pinhole collimator. As illustrated in Table 1, none of the obtained FWHM values showed a significant difference when compared with the theoretically calculated values. The error between theoretical and experimental values of FWHM was measured at 1.37% on average, indicating a well-validated result.

Fig. 4 shows the no-reference-based result using the NIQE graph with respect to the pinhole diameter using various magnification factors. Similar to the FHWM value, the NIQE value increased linearly as the pinhole diameter increased for all magnification factors used. When using magnification factor 6, NIQE values ranging from approximately 44.87 to 62.03 were derived, and when using magnification factor 2, values ranging from approximately 52.35 to 70.02 were derived. A comparative analysis of the NIQE value in the

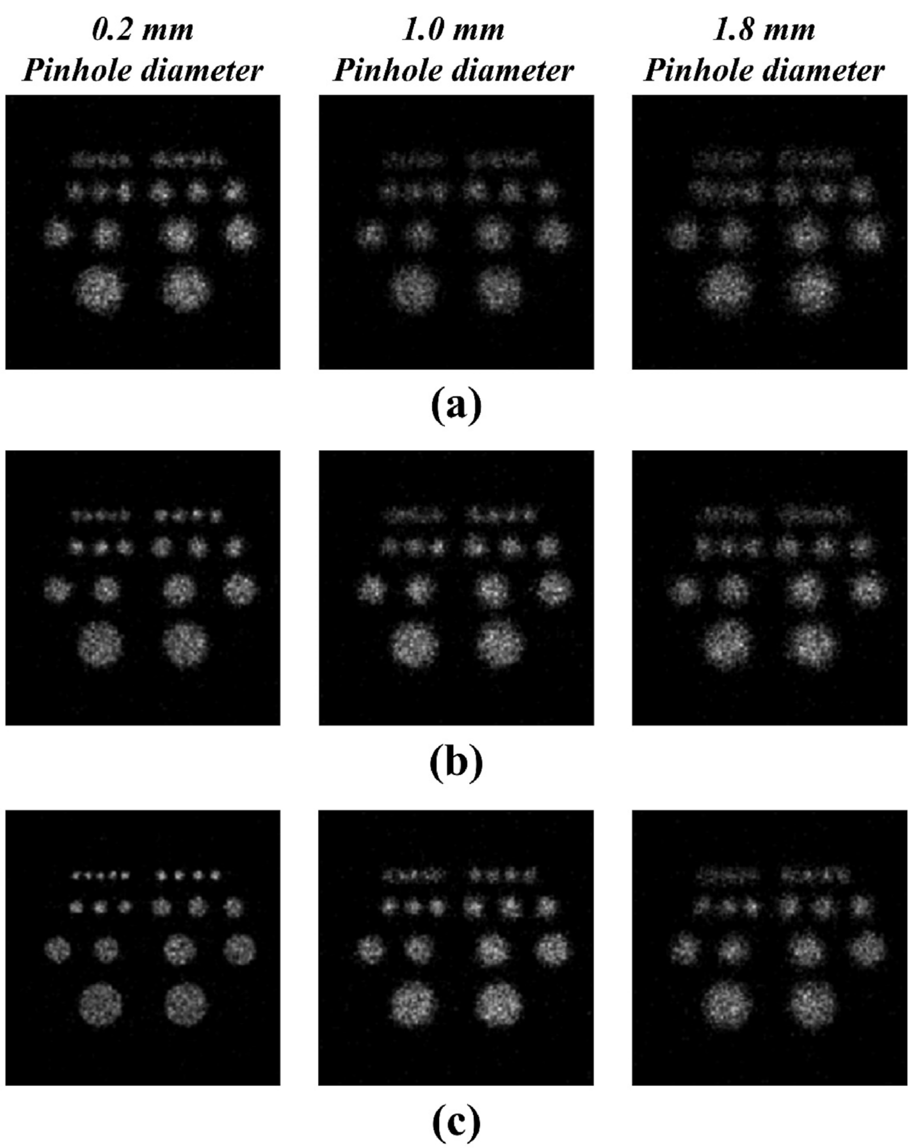

Fig. 2. Phantom images acquired using the LYSO detector system using various pinhole collimator geometries: magnification factors of (a) 2, (b) 3, and (c) 6.

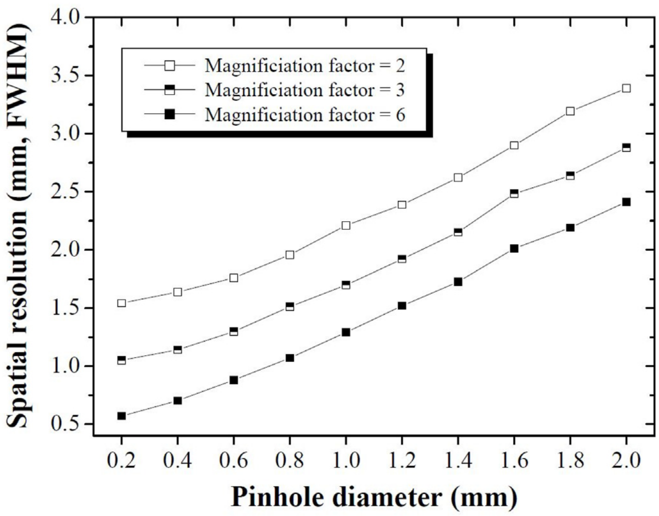

Fig. 3. FWHM result graph with respect to pinhole diameter using various magnification factors.

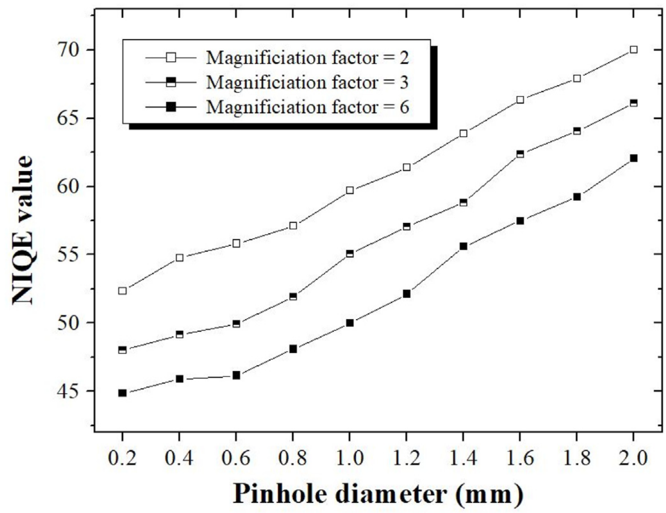

Fig. 4. No-reference-based result using NIQE graph with respect to pinhole diameter using various magnification factors.

system using magnification factors of 2 and 6 showed a difference from approximately 1.13 to 1.21 times, and the difference decreased as the pinhole diameter increased. Unlike the FWHM results, the NIQE results obtained by applying two magnification factors according to the increase in the diameter of the pinhole showed an inconsistent difference.

In this study, we present the image quality evaluation results according to the geometry of various pinhole collimators based on the LYSO detector. A detector using LYSO material has various advantages compared to the most widely used NaI(Tl) crystal, and the spatial resolution can be maximized using a pinhole collimator. In other studies using GATE simulation, a pixel-matched parallel-hole collimator was used for the LYSO detector system, but it did not show remarkable results in terms of the spatial resolution [9]. When the pinhole collimator proposed in this study is applied to the LYSO detector system, we expect that the image quality can be improved compared with previous studies. In this study, the NIQE results were derived using a new approach, including FWHM, which is the most widely used evaluation factor in the field of nuclear medicine. We conducted a study by applying the NIQE results to the quality evaluation of the LYSO detector system for the first time and proved that the FWHM and the tendency were almost similar. These results will form the basis for using no-reference-based parameters for nuclear medicine image evaluation in the future.

Despite the various advantages of LYSO-based detectors using pinhole collimators, their low sensitivity remains essential. Many researchers have conducted studies on multi-pinhole collimators that complement single-hole-type pinhole collimators. Bae et al. demonstrated the possibility of using a multi-pinhole collimator for gamma imaging of the heart through simulation, and Goorden et al. performed a theoretical analysis using a full-ring-type multi-pinhole collimator in brain gamma imaging [16,17]. However, for LYSO detector-based gamma ray imaging, it is necessary to check the line of the response design and system model verification method; thus, the authors intend to conduct future research on related content [18]. In this study, only the spatial resolution aspect according to the hole size of the pinhole collimator was analyzed; however, we plan to conduct additional studies related to sensitivity in the future.

Table 1
FWHM theoretical and measured results according to pinhole collimator geometry.

Magnification factor	Pinhole diameter (mm)	Theoretical FWHM (mm)	Measured FWHM (mm)
2	0.2	1.533	1.543
	0.4	1.621	1.638
	0.6	1.757	1.760
	0.8	1.931	1.958
	1.0	2.133	2.210
	1.2	2.355	2.388
	1.4	2.594	2.621
	1.6	2.844	2.899
	1.8	3.103	3.192
	2.0	3.368	3.390
3	0.2	1.039	1.051
	0.4	1.140	1.141
	0.6	1.289	1.298
	0.8	1.472	1.512
	1.0	1.680	1.698
	1.2	1.899	1.920
	1.4	2.130	2.152
	1.6	2.369	2.483
	1.8	2.613	2.639
	2.0	2.861	2.881
6	0.2	0.557	0.570
	0.4	0.692	0.703
	0.6	0.870	0.881
	0.8	1.070	1.071
	1.0	1.281	1.291
	1.2	1.498	1.519
	1.4	1.720	1.726
	1.6	1.944	2.012
	1.8	2.171	2.191
	2.0	2.398	2.414

4. Conclusion

In this study, the feasibility of using a gamma camera system with a pinhole collimator based on a LYSO scintillation detector was demonstrated. The spatial resolution according to various hole sizes was evaluated using the FWHM and no-reference-based evaluation parameters, and we expect that the LYSO detector system can be used in various fields in the future.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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