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Optimized Parallel-Hole Collimator Design that Balances Spatial Resolution and Sensitivity through Monte Carlo Simulation

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The quality of gamma camera images is determined by the characteristics of the image collimator. The size and length of the collimator's holes, as well as the thickness of its septa, directly impact sensitivity and spatial resolution. These factors have conflicting optimization relationships with each other, and sensitivity and spatial resolution variations manifest differently based on combinations of different variables such as larger or smaller diameter holes, shorter or longer holes, thinner or thicker septa, and so on. Accordingly, appropriate collimator design plays a crucial role in optimizing the quality of gamma camera images. In this study, referencing the structure of an ELEGP collimator, we design a collimator that optimizes sensitivity and spatial resolution. To achieve this, collimators with various hole sizes, lengths, and septa thicknesses were designed, and simulations were conducted. Through this process, the most suitable conditions for optimizing the image quality of the gamma camera system were obtained. Geant4 Application for Tomographic Emission (GATE) simulations were performed for collimator optimization. Among 820 simulation results, the best image quality was achieved with a hole diameter of 2.6 mm, length of 28 mm, and septa thickness of 0.4 mm. If the collimator designed in this study is used, it is expected to provide superior images compared to those obtained with existing gamma camera systems.

Keywords : gamma camera, collimator, sensitivity, spatial resolution, GATE, magnetic field, electromagnetic radiation

1. Introduction

Gamma rays emitted by radiopharmaceuticals into the body can be captured by a gamma camera, a nuclear medicine diagnostic device, and the distribution of radioisotopes can be imaged to help diagnose diseases. A gamma camera mainly consists of a detector and a collimator. The collimator serves as a physical filter, allowing gamma rays to pass that are incident in the direction effective for image reconstruction while blocking gamma rays emitted in other directions. If the collimator's hole size is large, the number of gamma rays transmitted to the detector increases, increasing sensitivity but reducing spatial resolution. In order to improve the image quality of a gamma camera, the hole size of the collimator has to be reduced, but as sensitivity decreases and the imaging time and dosage of radiopharmaceuticals used increase, an appropriate collimator has to be selected and used. Collimators are mainly made of metals with high atomic numbers such as lead and tungsten [1-7]. Various types of collimators are used depending on the radionuclide and energy of the radiopharmaceutical. Types of collimators include Low Energy High Resolution (LEHR), Low Energy General Purpose (LEGP), Extended Low Energy General Purpose (ELEGP), and Medium Energy General Purpose (MEGP) and High Energy General Purpose (HEGP) [8-10].

Currently, technetium-99m (^{99m}Tc) is a widely used radionuclide in gamma cameras, and it is used to diagnose various organs [11]. ^{99m}Tc has a physical half-life of 6 hours, allowing adequate time for preparation and transport of radiopharmaceuticals, patient administration, and imaging. In addition, the gamma ray emitted by ^{99m}Tc at 140 keV has adequate energy to penetrate the patient and be detected by the detector, and has excellent physical characteristics. Accordingly, in this study, in

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order to design a collimator that can satisfy both the sensitivity and spatial resolution of ^{99m}Tc, collimators of various structures were designed with reference to the characteristic conditions of the ELEGP collimator. For this purpose, verification and evaluation were performed using Geant4 Application for Tomographic Emission (GATE) [12, 13], a Monte Carlo simulation tool that can simulate the interaction between gamma rays and materials.

2. Material and Methods

Collimators of various structures were designed using the GATE simulation tool. Table 1 shows the characteristics of ELEGP [14]. Using GATE simulation, a gamma camera equipped with an ELEGP collimator was designed to obtain sensitivity and spatial resolution. In order to derive an optimized collimator structure, collimators with various hole sizes and lengths were designed and the sensitivity and spatial resolution performance were compared and evaluated with the existing ELEGP collimator.

Figure 1 shows the structure of a parallel hole collimator. In order to design an optimized collimator based on the basic structure of the ELEGP collimator being compared, the structural range of various collimators was calculated using the equation below.

$$t \geq \frac{6d/\mu}{l-(3/\mu)} \quad (1)$$

Here, t represents the thickness of the collimator's septa, d is the hole size, l is the hole length, and μ represents the linear attenuation coefficient of the collimator material at 140 keV. In order to optimize sensitivity and spatial resolution according to changes in the size and length of the hole in the collimator being compared, the collimator was designed to satisfy both sensitivity and spatial resolution by fixing the thickness of the septa and changing the size and length of the hole. The thickness of the septa was therefore set to 0.4 mm, and the hole size ranged from 1.5 mm to 3.4 mm at 0.1-mm intervals. The hole length ranged from 20 mm to 60 mm at 1-mm intervals, and a collimator was designed and data were acquired for a total of 820 variables.

Figure 2 shows a simulation schematic diagram of a gamma camera equipped with an ELEGP collimator. The overall structure of the collimator was made to conform to the configuration conditions of the ELEGP collimator. The size of the collimator was 540 mm × 400 mm × 40 mm, and the collimator material was lead. The shape of the collimator hole was hexagonal, the diameter of the hole was set to 2.5 mm, the length of hole was 40 mm,

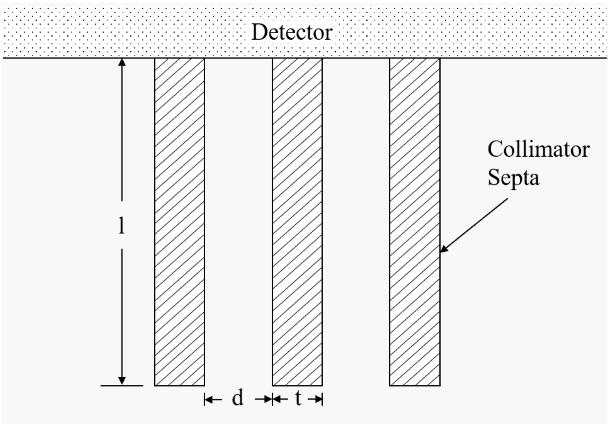


Fig. 1. Structure of a general parallel hole collimator. l represents the length of the colliamtor, d represents the hole size, and t represents the thickness of the septa.

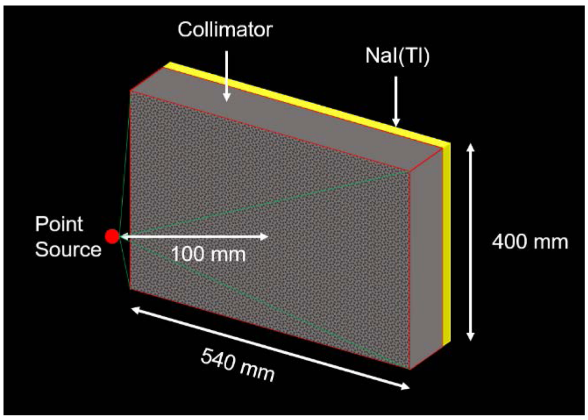
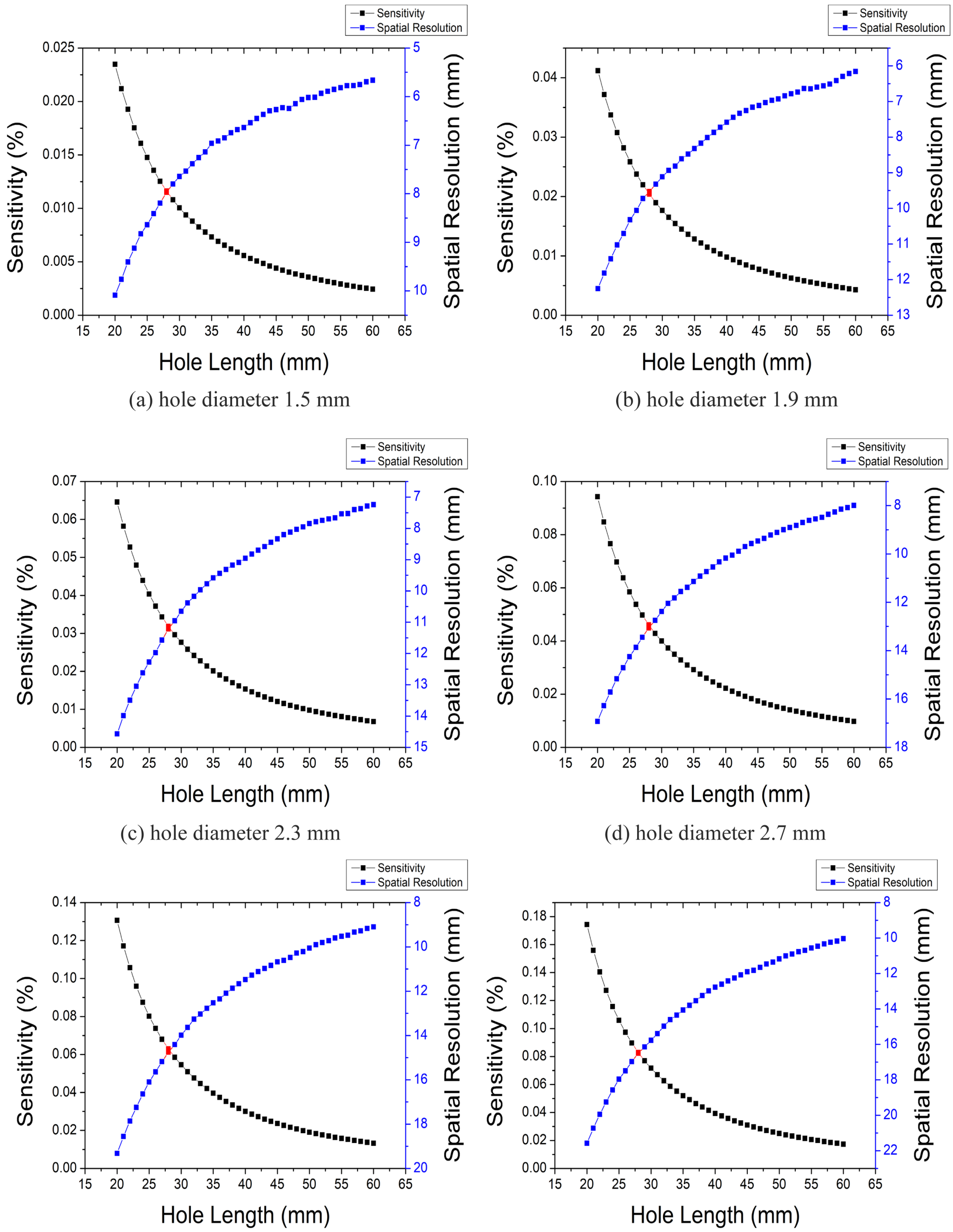


Fig. 2. (Color online) A gamma camera designed through GATE simulation to optimize spatial resolution and sensitivity for the collimator.

Table 1. Summary of ELEGP collimator characteristics. The ELEGP collimator is suitable for the energy of gamma rays generated from ^{99m}Tc, the most commonly used radionuclide in gamma cameras.

Description	Name	Field of View (cm)	Hole Type	Hole Diameter (mm)	Septal Thickness (mm)	Hole Length (mm)	Weight (kg)
Extended Low Energy General Purpose	ELEGP	54 × 40	Hexagon	2.5	0.4	40	60

and the thickness of the septa was set to 0.4 mm. A scintillator measuring 540 mm × 400 mm × 10 mm is located at the rear of the collimator, and NaI(Tl) [15] was used as the scintillator material. As an optical sensor that detects light generated by the interaction of gamma rays and the scintillator, a semiconductor optical sensor that is compact in size and unaffected by magnetic fields was determined suitable for use in the existing photomultiplier



(a) hole diameter 1.5 mm (b) hole diameter 1.9 mm

(c) hole diameter 2.3 mm (d) hole diameter 2.7 mm

(e) hole diameter 3.1 mm (f) hole diameter 3.4 mm

Fig. 3. (Color online) Spatial resolution and sensitivity obtained according to changes in collimator length and hole size. (a)~(f) represent the hole length at the point where sensitivity and spatial resolution according to hole size intersect.

tube. A 10 mCi ^{99m}Tc radiation source was placed 100 mm away from the front center of the collimator, and the number of emitted gamma rays and the location and number of interactions with the scintillator after passing through the collimator were measured. The detectors designed to compete with the performance of the ELEGP collimator were simulated by adjusting the hole size and length, and sensitivity and spatial resolution were obtained. Sensitivity was calculated through the ratio of the total number of gamma rays generated and the number of gamma rays detected by the gamma camera, and spatial resolution was measured by measuring the full width at half maximum (FWHM) [16, 17] of the profile of the acquired image. The intrinsic resolution of each detector was set to 3.7 mm by applying the basic characteristics of the ELEGP collimator, and the energy resolution was set to ± 20 %. In order to derive the optimal collimator structure that satisfies both sensitivity and spatial resolution, the point where sensitivity and spatial resolution intersect was selected as the optimal collimator variable.

3. Results and Discussion

Based on the characteristics of the ELEGP collimator, we designed a collimator with an optimized structure that can satisfy both sensitivity and spatial resolution when the septa is 0.4 mm thick. Varying the hole length led to 21 different length configurations ranging from 20 mm to 60 mm. Accordingly, a total of 820 collimators were configured and GATE simulation was performed to derive optimal variables through comparison and evaluation with existing collimators. The sensitivity appears to improve as the size of the hole increases, and spatial resolution appears to deteriorate. The sensitivity and spatial resolution values calculated through this were plotted and the intersection point was obtained. Therefore, the size and length of the collimator hole at this intersection point can be adopted as the optimal collimator variable.

Figure 3 shows the sensitivity and spatial resolution curves resulting from changes in the hole length for each hole size adopted in this work. From these plots, the intersection points of sensitivity and spatial resolution are used to create Fig. 4, the plot of optimized hole length by hole diameter. This shows that when the thickness of the septa is 0.4 mm, the sensitivity and spatial resolution depending on the hole size consistently intersect at the hole length of 28 mm for all proposed hole sizes. Therefore, the most optimized hole length can be determined as 28 mm.

Figure 5 shows the results of deriving the hole size that can satisfy both sensitivity and spatial resolution according to changes in the hole based on the optimal hole length derived previously. Therefore, when the hole size is 2.6 mm, the length is 28 mm, and the septa thickness is 0.4 mm. These values can be adopted as the optimal collimator variables that satisfy both sensitivity and spatial resolution.

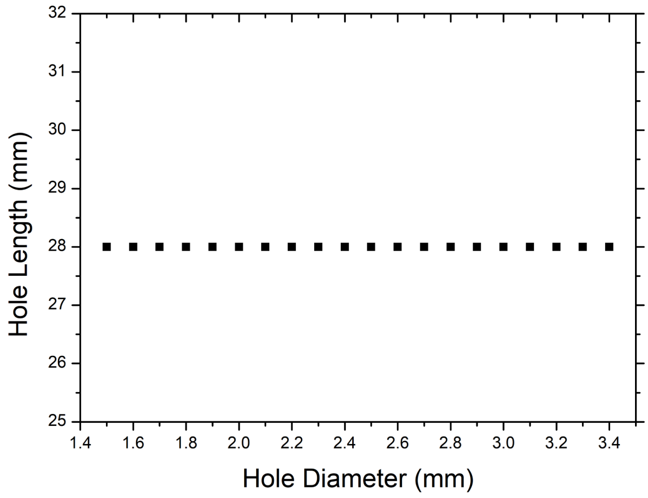


Fig. 4. Intersection of optimized collimator hole length by hole diameter when the septa is 0.4 mm thick. It can be seen that the hole length is the same for all hole sizes.

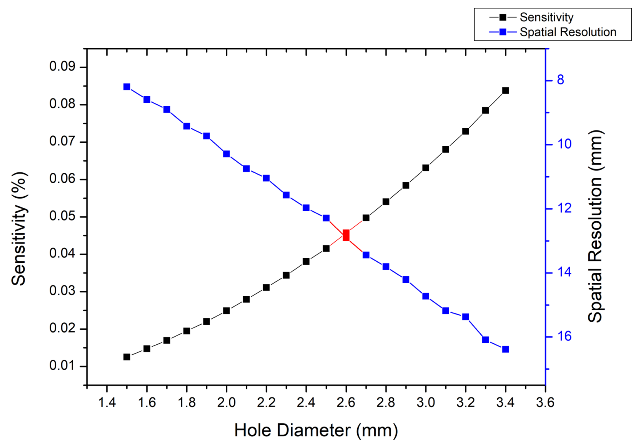


Fig. 5. (Color online) Spatial resolution and sensitivity results for each hole size when the optimized hole length is used. When the hole size is 2.6 mm, sensitivity and spatial resolution intersect.

To compare and evaluate the performance of the ELEGP collimator, the sensitivity and spatial resolution of the optimized collimator are shown in Table 2. The sensitivity and spatial resolution obtained from the ELEGP collimator, which is the subject of comparison, are 0.019 % and 9.49 mm, respectively. The sensitivity

Table 2. Sensitivity and spatial resolution results of the compared ELEGP collimator and the optimized collimator obtained through GATE simulation.

	Sensitivity (%)	Spatial resolution (mm)
ELEGP	0.019	9.49
Optimized Collimator	0.042	12.57

measured in the optimized collimator was 0.042 % and the spatial resolution was 12.57 mm. Thus, sensitivity is improved by 129.19 % in the optimized collimator, and spatial resolution is confirmed to be reduced by 32.46 %.

Depending on how the collimator parameters are set, the number of gamma rays ultimately detected varies, which affects the quality of the image. Through GATE simulation, collimators of various structures were designed and the obtained data were compared to derive optimal collimator variables. When using an optimized collimator, excellent sensitivity can be achieved compared to the ELEGP collimator, but the spatial resolution was reduced by comparison. The ELEGP collimator is designed to provide superior image resolution by prioritizing spatial resolution over sensitivity. The collimator variables derived in this study simultaneously satisfied sensitivity and spatial resolution performance, showing excellent improvement in sensitivity but also poorer spatial resolution. However, excellent image quality can be secured based on the acquisition of more gamma rays due to the improvement in sensitivity, a consideration that outweighs the decrease in spatial resolution. In the future, we plan to conduct optimization research on collimator variables according to various radionuclides and various energies by referring to all collimators currently in use.

4. Conclusion

If the collimator hole size is made larger or shorter, sensitivity improves, but spatial resolution deteriorates. Therefore, sensitivity and spatial resolution are determined depending on the characteristics of the collimator, which is expressed in image quality. In this study, referring to the structure of the ELEGP collimator, we obtained collimator performance that can satisfy both image sensitivity and spatial resolution when the hole diameter is 2.6 mm, the length is 28 mm, and the septa is 0.4 mm thick. Through GATE simulation, 820 collimators of different dimensions were designed and the acquired data was analyzed to derive optimized collimator structure values that intersect sensitivity and spatial resolution. Compared to the ELEGP collimator, the improvement in sensitivity was excellent when using the designed collimator; excellent image quality can be obtained based on the improved sensitivity. Based on the results of this study, we will be able to contribute to the design and optimization of gamma camera image quality.

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