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Development of a Gamma Camera with a Diverging Collimator Using DMLS 3D Printing

Jong-Hun Won[1], Dong-Hee Han[1], Seung-Jae Lee[2], and Cheol-Ha Baek[3]*

[1]*Department of Medical Health Science, Kangwon National University, Gangwon 25949, Republic of Korea*
[2]*Department of Radiological Science, Dongseo University, Busan 47011, Republic of Korea*
[3]*Department of Radiological Science, Kangwon National University, Gangwon 25949, Republic of Korea*

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The purpose of this study is to use a Monte Carlo simulation to derive optimal values for collimator design variables and to produce an optimized collimator for a gamma camera using a 3D printing direct metal laser sintering (DMLS) technique. For the optimization studies, GATE (Geant4 application for tomographic emission) simulation was used, and we tested lead, tungsten, and a full absorber. A total of 15 design variables were simulated using hole sizes of 0.5 mm, 0.7 mm, and 1.0 mm and slat heights from 10 mm to 20 mm at intervals of 2.5 mm. The scintillator used GAGG (gadolinium aluminum gallium garnet) and was set to a size of 25.8 × 25.8 mm^2. The radiation of the source used in the simulation was 37 MBq, and the source was a 140 keV point source. To obtain the diverging collimator optimization design variables, the point source was detected and an image was acquired to analyze the sensitivity and spatial resolution values. As a result, tungsten, which has good hardness, was used. If the source is located in the center of the diverging collimator, the FWHM is limited to 3.0 mm or less. The optimization value is obtained by considering the permeability, sensitivity, and spatial resolution at a height of 15 mm or higher. The results obtained by moving the source were also similar to those obtained when the source was located at the center. Based on the values of the optimized design variables, this study designed and produced a collimator using DMLS, which is a 3D printing technique. We believe this process can be applied in various fields, such as medical and industrial sectors; optimized collimators can be produced for different purposes while maintaining high precision.

Keywords : gamma camera, diverging collimator, optimization, GATE simulation, DMLS 3D printing technique

1. Introduction

A gamma camera consists of a collimator, a scintillation crystal, a photomultiplier tube, and rear electronic circuitry, which are configured for imaging. The imaging technology using the gamma camera is located at the radiation source, which can be identified visually, or near the cancer, and can be determined using integrated mechanisms in the medical field. This technique is widely used in various applications, including environmental monitoring, medical care, industry, and security, and has become increasingly popular. Gamma images vary depending on the performance of the detector and collimator. The collimator, which is one of the components of the gamma camera, is located at the front of the detection process. It influences both the sensitivity and the spatial resolution [1-5].

Pinhole collimators or diverging collimators are commonly used to view a wide range field of view (FOV) in a variety of application areas. Recently, pinhole collimators have been useful, but they vary in terms of their sensitivity depending on the distance. Their drawbacks include having non-uniform spatial resolution and sensitivity in the FOV [6, 7]. Alternatively, diverging collimators can be used for wide monitoring with uniform sensitivity and spatial resolution over the whole FOV. Currently, the technology for making gamma cameras is insufficient, and there is no company in Korea that produces collimators. In addition, the production of collimators relies on bending thin lead plates or making molds for each type of collimator, which is costly and time-consuming. It is also difficult to make collimators in various forms.

However, if the DMLS (direct metal laser sintering) 3D printing process is used, we can optimize a collimator for

©The Korean Magnetics Society. All rights reserved.
*Corresponding author: Tel: +82-33-540-3384
Fax: +82-33-540-3389, e-mail: baekch@kangwon.ac.kr

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the gamma-camera configuration. DMLS is a processing method that creates metal structures by layering thin layers (about 20 micrometers thick) in the direction modeled on a metal solid powder using a laser. When heated after pressure molding, sintering is used. This process is fast and it can produce more accurate, complex shapes than conventional methods.

Therefore, in this study, we derive parameters to optimize the structure and performance relationship of a diverging collimator by using Monte Carlo simulations, and the DMLS 3D printing technique is used to produce an optimized diverging collimator.

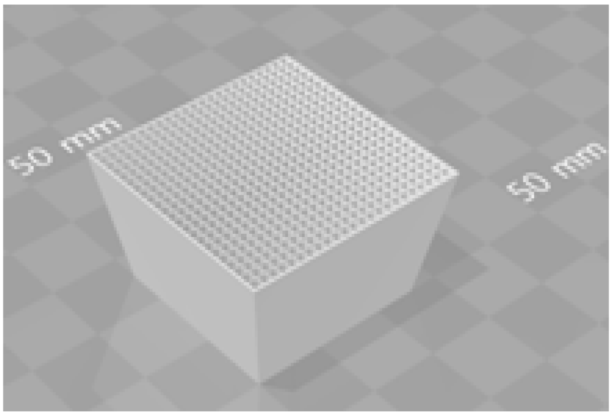

Fig. 2. Example of a diverging collimator STL file.

2. Material and Methods

2.1. Optimization of the Diverging Collimator Using GATE Simulation

The optimization study of the diverging collimator used the Geant4 application for tomographic emission (GATE), which is a Geant4-based simulation code [8]. This is a simulation using the Monte Carlo method, in which the probabilistic distribution of the target figures is obtained from the statistics of the experiment and simulations of the characteristics and forms of the actual device-like structure, phantom, source, etc. in the virtual space [9]. As the first design parameter, the materials of the collimator are set as three materials, i.e., lead (Pb), tungsten (W), and a full absorber, to compare the penetration.

The design parameter test used a 0.1 mm thick slat and a 45° field of view. The hole size was varied between 0.5 mm, 0.7 mm, and 1.0 mm, and the slat height was set as 10.0 mm, 12.5 mm, 15.0 mm, 17.5 mm, and 20.0 mm. This was done to simulate a total of 15 design parameters.

To construct the gamma camera system, the scintillator used GAGG (gadolium aluminum gallium garnet). GAGG is dense, efficient at stopping power, and responsive to secondary electrons produced by gamma rays. GAGG is a photon-efficient scintillator that emits about 55,000 photons for a gamma ray of 1 MeV [10].

The size of the detector was varied as follows. For the 0.5 mm hole size, 0.5 mm × 0.5 mm × 3 mm pixels are arranged to 38 × 38 mm, with the overall size set to 25.8 × 25.8 mm (including the slat thickness and exterior wall of 3 mm). For a 0.7 mm hole size, 0.7 mm × 0.7 mm × 3 mm pixels are arranged to 29 × 29 mm, with the overall

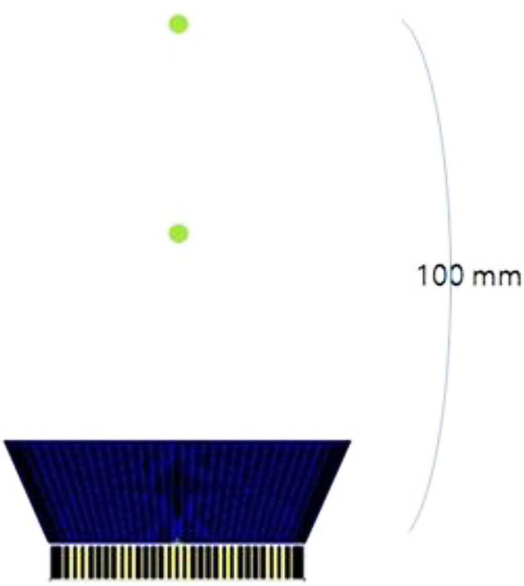

Fig. 1. (Color online) GATE simulation geometry for the point source.

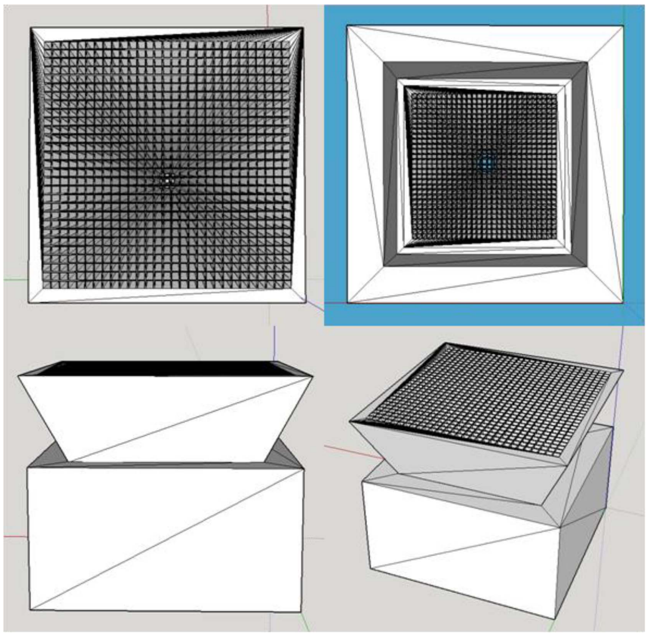

Fig. 3. (Color online) Design of a small diverging collimator.

size set to 25.8 × 25.8 mm (including the slat thickness and exterior wall of 2.6 mm). In addition, for the 1.0 mm-hole size, 1.0 mm × 1.0 mm × 3 mm pixels are arranged to 21 × 21 mm, with the overall size set to 25.8 × 25.8 mm (including the slat thickness and exterior wall of 2.7 mm). The radioactivity of the point source used in the simulations was set at 37 MBq (1 mCi) and the energy of the source was 140 keV. As shown in Fig. 1, the design parameters were used to obtain an image of the point source at distances 50 mm and 100 mm away from the collimator on the center axis of the detector. Sensitivity and resolution values were also obtained when moving

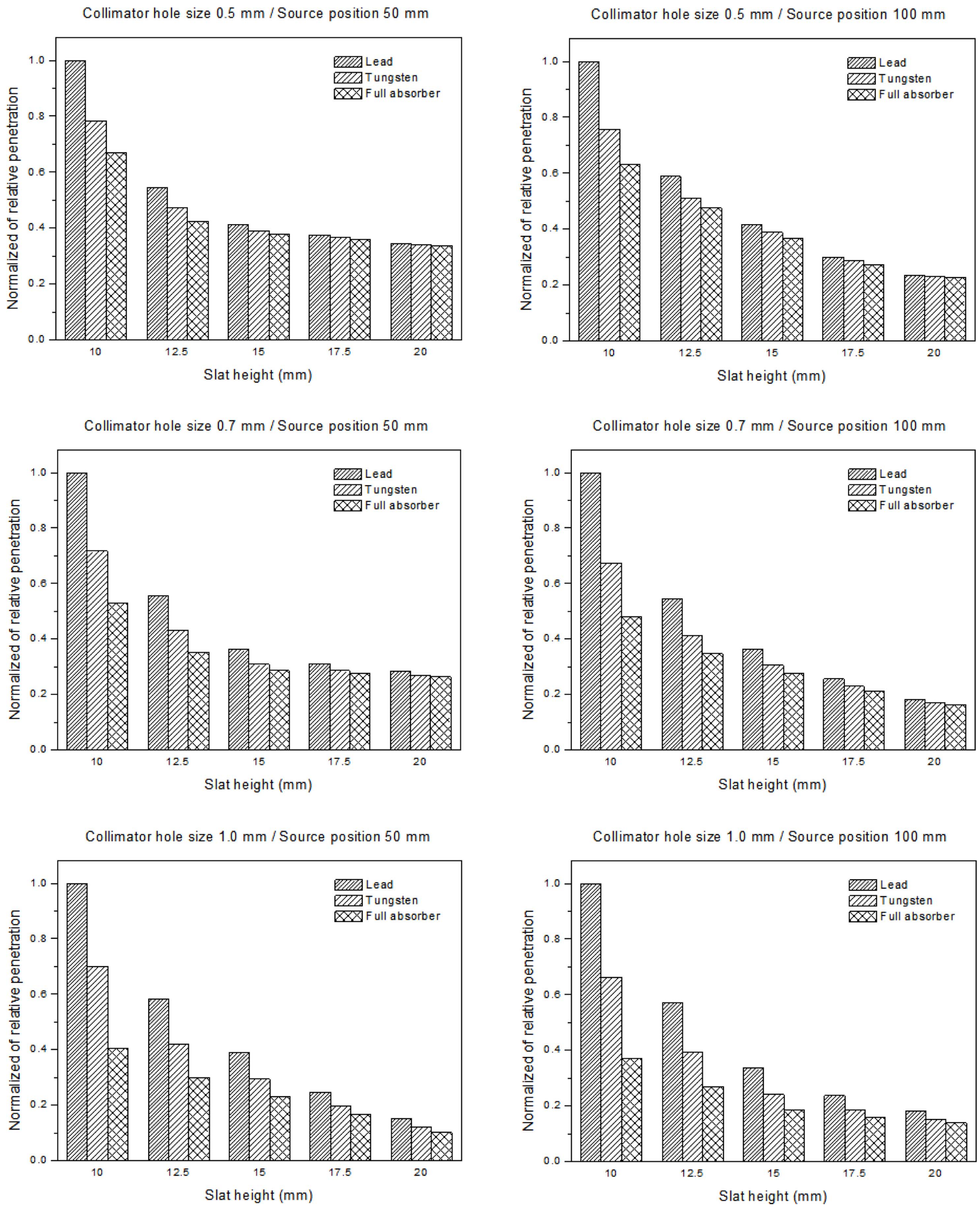

Fig. 4. Comparing the penetration with lead and tungsten, relative to the full absorber, when the distance from the source to the center is 50 mm and 100 mm.

the source to distances of 10 and 20 mm along the x-axis.

2.2. Optimized Diverging Collimator Using DMLS 3D Printing Technology

Recently, GATE simulations have been updated to support the STL (Standard Triangle Language) file extensions used for 3D printing. Based on the information obtained by optimizing the diverging collimator through Monte Carlo simulation, the collimator to be implemented with the design program was converted into an STL file, as shown in Fig. 2, and the files implemented using the TEST model were identified and simulated. Fig. 3 shows

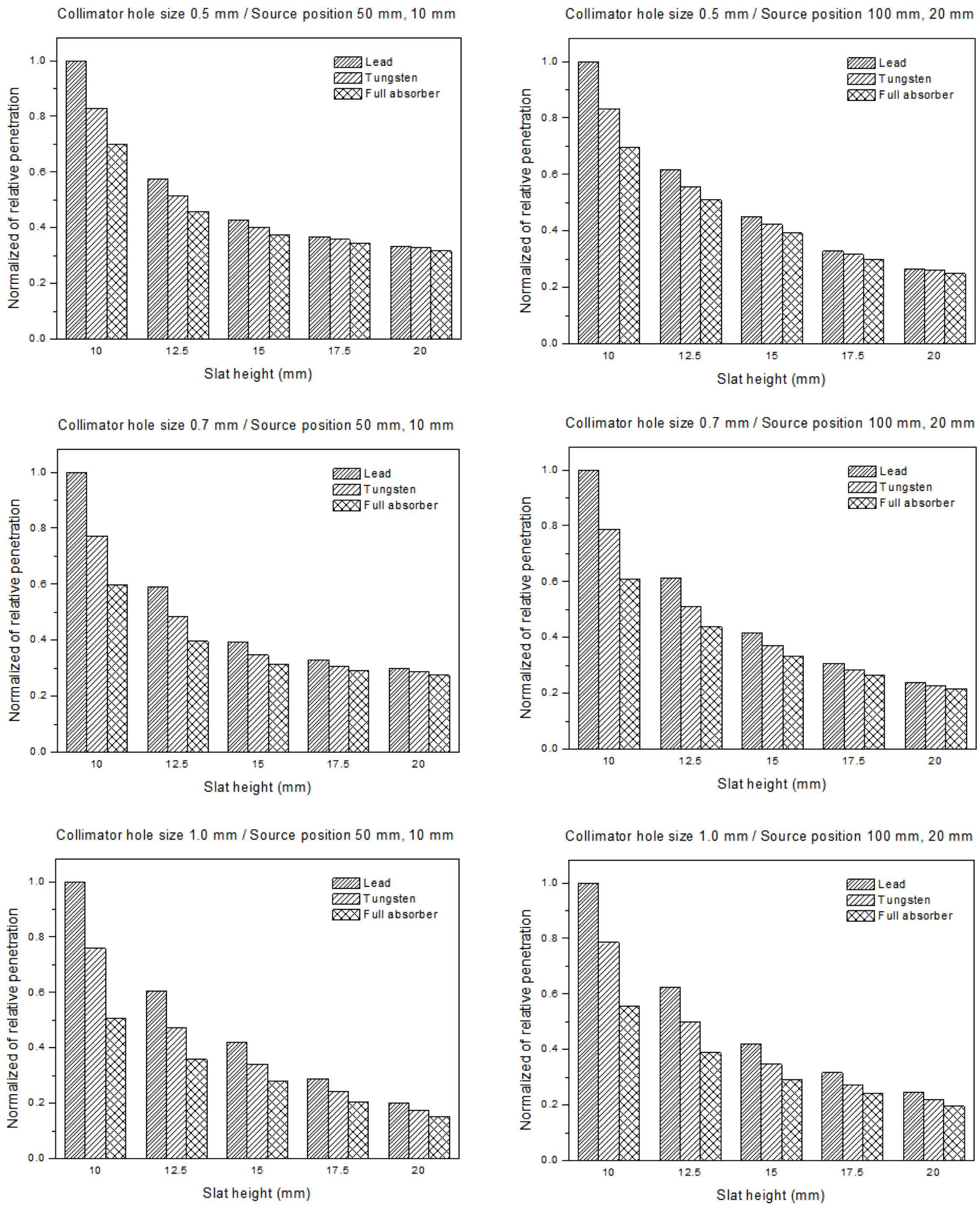

Fig. 5. Comparing the penetration with lead and tungsten, relative to the full absorber, when the source is placed 10 mm on the x-axis at a distance of 50 mm and 20 mm on the x-axis at a distance of 100 mm.

the design used as a target for small gamma-camera systems based on the final design variables and built using DMLS (direct metal laser sintering) 3D printing technology [11-13].

3. Results and Discussion

3.1. Optimization Results of a Diverging Collimator Using GATE Simulation

The penetration is obtained for lead and tungsten, relative to the full absorber, when the source is located at the center and the distance from the source to the center of the collimator is 50 mm or 100 mm. The correlation between the sensitivity and spatial resolution was calculated. As shown in Fig. 4, the penetration was higher for lead than tungsten. This confirmed that tungsten is a more suitable material due to its higher density. The height of the slat was between 7.5 mm and 15 mm, indicating a

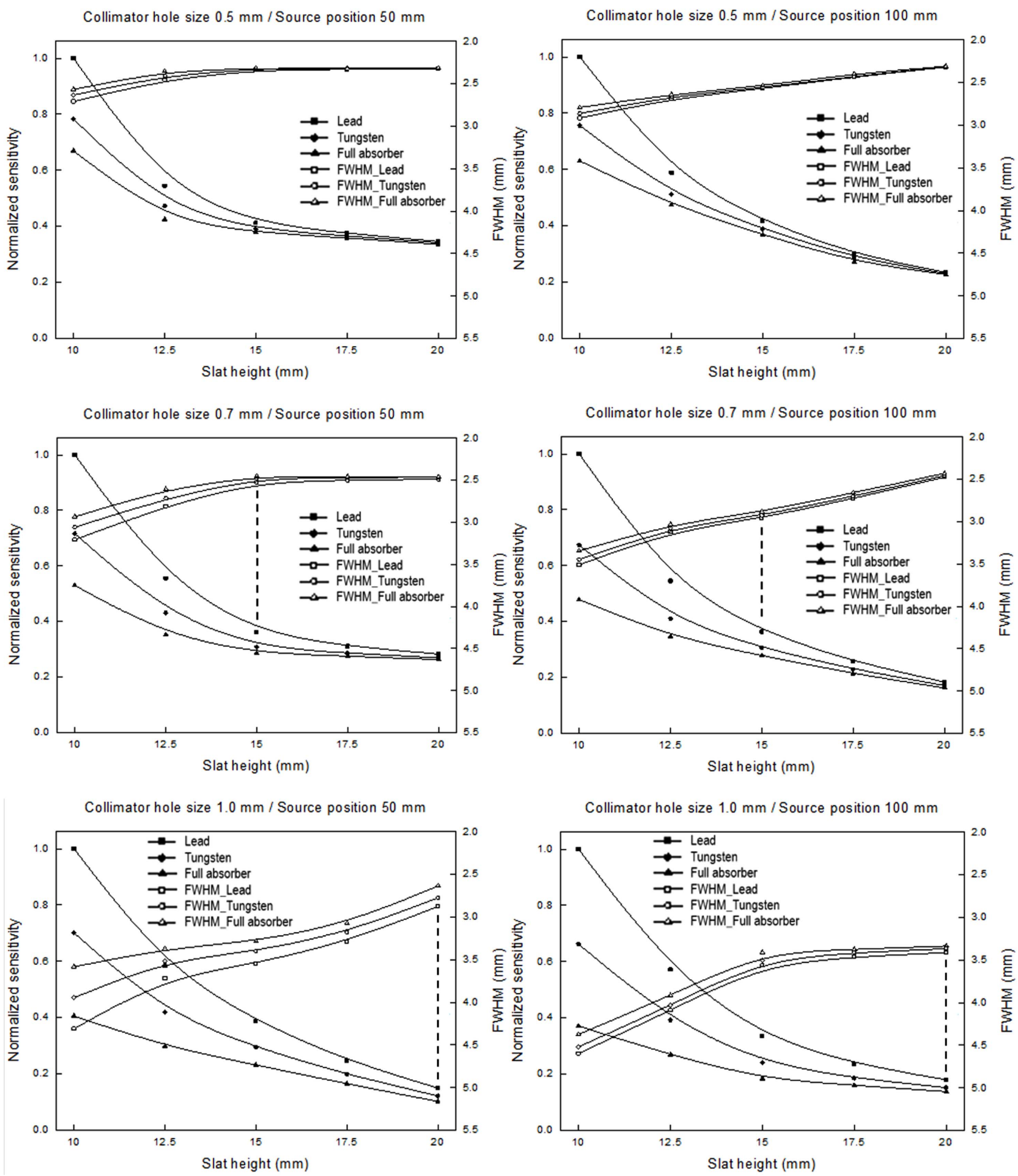

Fig. 6. Correlation between the sensitivity and spatial resolution when the distance from the source to the center is 50 mm and 100 mm.

variation in the penetration relative to the full absorber. Additionally the minimum penetration rate was obtained with a slat height of 15 mm or higher. Based on the simulated shielding performance for each element, the penetration rate of tungsten was 1.18 %, while that of lead was 6.28 %. This shows that tungsten, which allows less penetration than lead, is more suitable as the material for the collimator. If the height of the slat is 10.0 mm or less, the height of the slat is low and the relative penetration is very high. The penetration at the edges, as shown in Fig. 5, also shows a tendency similar to that at the center of the source.

When the distance from the source to the center is 50 mm or 100 mm, as shown in Fig. 6, the correlation between the sensitivity and spatial resolution is as follows. The height optimization of the diverging collimator slat is derived based on the trade-off curve of spatial resolution and sensitivity. The slat is deemed suitable if it is not less

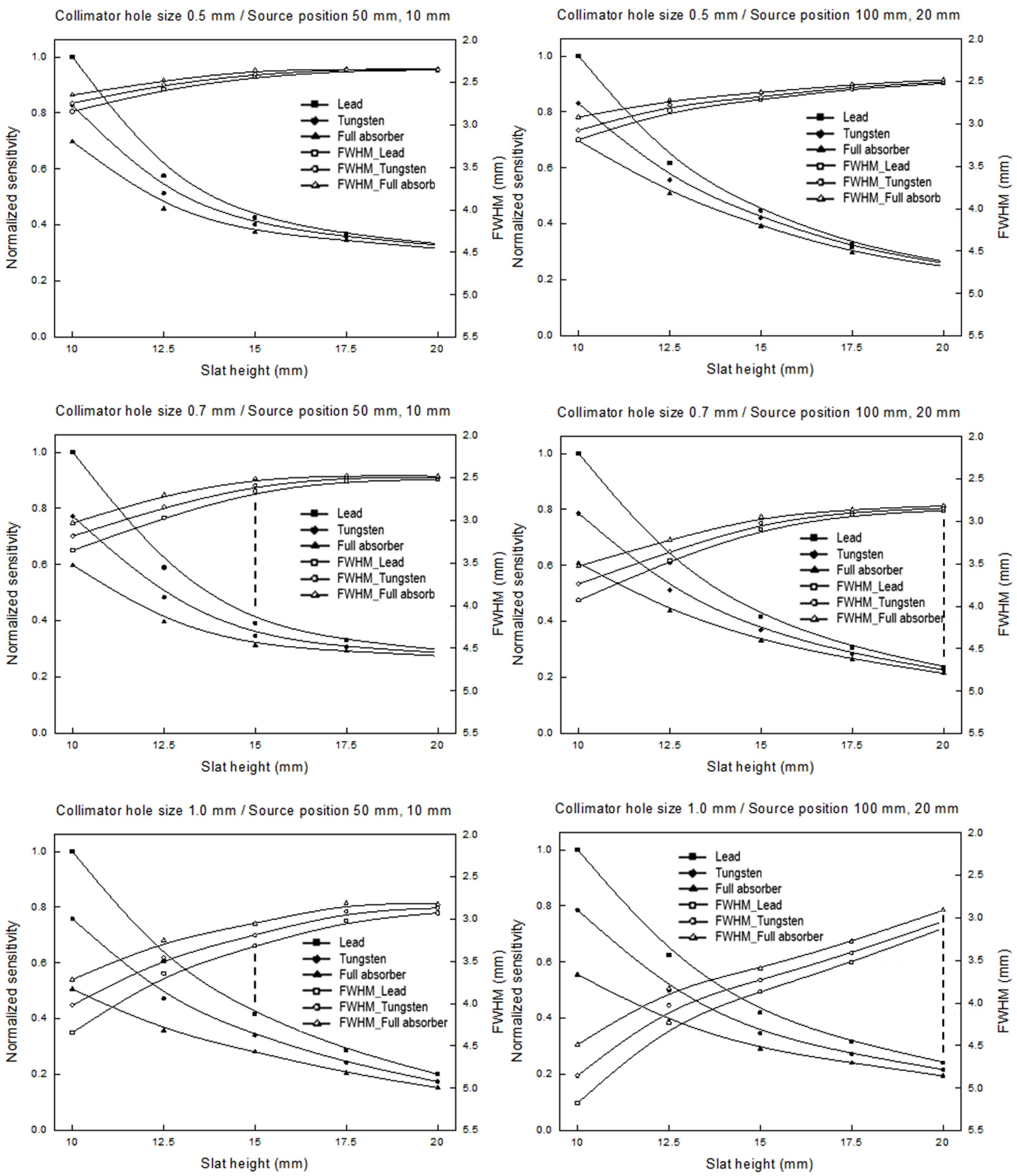

Fig. 7. Correlation between the sensitivity and spatial resolution when the source is placed 10 mm on the x-axis at a distance of 50 mm and 20 mm on the x-axis at a distance of 100 mm.

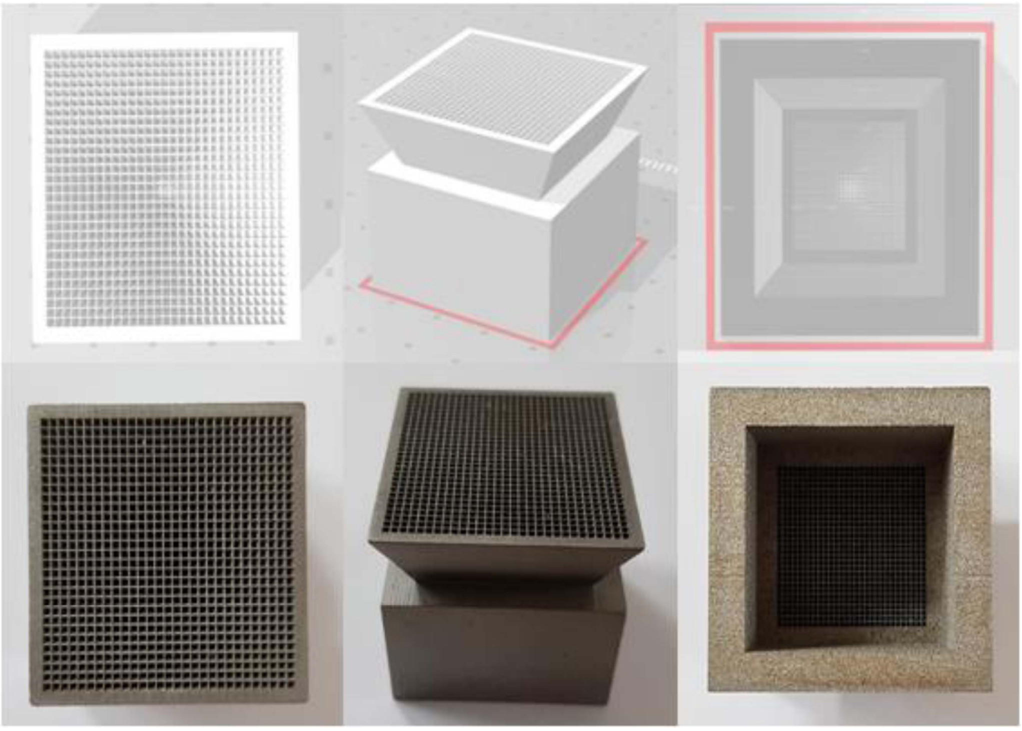

Fig. 8. (Color online) Diverging collimator outputs with DMLS 3D printing.

than 10 mm high with a hole size of 0.5 mm, not less than 15 mm high with a hole size of 0.7 mm, and not less than 30 mm high with a hole size of 1.0 mm. The lower limit of the slat height for obtaining a high-resolution image had a full width at half maximum that was not more than 3.0 mm; this was limited to a range close to 2.0 mm. The higher the height of the collimator slat, the higher the scattered absorption in the slat, and the higher the spatial resolution is judged to have improved. A FWHM of 2 to 3 mm was formed and maintained. The correlation between sensitivity and spatial resolution when the source is located on the edge, as shown in Fig. 7, also showed a tendency that is similar to when the source is in the center.

3.2. Manufactured Collimator Using DMLS 3D Printing Technology

As shown in Fig. 8, the optimization parameters of the diverging collimator are derived. The optimal design parameters featured a hole size of 0.7 mm, a slat height of 10 mm, and a slat thickness of 0.1 mm. The collimator was manufactured with tungsten.

4. Conclusion

The purpose of this study was to obtain design parameters based on the optimization study of diverging collimators. In this study, we developed and manufactured gamma cameras using DMLS 3D printing technology. The optimization study of the diverging collimator relied on obtaining the sensitivity and resolution values for each design parameter using GATE, which is a Geant4-based simulation code. As a result, to obtain a high-resolution diverging collimator, a hole size of 0.5 mm hole and a slat height of at least 10 mm are deemed suitable. For multi-purpose diverging collimators, a hole size of 0.7 mm and a slat height of at least 15 mm are deemed suitable. For high-sensitivity diverging collimators, a hole size of 1.0 mm and a slat height of at least 30 mm are deemed suitable.

Based on the simulations, collimators were designed and built using 3D DMLS techniques. Actual experiments were conducted to see if the collimator produced is similar to the optimization results obtained using simulation. Collimators can be manufactured and optimized for various purposes, while maintaining high precision. This method is expected to be applied in various fields, including medicine and industry.

Acknowledgments

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