

A Monte Carlo Simulation Study of Optimization for Pinhole Collimator Designs with CdTe Semiconductor Gamma Camera System

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Abstract

Background: In the gamma camera system, the appropriate utilization of detector and collimator design is very important. Among used detectors, the semiconductor detector based on cadmium zinc telluride (CZT) and cadmium telluride (CdTe) are considered the most promising material due to high density and better spatial resolution. Especially, the use of CZT and CdTe semiconductor detector with pinhole collimator can acquire the excellent spatial resolution because of high intrinsic resolution. However, the pinhole collimator system has low sensitivity due to small diameter of the hole. Thus, the optimization between the sensitivity and spatial resolution is an essential part for the determination of image performance in the gamma camera system. The purpose of this study was to design an optimized pinhole collimator to achieve appropriate the sensitivity and spatial resolution in gamma camera system using CdTe semiconductor detector.

Methods: For that purpose, we used Geant4 Application for Tomographic Emission (GATE) simulation toolkit. To evaluate image performances of proposed system, the sensitivity and spatial resolution were estimated by changing magnification factor and pinhole diameter. The optimal pinhole diameter was determined from trade-off curves with the compromise of the sensitivity and spatial resolution. Furthermore, we designed a hot-rod phantom to assess overall image performance.

Results: According to the results, we confirmed difference of tendency in sensitivity and spatial resolution variations with respect to the magnification factor and pinhole diameter. Finally, the optimal pinhole diameter is approximately evaluated 1.4 mm in trade-off curves using our proposed system.

Conclusion: In conclusion, we demonstrated optimum conditions of pinhole collimator with CdTe semiconductor detector.

Introduction

Nuclear medicine technology provides both functional, which is aimed to quantify the physiological process, and anatomical information. Accordingly, in the field of the diagnostic imaging, importance of this technology has been increased [1-2].

In the nuclear medicine imaging two major kinds of devices have been used: (1) gamma camera or single photon emission tomography (SPECT) with collimator and (2) positron emission tomography (PET) with non-collimator. The monoenergetic gamma ray source such as most commonly used ^{99m}Tc (140 keV energy peak and half-life of 6 hours) is generally used in the gamma camera or SPECT [3-4]. For detecting gamma ray source, we should be used radiation detector. In the field of the nuclear medicine, NaI(Tl) scintillation detector and conventional or newly developed semiconductor detectors are frequently used. Among these detectors, NaI(Tl) scintillation and conventional semiconductor detector using silicon (Si) or germanium (Ge) have low intrinsic resolution and low detection efficiency problems, respectively. Especially, Si or Ge has high cost and is required additionally cooling system. To overcome these problems, newly developed semiconductor detectors based on cadmium zinc telluride (CZT) and cadmium telluride (CdTe) has been developed during recent years. These detectors can be detected gamma ray in room temperature condition without cooling system, unlike conventional semiconductor detector. Especially, the main advantages of CZT and CdTe semiconductor detectors were good energy resolution of approximately 3-6% at 140 keV and high sensitivity due to high detection efficiency. Also, the excellent spatial resolution can be acquired by using these detectors because intrinsic resolution is same to the pixel size [5-10]. In this regard, by offering better sensitivity and spatial resolution, gamma cameras using CZT and

CdTe semiconductor detectors can overcome inherent limitations in image performance of the conventional gamma camera using Si or Ge semiconductor and NaI(Tl) scintillation detectors.

In the gamma camera or SPECT system, collimators play two main roles in nuclear medicine imaging. The one, this imaging is formed by selective absorption of the emitted gamma rays in the body. Thus, it is essential to know gamma rays direction finder. The other, gamma camera systems can cut-off unnecessary gamma rays such as scattering and conduct selective absorption by using a collimator. For these reasons, collimators are one of the most important components of gamma camera systems. Also, because of the image performance such as sensitivity and spatial resolution that characterize collimators, collimator design markedly influences the image performance of the gamma camera system [11-14]. Among collimators, pinhole collimator with geometric magnification effect can be used for the pre-clinical gamma camera system to achieve high spatial resolution. Especially, in CZT or CdTe semiconductor detector system, the magnification effect has influence on intrinsic resolution. Thus, pinhole collimator has been used for very small objects such as the thyroid. In addition, sensitivity of pinhole system is improved when closing the distance between the pinhole and the object being imaged [15].

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However, a main disadvantage of pinhole collimator is low sensitivity. Due to the small collimator hole size, when improving spatial resolution, the system loses sensitivity [16]. Therefore, we needed optimized image performance between the sensitivity and the spatial resolution.

In this study, we used a GEANT4 Application for Tomographic Emission (GATE) simulation to evaluate the sensitivity and spatial resolution. Then, we optimized pinhole collimator system with CdTe semiconductor detector with respect to the pinhole diameters and magnification factors. Finally, to confirm overall image performance, a hot-rod phantom was designed and acquired. For that purpose, pinhole collimator and a PID 350(AjatOy Ltd., Finland) CdTe semiconductor detector were simulated by GATE simulation.

Materials and Methods

Simulation set-up

In order to assess the effect of the pinhole diameter and magnification factor on image performance, a Monte Carlo simulation was conducted using GATE (version 6). GATE is dedicated code based on the general purpose GEANT4 code and it is suitable for use in nuclear medicine when especially modelling to planar gamma camera, PET and SPECT system [17-20].

The PID 350CdTe semiconductor detector was designed using GATE in this study. The geometries of the CdTe semiconductor detector are shown in Table 1. The detection efficiency and density of a 3 mm-thick CdTe semiconductor, Si semiconductor and NaI(Tl) scintillation detector at gamma ray energy of 140 keV are shown in Figure 1. The 3 mm-thick CdTe semiconductor detector was 76% and 7.6 and 1.4 times higher than that of Si semiconductor and NaI(Tl) scintillation detectors, respectively. Accordingly, CdTe semiconductor detector has high efficiency in comparison with other detectors due to high density and high atomic number.

The pinhole collimator is cone-shaped with single aperture. In addition, this collimator is generally consisted of lead or tungsten material due to low cost and appropriate stiffness. Recently, there have been many researches about other collimator materials such as gold and uranium but they have problems with manufacturing and are not commonly available due to relatively high cost [21-22]. Thus, we choose the tungsten material for pinhole collimator in this study. Figure 2 illustrates the schematic diagram of pinhole collimator in simulation. The spatial resolution (R_{system}) and geometric efficiency (g) in the pinhole gamma camera system was calculated by the following formulas [23]:

where $R_{intrinsic}$ is intrinsic resolution of the detector (0.35 mm in this study), $R_{collimator}$ is the collimator resolution, a is the distance from the pinhole aperture to the detector surface, b is source-to-aperture distance, $d_{effective}$ is the effective diameter of pinhole, d is the diameter of pinhole, μ is the linear attenuation coefficient of the pinhole collimator material and θ is the acceptance angle of pinhole aperture.

Thickness (mm)	3 mm
Total detector size (mm ²)	44.8 × 44.8 mm ²
Pixel size (mm ²)	0.35 × 0.35 mm ²
Number of pixels	128 × 128

Table 1: The geometries of the used CdTe semiconductor detector.

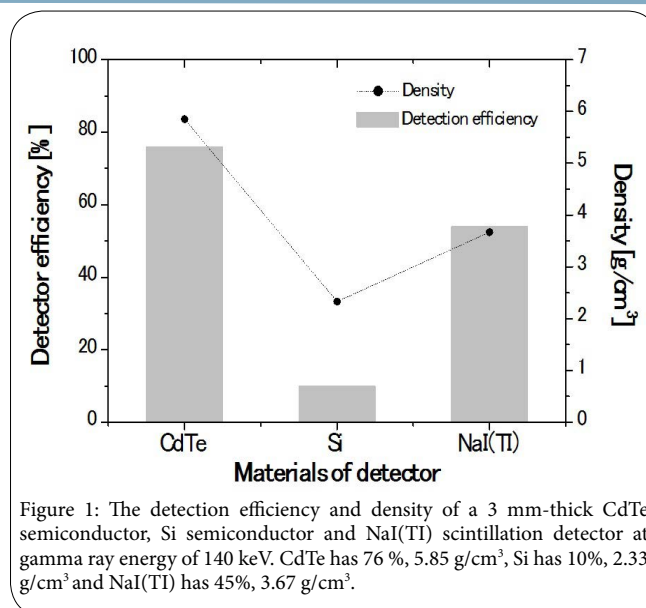


Figure 1: The detection efficiency and density of a 3 mm-thick CdTe semiconductor, Si semiconductor and NaI(Tl) scintillation detector at gamma ray energy of 140 keV. CdTe has 76 %, 5.85 g/cm³, Si has 10%, 2.33 g/cm³ and NaI(Tl) has 45%, 3.67 g/cm³.

$$R_{system} = \sqrt{R_{intrinsic}^2 + R_{collimator}^2}$$

$$[R_{intrinsic} = \frac{pixelsize}{magnificationfactor} (magnificationfactor = \frac{a}{b})]$$

$$R_{collimator} = \frac{d_{effective} (a + b)}{a} (d_{effective} = \sqrt{d \left(d + 2\mu^{-1} \tan \tan \left(\frac{\theta}{2} \right) \right)})]$$

$$g = \frac{d_{effective}^2 \cos^3 \theta}{16b^2}$$

Evaluation of image performance

To evaluate the image performance with our pinhole systems, the sensitivity and spatial resolution were estimated. A ^{99m}Tc point source was measured to evaluate image performance in this study. The activity of ^{99m}Tc point source and scan time is 1 MBq and 900 seconds, respectively. Both the sensitivity and spatial resolution were estimated when pinhole diameter was varied from 0.2 to 2 mm by 0.2 mm increment at step for each magnification factor of 2, 3 and 6. Estimated sensitivity was defined as counts per second per kBq (cps/kBq) and spatial resolution was represented in the full width at half maximum (FWHM) of the point spread function. Then, we plotted trade-off curves that express the relationship of sensitivity and spatial resolution to optimize collimator design with respect to the pinhole diameters and magnification factors.

Finally, to confirm overall image performances, we designed a hot-rod phantom. The diagram of the phantom is shown Figure 3. The six areas with rods of different diameter were filled with different activity of ^{99m}Tc. The phantom was filled with a water solution of ^{99m}Tc.

Results and Discussion

The estimated sensitivity and spatial resolution were plotted as a function of the collimator diameters for each magnification factor of 2, 3 and 6 (Figure 4). The results showed that both sensitivity and spatial resolution was improved with increasing magnification factors. The increase of magnification factor means the decrease of source-to-aperture distance with fixed aperture-to-detector distance. It leads to the improvement of geometric efficiency and it makes to the

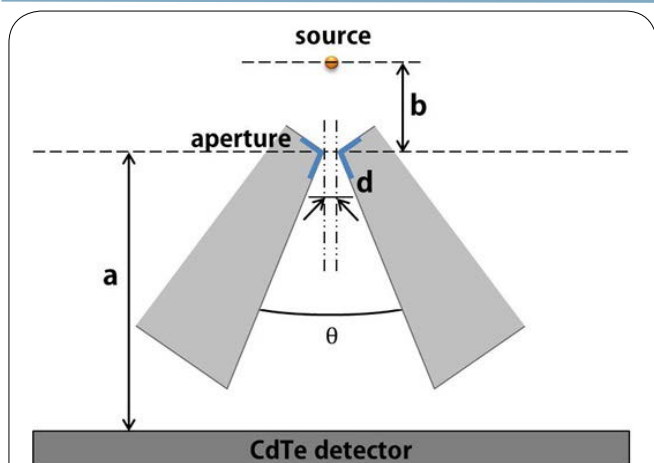


Figure 2: Schematic diagram of the pinhole collimator. In this study, we simulated 5, 10 and 15 cm source-to-aperture distances with 30 cm aperture-to-detector distance and pinhole diameter was varied from 0.2 mm to 2 mm with 51° acceptance angle.

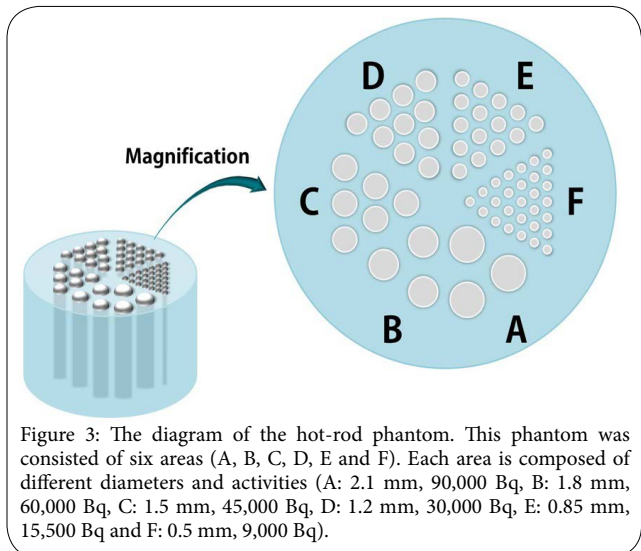


Figure 3: The diagram of the hot-rod phantom. This phantom was consisted of six areas (A, B, C, D, E and F). Each area is composed of different diameters and activities (A: 2.1 mm, 90,000 Bq, B: 1.8 mm, 60,000 Bq, C: 1.5 mm, 45,000 Bq, D: 1.2 mm, 30,000 Bq, E: 0.85 mm, 15,500 Bq and F: 0.5 mm, 9,000 Bq).

improvement of overall spatial resolution. However, in the most gamma camera system using collimator, it is difficult simultaneously to obtain both high sensitivity and high spatial resolution. For example, in cardiac study in gamma camera system, the acquisition time generally needs to 20 minutes. Due to comparatively long acquisition time, we need to choose high sensitivity collimator. However, when we used high sensitivity collimator, deterioration of spatial resolution must occur. For this reason, we plotted trade-off curve between sensitivity and spatial resolution to find the best optimal pinhole design. In Figure 5, the trade-off curves of sensitivity and spatial resolution as a function of the pinhole diameter while magnification factor fixed was shown.

Compared to the each graph in Figure 5, regardless of changes in magnification factor, we found that the optimal pinhole diameter was approximately 1.4mm.

The images of hot-rod phantom to confirm overall image performance were shown in Figure 6. We obtained phantom images with pinhole diameters of 0.4, 1.0 and 1.6 mm and magnification factors of 2, 3 and 6. We found that all rods with diameter of 2.1, 1.8, 1.5, 1.2 and 0.85 mm could resolve at all magnification factors and

case of the change of the pinhole diameter, the results of sensitivity and spatial resolution show difference tendency. When increasing pinhole diameter, sensitivity was improved but spatial resolution was aggravated. By using a larger pinhole diameter, we can improve geometric efficiency with larger effective diameter. On the other hand, the larger effective diameter makes to the poorer collimator resolution. Thus, trade-off between sensitivity and spatial resolution is very important for determination of pinhole diameter.

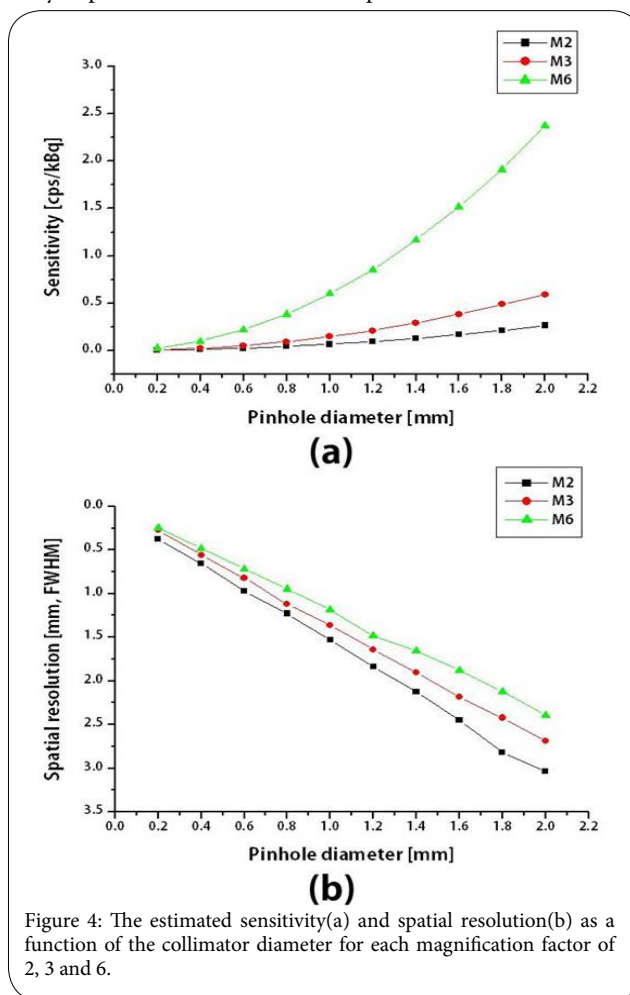


Figure 4: The estimated sensitivity(a) and spatial resolution(b) as a function of the collimator diameter for each magnification factor of 2, 3 and 6.

pinhole diameter of 0.4 mm. The 0.5mm rods were certainly resolved when magnification factor and the pinhole diameter were 6 and 0.4, respectively. According to the phantom results, the spatial resolution corresponds to between our proposed system and phantom image.

Conclusion

In this study, we designed pinhole gamma camera system with CdTe semiconductor detector using a GATE simulation and evaluated its image performance. The sensitivity and spatial resolution were estimated to evaluate image performance with verifying magnification factors and pinhole diameters. To compromise between sensitivity and spatial resolution, trade-off curve was plotted and we found the optimal pinhole diameter. Finally, we validated overall image performance using a hot-rod phantom. As a result, when pinhole diameter of approximately 1.4 mm is used in all magnification factors, we confirmed that our proposed system acquired the best image performance with reasonable value between the sensitivity and spatial resolution.

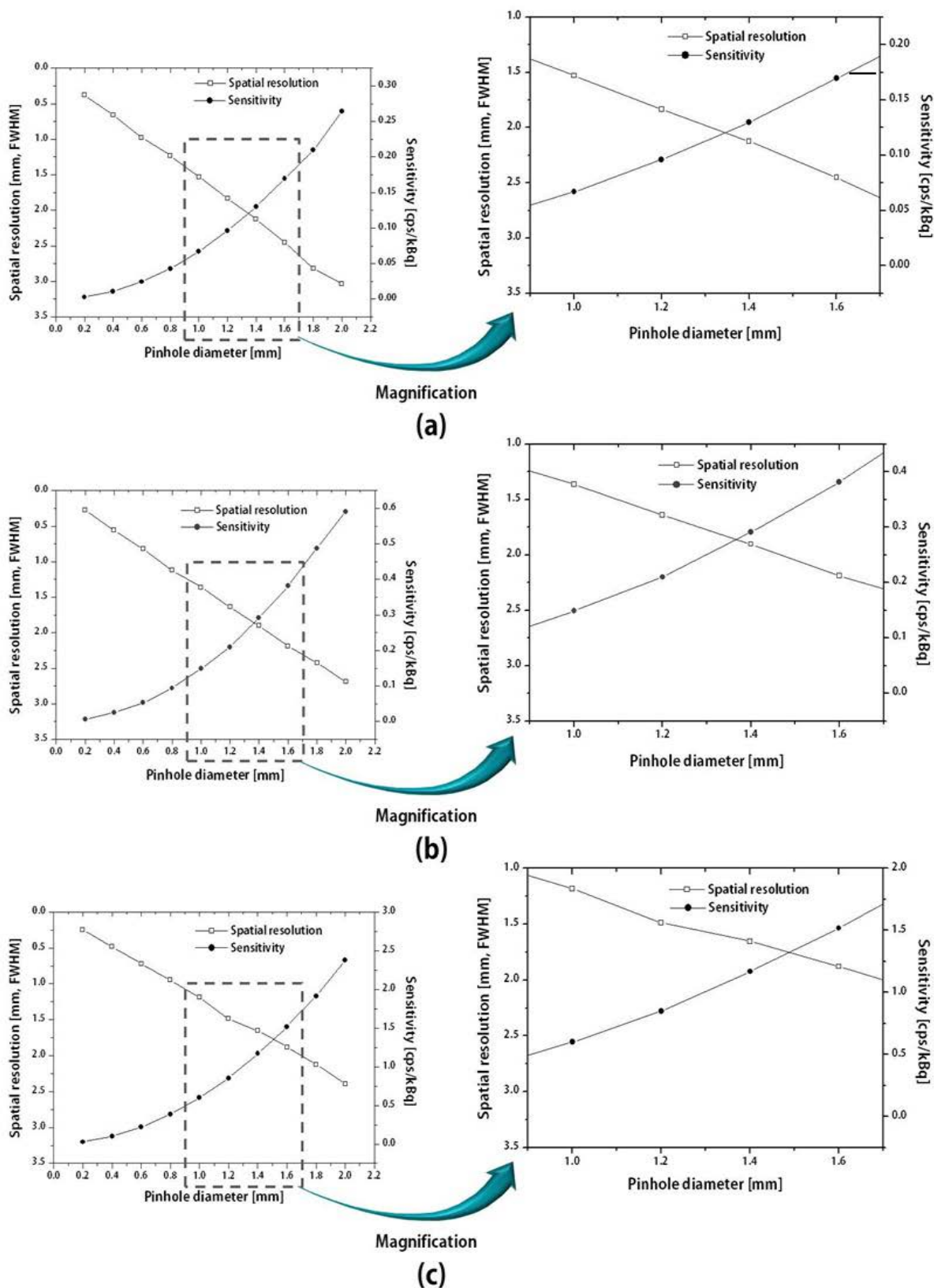


Figure 5: The trade-off curves of sensitivity and spatial resolution as a function of the pinhole diameter for each magnification factor of (a) 2, (b) 3, and (c) 6. Right graphs are magnification view of dashed line of left.

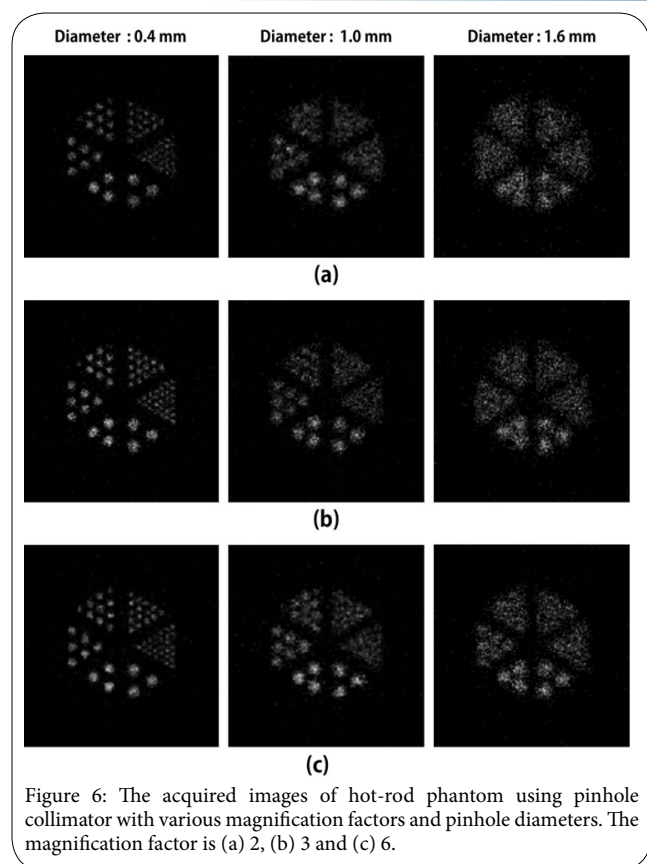


Figure 6: The acquired images of hot-rod phantom using pinhole collimator with various magnification factors and pinhole diameters. The magnification factor is (a) 2, (b) 3 and (c) 6.

Competing Interests

The authors have no competing interests with the work presented in this manuscript.

Author Contributions

All the authors substantially contributed to the literature review, drafting the manuscript and approve the final version of the manuscript.

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