

Visualization of the scatter radiation in real time using a high-sensitivity CMOS camera with pinhole collimator

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Abstract

Purpose This study proposes a method for real-time visualization of scatter radiation using a high-sensitivity CMOS camera with a pinhole collimator, within the energy range relevant to diagnostic imaging. Additionally, Monte Carlo simulations were employed to validate whether the measured data accurately represent actual scatter radiation.

Methods A real-time scatter radiation imaging system was developed using a CMOS camera, CsI scintillator, and pinhole collimator. Various parameters, including pinhole diameter and exposure time, were evaluated to identify the optimal configuration. Monte Carlo simulations were used to compare the measured data against the simulated scatter radiation distribution.

Results The system successfully visualized scatter radiation sources with high spatial resolution. The optimal parameters were identified as a 2 mm pinhole diameter and 50 ms exposure time, balancing image clarity and efficiency. The measured data closely matched the simulation results, confirming the accuracy of the system.

Conclusion The proposed system offers significant potential for enhancing radiation protection in clinical settings by enabling real-time visualization of scatter radiation. It is expected to contribute to safer working environments and more effective radiation safety management during diagnostic procedures.

Keywords

Scatter radiation, Real-time visualization, CMOS camera, Pinhole collimator, Radiation safety management

1 Introduction

The use of radiation in healthcare settings has been expanding, with x-rays being extensively employed for diagnostic purposes. Accurate diagnostic imaging often requires the assistance of caregivers and medical staff for patients who are unable to remain still, such as the elderly, children, trauma patients requiring cervical spine immobilization, and critically ill patients needing respiratory support [1–3]. However, scatter radiation, which primarily originates from the patient during exposure, poses a potential risk to caregivers and medical staff [4–6]. As these sources of scatter radiation are imperceptible to the human eye, visualizing them can offer critical information for identifying high-dose hazardous zones and low-dose safe zones. This visualization supports caregivers and medical personnel in implementing appropriate protective measures during procedures [7–9].

Research on scatter radiation visualization includes methods utilizing Monte Carlo simulations and imaging plates (IP) [10–15]. Monte Carlo simulations enable the analysis of scatter radiation

distribution but are constrained by lengthy computation times and the need for accurate replication of device structures and conditions, which limits their practical application. On the other hand, methods using IP can directly capture the distribution of scatter radiation; however, they require a reading device, and the delay in accessing recorded images makes them unsuitable for real-time observation.

Considering these challenges, this study proposes a method for real-time visualization of scatter radiation using a scintillator and a digital camera. Previous studies have utilized configurations combining a scintillator and a digital camera to visualize the primary beam, but their application to scatter radiation has been insufficiently investigated [16]. In this study, we adapt and apply this technique specifically for the observation of scatter radiation.

This study aims to propose a method for real-time visualization of scatter radiation using a high-sensitivity Complementary Metal-Oxide-Semiconductor (CMOS) camera equipped with a pinhole collimator, within the energy range relevant to diagnostic x-ray imaging. Monte Carlo simulations were also employed to validate whether the measured data accurately represent actual scatter radiation. Furthermore, by varying the pinhole size and the camera's exposure time, the study seeks to identify the optimal pinhole size and the minimum exposure time required for effective visualization.

2 Materials and Methods

2.1 Experimental setup for real-time scatter radiation imaging

2.1.1 Scatter radiation real-time imaging system

In this study, a scatter radiation real-time imaging system was developed to enable real-time visualization of scatter radiation. The system comprises a Complementary Metal-Oxide-Semiconductor (CMOS) camera (ORCA-Quest, Hamamatsu Photonics Corporation, Shizuoka, Japan), a Cesium Iodide (CsI) scintillator (Great Performance X-ray CsI Scintillator J13113, Hamamatsu Photonics Corporation, Shizuoka, Japan), an RGB camera (Intel RealSense Depth Camera D435, Intel Corporation, USA), a pinhole collimator, and a supporting device. The constructed system is shown in Figure 1.

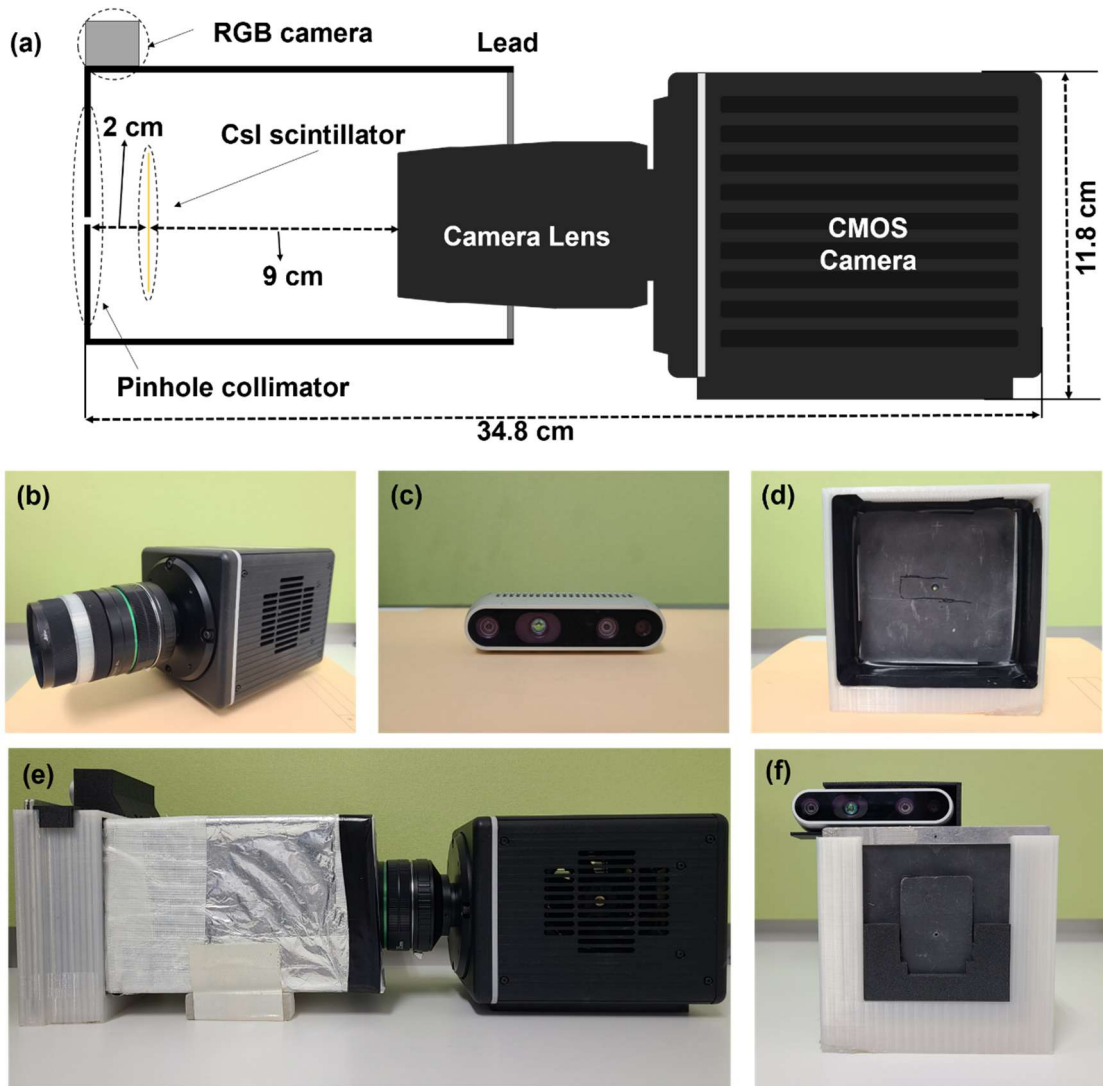


Fig. 1 Configuration and assembly of the scatter radiation visualization system using a pinhole collimator. (a) Schematic diagram of system, (b) CMOS camera, (c) RGB camera, (d) Pinhole collimator and lead case, (e) Side view of system, (f) Front view of the system.

The CMOS camera offers high quantum efficiency and low noise performance, enabling the precise detection of weak light signals [17]. Its ability to maintain signal quality even with short exposure times facilitates high-speed imaging. Image data were processed using the High-Speed Recording Software (Hamamatsu Photonics Corporation, Shizuoka, Japan), a dedicated application designed for the CMOS camera. To optimize light collection, the camera was equipped with an F2.4 lens (SMC Pentax-Da 35 mm, Pentax Corporation, Japan).

The CsI scintillator is a high-performance X-ray scintillator made of CsI (TI) (thallium-activated cesium iodide) with a columnar structure. This structure prevents light scattering and provides high spatial resolution [18]. The external dimensions of the CsI scintillator are $50 \times 50 \text{ mm}^2$, with an effective detection

area of $45 \times 45 \text{ mm}^2$. The scintillator layer has a thickness of $400 \text{ }\mu\text{m}$, while the substrate thickness is 0.5 mm .

Visible light images of X-ray devices, phantoms, and other objects were captured using an RGB camera. The camera was positioned 7.1 cm above the center of the pinhole to ensure optimal image acquisition.

The pinhole collimator utilized pinholes with diameters of 2 mm and 3 mm . It was constructed from a lead plate with dimensions of $12.0 \times 12.0 \times 0.3 \text{ cm}^3$, designed to restrict scatter radiation to specific directions for improved imaging accuracy.

The pinhole, scintillator, and camera lens were enclosed within a $10.2 \times 15.5 \times 10.5 \text{ cm}^3$ housing made of 2 mm -thick lead to provide shielding and prevent the intrusion of scatter radiation and external light, except through the pinhole. Additionally, a custom fixture was fabricated using a 3D printer (Flash Forge Finder, Flashforge Corporation, China) to ensure precise vertical alignment of the pinhole collimator and scintillator.

The distance between the pinhole collimator and the scintillator was set to 2 cm , while the distance between the scintillator and the camera was set to 9 cm . The distance between the pinhole collimator and the scintillator was set to 2 cm to ensure that scatter radiation passing through the pinhole is efficiently projected across the entire scintillator, covering the entire observation area. This configuration was determined based on the field of view (2.7 cm) captured by the camera positioned 9 cm from the scintillator.

Furthermore, the distance between the scintillator and the camera was set to 9 cm , as this was determined to be the minimum distance at which the camera's optical characteristics allow for clear and focused imaging without blurring. These distance parameters were optimized to facilitate the real-time visualization of scatter radiation, contributing to the development of an effective system design.

2.1.2 Experimental conditions and structure

X-ray irradiation was performed using an X-ray tube device (UD150L-30). Detailed experimental conditions are shown in Table 1. The irradiation conditions were based on an example of abdominal imaging parameters [19].

Table 1 Experimental X-ray irradiation conditions

Tube voltage [kV]	74
Tube current [mA]	250
Exposure time [s]	0.14

Source-to image distance [cm]	101
Field size [cm ²]	30 × 30

The experimental setup for the scatter radiation imaging system is illustrated in Figure 2. A water phantom with dimensions of $30 \times 30 \times 15 \text{ cm}^3$ was utilized as a scatter object to mimic a patient. The phantom was placed on the patient table, with the X-ray beam directed from the ceiling toward the floor. The pinhole camera was placed 150 cm from the center of the water phantom, and its height was adjusted to ensure that both the phantom and the X-ray tube were within the camera's field of view. The distance from the center of the pinhole to the floor was measured at 94.2 cm.

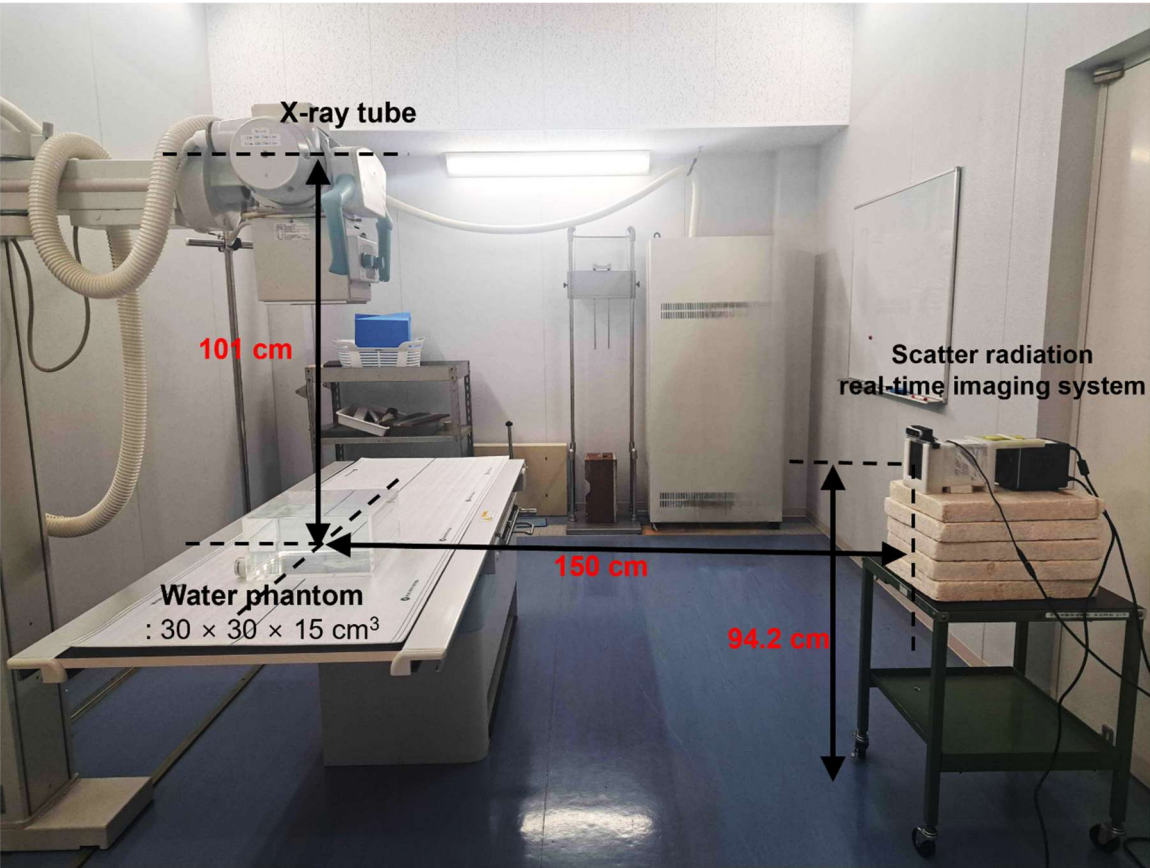


Fig. 2 Experimental setup for scatter radiation visualization

For image acquisition with the CMOS camera, the resolution was set to 1024×576 pixels with 4×4 binning and a bit depth of 16 bits. Exposure times of 2, 5, 50, and 200 ms were compared to determine the optimal imaging conditions. Additionally, to evaluate the dose rate of the scatter radiation images, a semiconductor-based survey meter (Raysafe X2, Unfors Raysafe, Billdal, Sweden) was utilized. This measurement validated that the specified dose rate enables the current level of scatter radiation visualization,

providing a foundation for understanding the relationship between dose rate and visualization quality. The survey meter was positioned at the location of the pinhole collimator to measure the dose rate reaching the collimator.

2.1.3 Visualization of the scatter radiation in real-time

To provide caregivers and medical staff with data for appropriate protective measures, it is essential to identify the sources of scatter radiation. Overlaying scatter radiation visualization images with background images is highly effective for this purpose. A custom application was employed to combine these images.

Since a CMOS camera and an RGB camera were used to capture scatter radiation images and background images, respectively, the application corrected positional misalignments caused by differences in the field of view and installation positions of the two cameras. The method for combining scatter radiation visualization images and background images is shown in Figure 3. As shown in Figure 3(a), eight blue Light Emitting Diode (LED) bulbs were attached to the vertices of the collimator and phantom. The setup, including the LEDs, was then captured using an RGB camera to create a background image. Subsequently, as depicted in Figure 3(b), tracing paper was placed at the position of the scintillator inside translated to align the centers of each LED lights in Figure 3(a) with those in each LED visualization image in Figure 3(b). This process corrected any positional discrepancies.

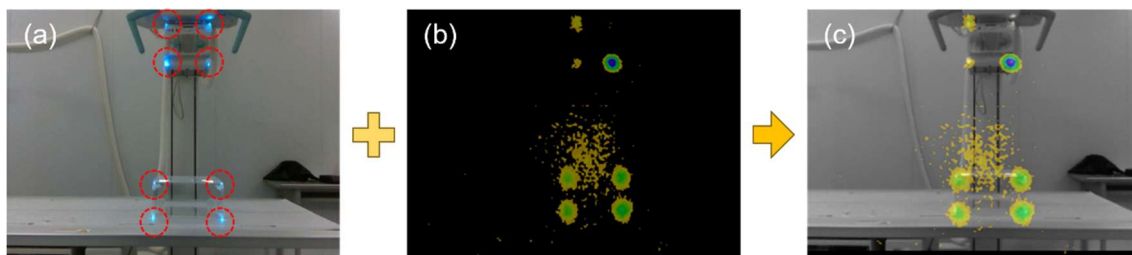


Fig. 3 Method for combining scatter radiation images with background images. (a) LED bulbs positions captured by the RGB camera (red dashed circle regions), (b) Scatter radiation image, (c) Final comprehensive image.

2.2 Image evaluation index

To evaluate image quality, analysis was performed using the Signal-to-Noise Ratio (SNR) and contrast. For SNR calculation, two Regions of Interest (ROIs) were defined within the image: one representing the signal region and the other background region. The signal region encompassed the X-ray tube and the phantom. The distinguishability of the signal was evaluated based on the average intensity of the background region.

For contrast analysis, the Michelson contrast method was employed. This approach evaluates the clarity of signal intensity variations within the image based on the difference between the maximum and minimum intensities within the region of interest. Michelson contrast is a widely used metric in image analysis and is particularly useful for assessing the impact of imaging conditions on the distinguishability of signals from the background in the image.

These analyses were conducted using ImageJ (version 1.54g, National Institutes of Health, MD, USA). The software was utilized to extract statistical values within the defined ROIs, enabling a quantitative evaluation of SNR and contrast across various imaging conditions. This approach clarified the effects of pinhole size and camera exposure time on image quality, ultimately identifying the optimal imaging conditions.

2.3 Validation of the images obtained using Monte Carlo simulation

Monte Carlo simulation was conducted to verify whether the radiation passing through the pinhole and reaching the scintillator consisted of scatter radiation. The Particle and Heavy Ion Transport Code System (PHITS) version 3.341 was utilized for this purpose, and comparisons were made between the measured data and simulation results [20]. In the simulation, the flux distribution on the scintillator was calculated, and data along the vertical axis through the center of the phantom were extracted as plot files from both the measured data and the simulation results.

As shown in Figure 4, the simulation geometry was designed to replicate the configuration of the Scatter radiation real-time imaging system and the arrangement of the scintillator used in the experiment. The pinhole diameters were set to 2 mm and 3 mm, while the distances from the pinhole to the scintillator (2 cm) and from the scintillator to the camera (9 cm) were maintained identical to the experimental conditions.

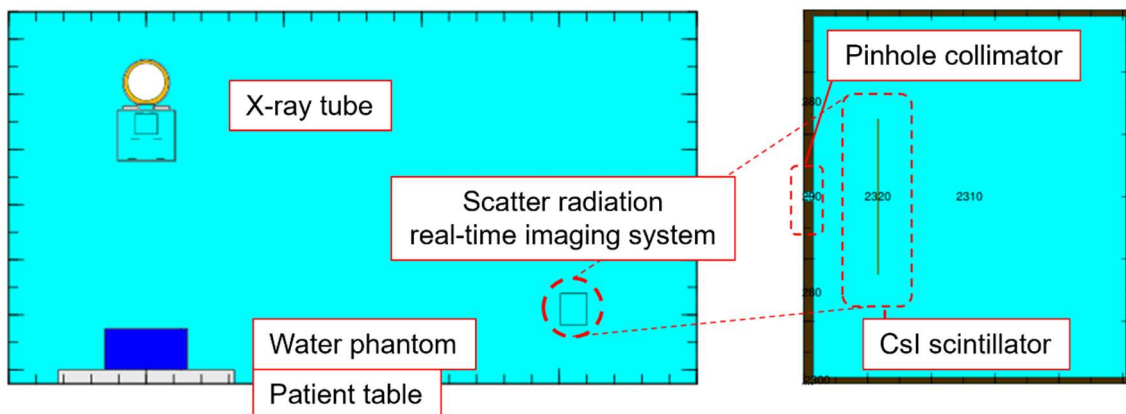


Fig. 4 System configuration used in the Monte Carlo simulation

The number of particle tracks was set to 1×10^5 to ensure sufficient statistical accuracy. To

enhance computational efficiency, photon energies below 10 keV and electron or positron energies were excluded from the calculations. SpekPy website was used to determine the X-ray spectrum, and a photon source with a continuous spectrum was configured as the radiation source, with an energy range of 0 keV to 74 keV [21].

The T-point tally, a function of PHITS, was utilized to measure the scatter radiation flux on the scintillator surface. The T-point tally deriving the fluence at a specific point. Based on the camera's field of view (2.7 cm), a total of 288 points were evenly distributed within a range of ± 1.35 cm, centered on the camera. This setup enabled efficient and detailed evaluation of the spatial distribution of scatter radiation. Each T-point statistically calculated the scatter radiation flux at its specific position. Through this process, plot files representing the distribution of scatter radiation were obtained. The obtained plot files were compared with the measured data and simulation results. For comparison, normalization was performed by setting the maximum value to 1.

3 Results

3.1 Scatter radiation source distribution from experiment

Figure 5 shows a real-time visualization of a composite RGB image and scatter radiation image. The visualization was conducted using different camera exposure times and pinhole sizes. Scatter radiation sources were identified in two locations: the X-ray tube and the water phantom. It was observed that increasing the camera exposure time improved the clarity of the scatter radiation distribution. In the images, the colors represent radiation intensity, with blue indicating high intensity and red indicating low intensity, corresponding to pixel values.

For the 2 mm pinhole size, the shapes and distributions of the scatter radiation sources were observed with relatively sharp detail, achieving higher spatial resolution. In contrast, the 3 mm pinhole size resulted in broader distributions and a noticeable decrease in spatial detail resolution compared to the 2 mm pinhole. This demonstrates that pinhole size significantly impacts the visualization of scatter radiation sources. Additionally, the dose rate reaching the pinhole collimator was 10.71 $\mu\text{Sv/s}$, with a total dose of 2.10 μSv .

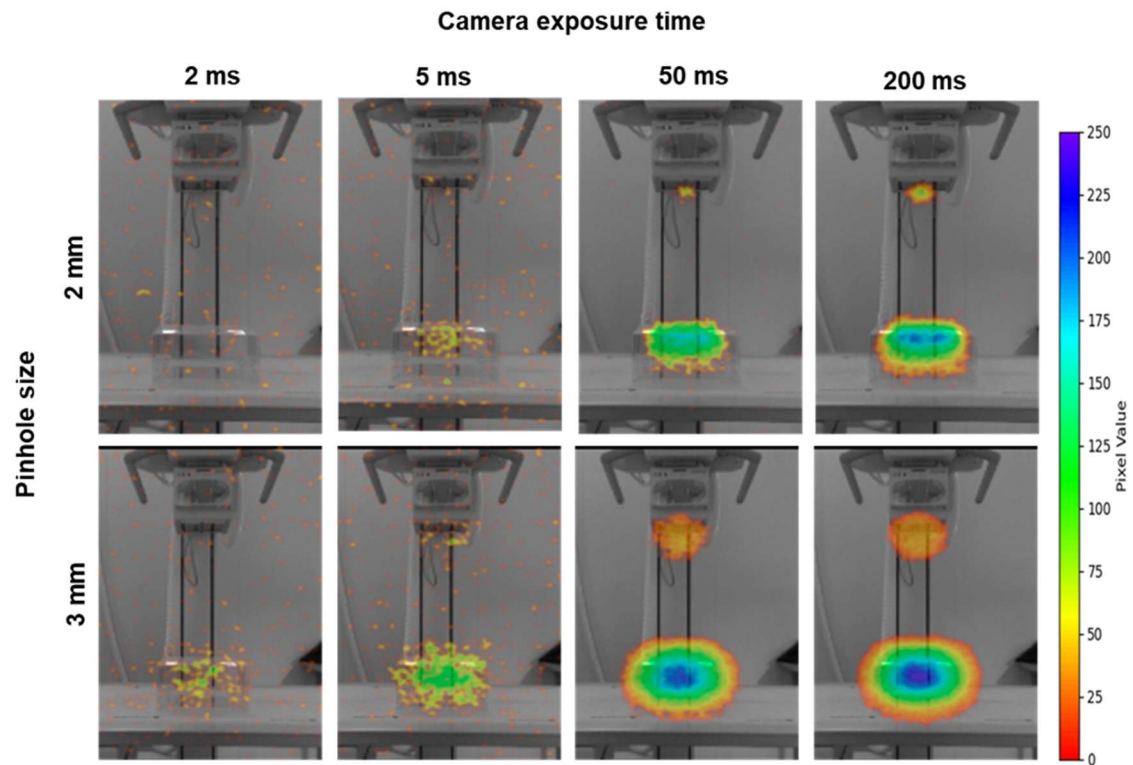


Fig. 5 Comparison pinhole and camera exposure time scattered radiation image.

3.2 Image analysis

As shown in Table 2, both SNR and contrast exhibited an overall increasing trend with longer camera exposure times. For pinhole sizes of 2 mm and 3 mm, SNR and contrast improved as exposure time increased, although the rate of improvement varied between the two pinhole sizes across different intervals.

Regarding the effect of pinhole size, the 3 mm pinhole demonstrated consistently higher SNR values compared to the 2 mm pinhole. This difference is likely attributable to the larger pinhole allowing the collection of more signals. Conversely, no significant differences in contrast were observed between the two pinhole sizes, with changes in contrast being primarily influenced by variations in exposure time.

Table 2 Relationship between camera exposure time, SNR, and contrast for different pinhole sizes

Pinhole size [mm]	2				3			
	Water phantom		X-ray tube		Water phantom		X-ray tube	
Exposure time [ms]	SNR	Contrast	SNR	Contrast	SNR	Contrast	SNR	Contrast
2	1.14	0.07	1.09	0.04	1.77	0.23	1.06	0.03

5	1.59	0.23	1.25	0.11	2.89	0.49	1.64	0.24
50	5.25	0.68	2.98	0.5	30.9	0.94	9.27	0.8
200	12.57	0.85	6.66	0.74	77.61	0.98	23.18	0.92

3.3 Comparison between Monte Carlo simulation and experimental measurements

To determine whether the measured data accurately represents the scatter radiation distribution from the water phantom and X-ray tube, a comparison was conducted using Monte Carlo simulation. Specifically, the measured data obtained from the real-time scatter radiation imaging system were compared with scatter radiation distribution profiles generated by PHITS.

Figure 6 presents the spatial distribution profiles of scatter radiation obtained from both experimental measurements and simulations. Figure 6(a) depicts the measured data, while Figure 6(b) shows the corresponding profile generated from the simulation. The vertical axis represents normalized intensity values, while the horizontal axis represents spatial positions in centimeters within the field of view (FOV).

In the experimental setup, scatter radiation was visualized over a 2.7 cm FOV, and the corresponding pixel positions were mapped to physical distances based on the optical characteristics of the imaging system. To enable direct comparison, the PHITS simulation extracted fluence values at the same spatial range, maintaining consistency with the experimental setup.

The comparison revealed that both the simulation and the measured data exhibited two prominent peaks, corresponding to scatter radiation originating from the water phantom and the X-ray tube. Regarding pinhole size, the 2 mm pinhole diameter provided better peak separation and higher spatial resolution, whereas the 3 mm pinhole diameter yielded greater signal intensity at the expense of reduced peak separation.

These findings confirm that the real-time imaging system effectively visualizes scatter radiation and that the PHITS simulation provides a reliable framework for optimizing and evaluating the system's performance.

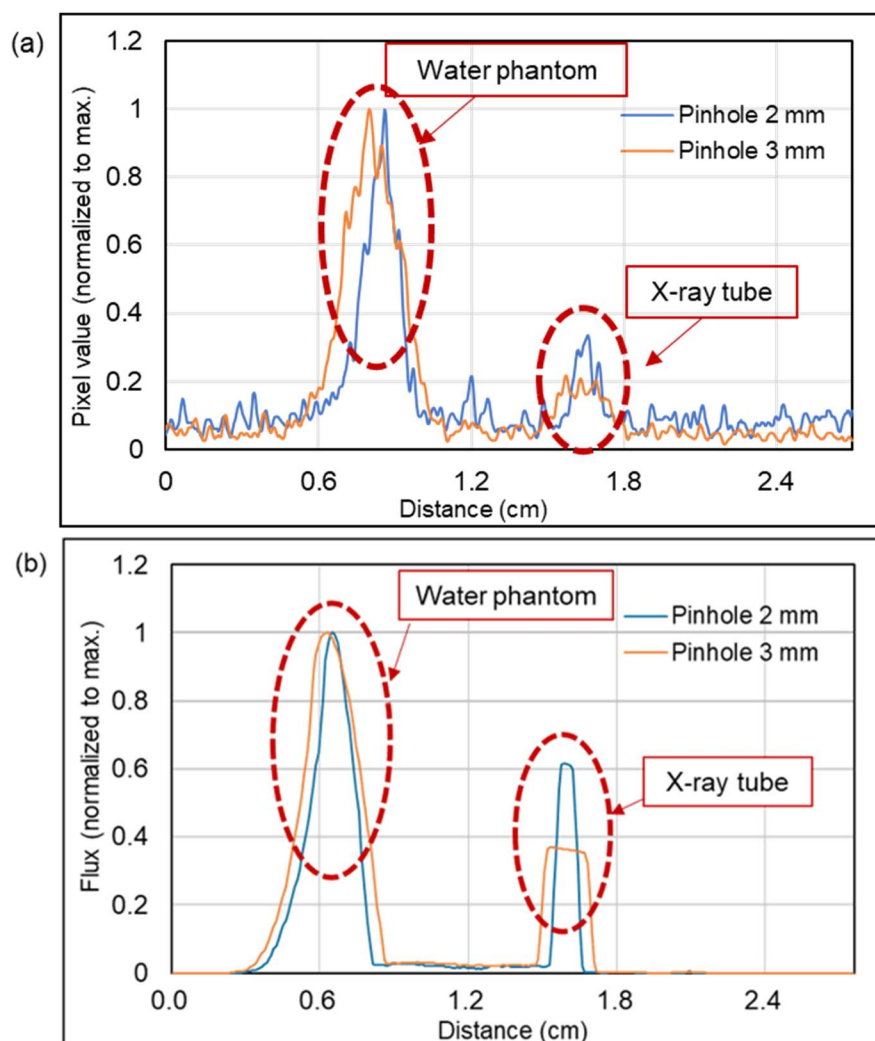


Fig. 6 Comparison of scatter radiation distribution between Monte Carlo simulation and experimental measurements (a) Measured plot profile (b) Simulation plot profile

4 Discussion

In this study, real-time visualization of scatter radiation was achieved using a high sensitivity CMOS camera, and the effects of pinhole size and camera exposure time on scatter radiation observation were evaluated. Among the exposure times of 2, 5, 50, and 200 ms, the 50 ms condition was identified as a balanced setting between short exposure time and image quality. Longer exposure times were found to be unnecessary, enabling the determination of efficient conditions for real-time observation. Short exposure times (2 ms and 5 ms) tended to result in decreased image quality due to noise. Additionally, the results of this study confirmed that the dose rate reaching the pinhole was $10.71 \mu\text{Sv/s}$, demonstrating sufficient applicability for real-time observation in general radiography. Based on this dose rate, it is possible to estimate the environmental dose rate conditions under which scatter radiation imaging is feasible. This estimation allows for discussions on the applicability of the system to portable imaging and more distant

observations.

The scatter radiation imaging system developed in this study may be influenced by setup errors arising from the use of 3D-printed structures and manual assembly. Minor variations in the alignment of the pinhole collimator and scintillator, distances between components, and the arrangement of equipment could affect image quality and the reproducibility of scatter radiation distribution. To minimize these variations, it is necessary to design fixtures that secure the alignment and positions of the experimental equipment and to standardize the setup process. Furthermore, conducting repeated experiments to quantitatively analyze the impact of setup errors and defining acceptable margins of error will enhance the reproducibility and reliability of the system.

Next, the impact of pinhole size differences on image spatial resolution was evaluated. With a 2 mm pinhole size, the scatter radiation distribution was observed sharply, indicating its suitability for detailed evaluations. These results suggest that selecting an appropriate pinhole size based on the objective can improve the accuracy of image analysis.

Additionally, the comparison between the profiles of the simulation and the measured data confirmed the presence of two peaks. The consistency in peak shapes suggests that the simulation can be utilized for optimizing the camera system. However, slight differences were observed in intensity distribution and peak positions, which may be attributed to the reproducibility of the internal structure of the X-ray device in the simulation or the influence of the experimental environment. Improving the accuracy of the simulation remains a challenge for future work.

Improving the accuracy of the simulation remains a challenge for future work. The ability to visualize scatter radiation in real time can provide immediate feedback to medical staff and caregivers regarding potential high-exposure areas, enabling them to adjust their positioning and protective measures accordingly. By integrating this system into clinical workflows, such as during fluoroscopic procedures or bedside radiography, it may contribute to improved radiation safety management and reduce unnecessary exposure.

While this study demonstrated the feasibility of real-time scatter radiation visualization, further research is needed to assess its direct impact on radiation exposure reduction. Future studies may involve clinical trials or controlled experiments to compare staff and caregiver dose levels with and without the system's implementation. Additionally, investigating its applicability to different imaging modalities and operational environments could further enhance its clinical utility.

5 Conclusion

This study successfully developed and evaluated a real-time scatter radiation visualization system using a high-sensitivity CMOS with pinhole collimator. The proposed system demonstrated the ability to identify scatter radiation sources with high spatial resolution while maintaining real-time observation capabilities. Through systematic evaluation, a pinhole diameter of 2 mm and an exposure time

of 50 ms were identified as optimal parameters for achieving a balance between image clarity and efficiency. This system offers significant potential for enhancing radiation protection in clinical settings by enabling medical staff to visually assess scatter radiation distribution. It is anticipated that the application of this technology will contribute to safer working environments and more effective radiation safety management during diagnostic.

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