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# Development of a new pinhole camera for imaging in high dose-rate environments

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ABSTRACT

After Fukushima's nuclear disaster in Japan, the decontamination operation is successfully ongoing, and restrictions from some areas were lifted in April 2017. However, the radiation dose rate in the Fukushima Daiichi Plant is still so high (e.g., from a few mSv/h up to 530 Sv/h) that the decommissioning operation of the reactor remains a serious problem. Visualization of radioactive materials would help address this, but no gamma camera is available at this moment that can take images in such a high dose-rate environment. In this study, we developed a new gamma camera featuring a wide dynamic range from sub-mSv/h to more than 680 Sv/h, for a quick and accurate visualization of radioactive materials. The camera consists of a pinhole collimator, a $Gd_2O_2S$:Tb (GOS) scintillator sheet, and an electron multiplying charge-coupled device (EM-CCD). Gamma rays passing through the pinhole collimator hit the GOS scintillator sheet, which emits scintillation light. The luminescence of the GOS scintillator sheet is monitored in real-time with an EM-CCD with an internal multiplication gain of up to 20. By changing the exposure time, electron multiplication gain, and aperture of the EM-CCD, a wider dynamic range covering five orders of magnitude in the radiation dose can be monitored for the first time. We show that the positions of a $^{137}$Cs source (662 keV) and $^{60}$Co source (1173, 1333 keV) are identified correctly with a typical angular resolution of 10° full width at half maximum (FWHM). We also confirmed a linear relation between the absorbed dose and the luminescence of the GOS scintillator sheet. Finally, we propose a new concept of "color imaging", by using multi-layered scintillators consisting of a $Ga_3Al_2Gd_3O_{12}$ (GAGG) scintillator, fluorescent glass, and a plastic scintillator.



## 1. Introduction

After the Fukushima nuclear disaster in March 2011, various attempts have been made for efficient decontamination operations in that area; one is using a gamma camera, which can visualize radioactive materials that emit gamma rays, particularly, long-lived sources such as $^{137}$Cs [1–4]. Most of these cameras are designed to find weak hotspots, typically in the mSv/h to mSv/h level, to fit the dose rate of the restricted areas near the Fukushima Daiichi Plant (FDP) [5,6]. However, the dose rate inside FDP is much higher; at the extreme, the radiation dose inside the containment vessel of the reactor can be up to 530 Sv/h [7]. Thus, the decommissioning operation of the reactor remains extremely difficult. To our knowledge, no gamma cameras currently available can work in such a high-dose environment.

Hence, in this paper, we propose a new-concept gamma camera to image in a high dose-rate environment [8–10]. The conventional method of gamma imaging, which calculates the incident direction of each photon, is not applicable, because the incident rate is too high and the output pulses will be "piled up". Rather, we chose a pulse integration method, where the output signals are integrated over a certain period of integration time. The gamma camera consists of a pinhole collimator, a $Gd_2O_2S$:Tb (GOS) scintillator sheet, and an electron multiplying charge-coupled device (EM-CCD). Gamma rays passing through the pinhole collimator hit the GOS scintillator sheet, which emits scintillation light. The luminescence from the GOS scintillator sheet is monitored in real time with an EM-CCD with an internal multiplication gain of up to 20. With such a simple design, the spatial distribution of radioactive materials can be easily resolved in a wide dynamic range of radiation

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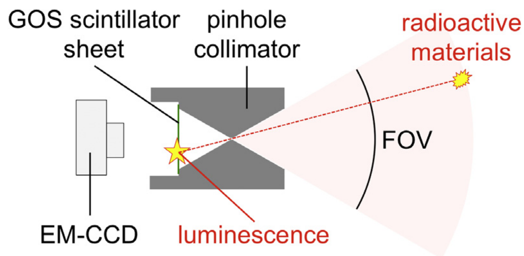


**Fig. 1.** Schematic of the developed pinhole camera.

dose, from sub-mSv/h to more than 680 Sv/h, by changing the exposure time, electron multiplication gain, and aperture of the EM-CCD.

## 2. Materials and methods

A schematic of the developed pinhole camera is shown in Fig. 1. The pinhole camera consists of a pinhole collimator (Silveralloy Co., Ltd), a GOS scintillator sheet (Fujifilm Corporation, HR-16), and an EM-CCD (BITRAN Corporation, BU-66EM-UV). For pointed observations, a pinhole collimator, made of tungsten, is used to limit the incident photon directions. The GOS scintillator sheet is a type of ceramic scintillator, and is a sheet coated with $Gd_2O_2S$:Tb as a phosphor. When radiation is irradiated on the phosphor in the scintillator sheet, the phosphor absorbs the energy of the radiation and converts it into scintillation light. This GOS sheet exhibits an excellent amount of light emission, and has advantages such as enlargement, easy processing, and low cost. The EM-CCD is a CCD with an electron multiplying function; it drastically multiplies the signal without increasing the readout noise and realizes high sensitivity.

The luminescence of the GOS scintillator sheet is monitored with the EM-CCD. It is possible to visualize the spatial distribution of radioactive materials from the relative position of the integrated light emission of the GOS scintillator sheet and the pinhole. The size of the detector is (W)84 mm × (D)160 mm × (H)84 mm, the weight is approximately 10 kg, and the field of view (FOV) of the pinhole camera is 60°. The maximum electron multiplication gain is 20, and the exposure time can be changed from 1 ms to 60 s.

## 3. Performance verification at < 1 Sv/h

### 3.1. *Performance test under $^{137}$Cs irradiation*

First, we evaluated the performance of the new pinhole camera in the $^{137}$Cs irradiation facilities at the Facility of Radiation Standards (FRS), JAEA, Japan. It should be noted that $^{137}$Cs emits 662-keV gamma rays and is the dominant source in Fukushima [11]. As shown in Fig. 2, we examined source directions of 0°(45 mSv/h) and 15° (~45 mSv/h). The EM-CCD monitored the image after reflection by a mirror to avoid unnecessary exposure. The exposure time and electron multiplication gain of the EM-CCD were set to 30 s and 20. Fig. 3 shows a pinhole camera image obtained with a $^{137}$Cs point source, overlaid on the optical image. The position of the $^{137}$Cs point source determined by the pinhole camera agrees well with the position of the optical image. The incident directions of the gamma rays were identified to be 0.14 ± 1.60(sys) ± 0.01° (stat) for a source direction of 0°, where the first and second errors represent systematic and statistical errors, respectively. Here, the systematic error was crudely estimated as a 2 cm shift of the pinhole camera from the correct position. Similarly, the incident directions of the gamma rays were identified to be 15.34 ± 1.60(sys) ± 0.01° (stat) for a source direction of 15°. Hence, the new pinhole camera can visualize the position of the $^{137}$Cs point source under a relatively low dose rate on the order of several tens of mSv/h. The angular resolution was 9.09 ± 0. 03° (source direction 0°) and 9.34 ± 0. 04°(source direction 15°) full width at half maximum (FWHM).

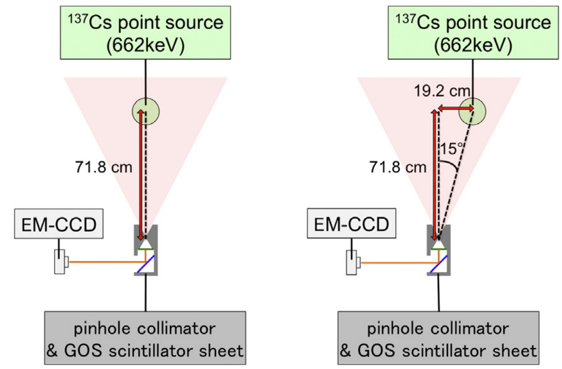


**Fig. 2.** Schematic of the geometry at FRS. Left: source direction of 0°; right: source direction of 15°.

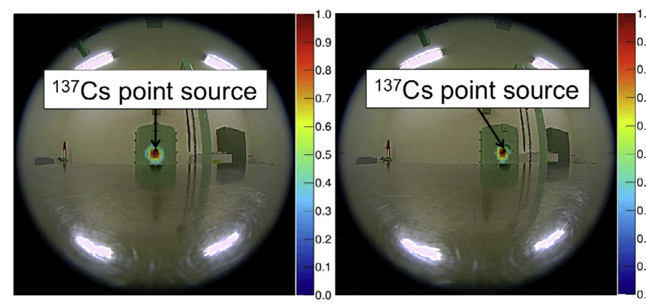


**Fig. 3.** Pinhole camera image obtained with a $^{137}$Cs point source in FRS. Left: source direction of 0°; right: source direction of 15°.

### 3.2. *Linearity between absorbed dose and luminescence*

Next, in the FRS test, we confirmed the linear relationship between the absorbed dose and luminescence in order to demonstrate that our new pinhole camera can visualize radioactive materials in a wide dynamic range of radiation dose. $^{60}$Co emits 1.17 and 1.33 MeV gamma rays and is reported to exist inside the FDP [11]. We used two $^{60}$Co point sources having different intensities (3.7 and 7.4 TBq) that were switched to cover a wide range of radiation dose, from 14 to 500 mSv/h. Accordingly, an exposure time of the EM-CCD was varied from 1 to 10 s, but the electron multiplication gain was fixed at 20. Fig. 4 plots the luminescence versus absorbed doses that were obtained by multiplying the calculated dose rate with the exposure time. From Fig. 4, we confirm the linear relationship between the absorbed dose and luminescence. The slight deviation from the line at the lowest absorbed dose is because the signal charge is comparable to the EM-CCD read-out noise.

## 4. Performance verification at > 1 Sv/h

A subsequent performance test was conducted in the $^{60}$Co irradiation facility at Tokyo Tech, Japan. As shown in Fig. 5, we tested our new pinhole camera for source directions of 0° 12.1 Sv/h) and 15° (11.6 Sv/h). The exposure time and electron multiplication gain of the EM-CCD were set to 1 s and 10. Fig. 6 shows a pinhole camera image obtained with a $^{60}$Co source, overlaid on the optical image. The incident directions of the gamma rays were identified as 1.18 ± 1.62(sys) ± 0.04°(stat) (source direction 0°) and 14.36 ± 1.62(sys) ± 0.04°(stat) (source direction 15°). The angular resolution was 14.39 ± 0. 34° (source direction 0°) and 14.03 ± 0. 20° (source direction 15°) at FWHM. The slight degradation of angular resolution is due to (1) the pinhole collimator's transparency to the high-energy gamma rays emitted from $^{60}$Co, thus increasing the effective diameter of the pinhole; and (2) the narrow size of the Tokyo Tech irradiation room compared to that of the FRS, thus increasing the significance of contamination by scattered gamma rays.



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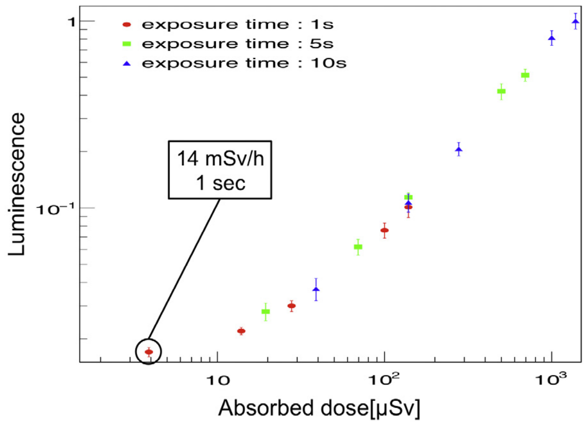


**Fig. 4.** Dependence of luminescence on absorbed dose.

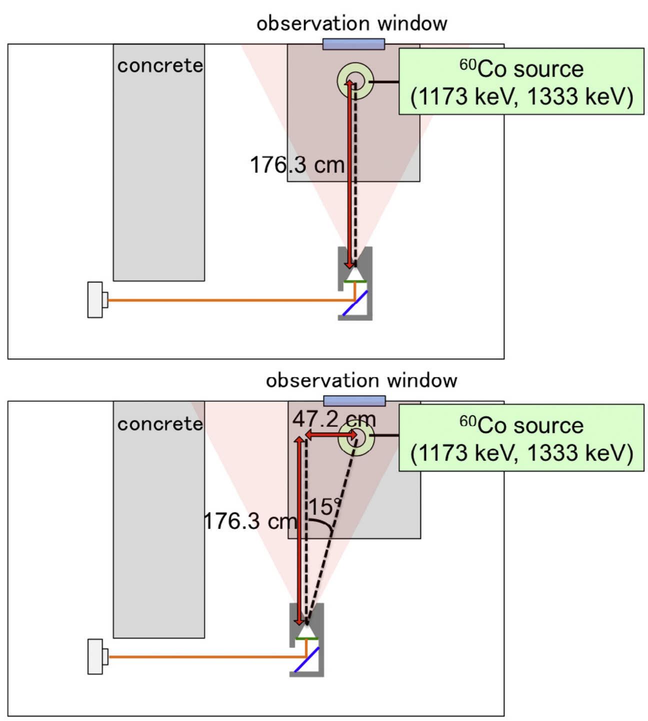


**Fig. 5.** Schematic of geometry at Tokyo Tech. Upper: source direction of 0°; lower: source direction of 15°.

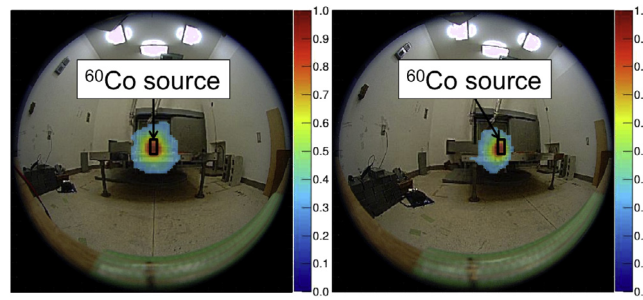


**Fig. 6.** Pinhole camera image obtained with a $^{60}$Co point source at Tokyo Tech. Left: source direction of 0°; right: source direction of 15°.

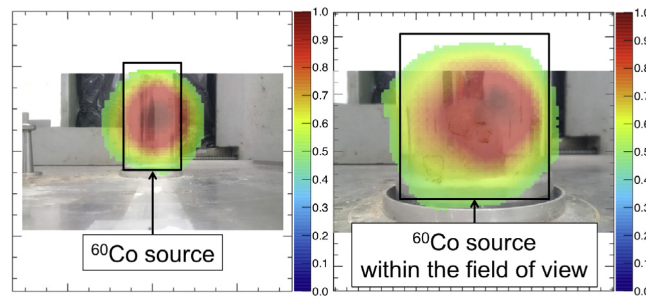


**Fig. 7.** Pinhole camera image obtained at Tokyo Tech. Left: dose rate of 114 Sv/h; right: dose rate of 680 Sv/h.

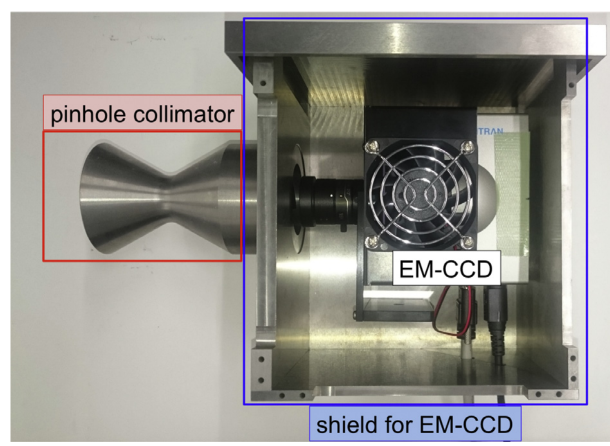


**Fig. 8.** Photograph of the improved pinhole camera.

In an additional test, we also placed the pinhole collimator closer to the $^{60}$Co source so that the corresponding dose rates were 114 and 680 Sv/h. Fig. 7 shows a pinhole camera image, overlaid on the optical image. From these results, the new pinhole camera is shown to be useful, even under an extremely high dose rate of over 11.6 Sv/h.

## 5. Future works

Although we successfully demonstrated the basic performance of the newly developed pinhole camera, several issues still remain to be addressed in future research.

First, the pinhole collimator and EM-CCD should be enclosed within the same shielding system to avoid unnecessary exposure to the EM-CCD. For this purpose, we are developing an improved pinhole camera (Fig. 8). The radiation exposure to the EM-CCD can be reduced by a factor of 40 by integrating the device including the EM-CCD and covering the surrounding area with heavy metal. Because the radiation resistance of the EM-CCD is approximately 100 Gy, the camera can operate for 40 h even under an extremely high dose rate environment (100 Sv/h). In addition, by removing the surplus portion of the pinhole collimator and changing it to a drum type, it is possible to reduce the weight by a factor of 4 while maintaining the angular resolution. The total weight of the improved pinhole camera is approximately 20 kg. It is expected to realize safe and efficient decontamination work of FDP by placing the improved pinhole camera on a research robot.

Second, the current pinhole camera provides only a black-and-white image, because the signal output from the EM-CCD is integrated over a certain period of time. We cannot discriminate whether the source of radiation is $^{137}$Cs or $^{60}$Co, or even other sources, only from the obtained image. We thus propose a novel gamma camera that may provide color images to identify radioactive sources. Specifically, we will adopt multi-layered scintillators consisting of a $Ga_3Al_2Gd_3O_{12}$ (GAGG) scintillator (first-layer), fluorescent glass (second-layer), and a plastic scintillator

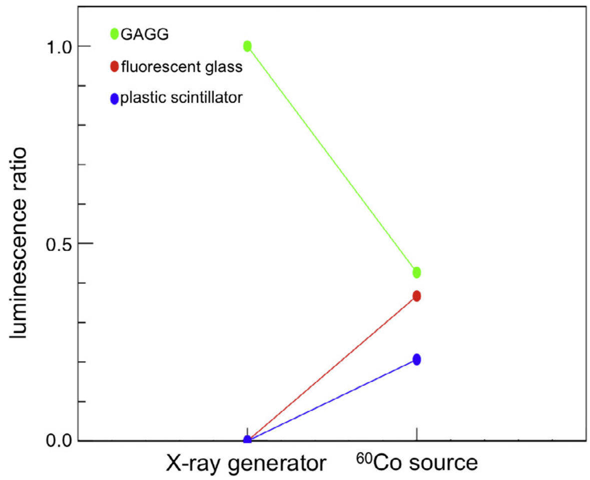


**Fig. 9.** Luminescence ratio in the case of an X-ray generator and a $^{60}$Co source.

(third-layer) rather than the GOS screen as described previously. Differing characteristics between these scintillators include wavelength spectrum, density, and effective atomic number. The peaks of the wavelength spectrum are 520 nm, 610 nm, and 430 nm, respectively. The densities are 6.63 g/cm$^3$, 3.77 g/cm$^3$, and 1.02 g/cm$^3$, respectively. RGB optical filters in front of the EM-CCD will select scintillation light from each layer. Lower-energy gamma rays would be absorbed only by the first-layer scintillator, which has a high density. On the other hand, higher-energy gamma rays would be absorbed by all scintillators. Therefore, by measuring the luminescence ratio of an RGB image, we can roughly obtain the spectral energy information of the radioactive source that is being measured. In a first trial, we compared the RGB ratios obtained using an X-ray generator (tube voltage of 150 kV, tube current of 3 mA) and a $^{60}$Co source. Fig. 9 shows the luminescence ratio in both cases, which confirms that the luminescence ratio varies depending on the energy of the radioactive sources.

## Acknowledgment

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