Measurement of Spatial Dose Distribution of High Radiation Field by Radiophotoluminescence Photography

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accepted Jun. 14, 2017

"This paper is a translation from the Japanese (Jpn. J. Radiat. Manag., Vol 15, 40–45, 2016)"

Radiophotoluminescence (RPL) photography has been proposed for the measurement of the spatial dose distribution of high radiation fields. A pulsed UV-LED illuminator was prepared as an excitation light source for the RPL photography. The fluorescence image of RPL material was observed by a gated intensified CCD camera. In a preliminary experiment, several tens of spherical RPL detectors were placed near an intense 60Co source. The pulsed UV-LED illuminator and the gated intensified camera were pulse-operated to obtain the RPL photograph of the ball-shaped RPL detectors. The spatial dose distribution was calculated from the brightness of obtained RPL images.

Key Words: radiophotoluminescence glass dosimeter, gated intensified CCD camera, spatial dose distribution of high radiation field

[doi:10.12950/rsm.170614]

1. Introduction

A fluorescent glass dosimeter is a high-sensitivity, integrated-type dosimeter. It has been used as an individual dosimeter in practical applications3). The detection elements used in fluorescent glass dosimeters are made of silver-activated phosphate glass, which produces orange fluorescence according to the absorbed dose under ultraviolet (UV) excitation. The center wavelength of this fluorescence is extremely stable and exhibits little fading at room temperature. Thus, the fluorescence intensity does not decrease, even under repeated UV excitation. For this reason, the fluorescent glass dosimeter can repeatedly read a radiation dose. This fluorescence characteristic is called radiophotoluminescence (RPL). Silver-activated phosphate glass exhibits superior fading characteristics and fluorescence efficiency when compared with other dosimeter materials2).

Therefore, in our research group, we have been developing a spatial dose distribution visualization technology5) based on the RPL characteristics of silver-activated phosphate glass.

Figure 1 shows a schematic of the RPL photography method. UV light generated by a UV illuminator irradiates spherical RPL detectors placed on the object being observed. The dose distribution is then characterized visually through fluorescence observation. This technology can potentially be used for the simple measurement of high-dose fields within the Fukushima Daiichi Nuclear Plant.

In this paper, we will first describe the RPL characteristics of the fluorescent glass dosimeter material. We will then describe the RPL photography conditions using a gated intensified charge coupled device (ICCD) camera. In our previously reported RPL photography method3), a direct current (DC)-operated UV
light-emitting diode (UV-LED) was used as the light source. Moreover, during measurements of the dose, the contribution of stains or predose, which is a glass-specific fluorescence, could not be removed. However, in this study, a pulse-operated UV-LED light source and a gate ICCD camera will be used, which enable high-sensitivity measurements with superior linearity.

2. Characteristics of the fluorescent glass dosimeter

The characteristics of the silver-activated phosphate glass used in fluorescent glass dosimeters have been reported previously. Here, we describe the features of the RPL photography method. Silver-activated phosphate glass produces orange fluorescence according to the absorbed radiation dose under UV excitation. Figure 2 shows the RPL-centric generated mechanism. Silver atoms in silver-activated phosphate glass have a glass structure and exist in a stable state as Ag⁺. If ionizing radiation irradiates the glass, electrons and holes are generated. The electrons are trapped by Ag⁺, which is converted into metastable Ag⁰. Furthermore, after the holes are trapped by the PO₄ tetrahedra, as time passes, positive charge is transferred to Ag⁺, which reaches the metastable state Ag⁺⁺. These Ag⁰ and Ag⁺⁺ states both exhibit fluorescence characteristics. The resulting RPL center does not lose the absorbed dose information after producing orange fluorescence under UV excitation. Thus, the information can be read repeatedly. Heat treatment (e.g., 400°C for 60 min) is required to destroy the RPL center.

The fluorescence spectra obtained when UV light was irradiated onto a 5-Gy-absorbed-dose fluorescent glass dosimeter and an annealed-fluorescent-glass dosimeter are shown in Fig. 3. The fluorescence spectrum uses a 365-nm LED (NCSU033A, Nichia Corp., Tokushima, Japan) as the UV excitation source and a multichannel spectroscope (QEPro, Ocean Optics Inc., FL, USA) to acquire the spectra. The RPL glass fluorescence spectrum includes wide-area elements based on absorbed-dose-dependent peaks at 635 nm and elements based on absorbed-dose-independent peaks around 420 nm. Furthermore, Fig. 3 includes the filtering characteristics of a commercially available color filter. During the RPL measurements, the installation of an appropriate colored filter in front of the optical output enables detection of a wavelength field fluorescence that is strongly dependent on the absorbed dose. This approach thus improves the signal-to-noise (S/N) ratio of the RPL measurement.
Figure 4 shows the RPL time response for 355-nm UV laser excitation detected using a photomultiplier tube (R9880U-20, Hamamatsu Photonics, Shizuoka, Japan) equipped with a color filter (R-60, HOYA Corp., Tokyo, Japan). While the fluorescence of the annealed-fluorescent-glass dosimeter significantly attenuates immediately after UV pulse excitation, the fluorescence of the fluorescent-glass-dosimeter irradiated with γ-rays has a lifetime of several microseconds after the excitation. Therefore, the integral values subtracted from the solid line to the dotted line in Fig. 4 are the true RPL elements that depend on the absorbed dose. The integration of the signal processing circuit that calculates this fluorescence lifetime into the reading device of the practical individual dosimeter has greatly improved the lower limit of dose measurement6, 7).

3. Radiophotoluminescence (RPL) photography device

The RPL properties of wavelength and lifetime described in the previous section were used to obtain highly precise dosage evaluations using RPL photography. Figure 5 illustrates the RPL photography device, which mainly comprises a UV-LED light source and a gated ICCD camera. The pulsed UV-LED light source has 990 UV-LEDs with a central wavelength of 365 nm (NS365L-5RLO, Nitride Semiconductors Corp., Tokushima, Japan). These are mounted on a homemade drive circuit, thereby enabling pulse drive via external pulse signals. The gated ICCD camera comprises a cooling CCD (ORCA-R2, Hamamatsu Photonics, Shizuoka, Japan) and an image intensifier (Hamamatsu Photonics V8070D) (hereafter I.I). The fluorescence from the RPL detector is observed using the ICCD camera. The camera lens (EF-18M-55 mm, Canon Inc., Tokyo, Japan) has a camera filter and an attached UV cutoff filter (Kenko-Tokina Corp., Tokyo, Japan). The images captured by the camera are formed on the photoelectric surface of the I.I. After the images on the photoelectric surface are amplified by the I.I, they are captured by the cooling CCD. Using the I.I, gated operation is possible, where the fluorescent surface image is only output when the gate is set to ON. The pulse UV-LED light source and I.I generate pulse signals with the timing shown in the top-right part of Fig. 5. The pulse signals are generated using an oscillator and a homemade delay generator and transmitted to the pulse UV-LED light source drive circuit and I.I gated drive circuit. The pulse signal repeat frequency is 10 kHz, and the I.I operates from the time the pulse UV-LED light source lights up until delay time d. The pulse UV-LED light source and I.I operating time was set to 1 μs.

4. Tests of RPL photography features

Figure 1 shows the RPL photographs for the case where 60Co γ-rays are irradiated at 100 Gy onto the ball-shaped RPL detector and for the case where they are not. The ball-shaped RPL detector contains silver-activated phosphate glass particles with an average diameter of 70 μm. These are embedded in a transparent polystyrene capsule with a diameter of 30 mm.
Polypropylene hollow balls fill the center of the sphere. Because the glass particles are obtained from the same crushed glass, we investigate whether the sensitivity differences based on individual differences in the ball-shaped RPL detectors are 8% or less.

Figure 6 shows the fluorescent images obtained from the ball-shaped RPL detector when the color filter and delay time \( d \) are changed. The ball-shaped RPL detector with an absorbed dose of 100 Gy is irradiated evenly with \(^{60}\text{Co} \) \( \gamma \)-rays, where 0 Gy represents nonirradiation. The color filters used are red (R-60, HOYA), green (G-533, HOYA), and blue (B-440, HOYA). The respective transmittance spectra are shown in Fig. 3. The distance between the ball-shaped RPL detector and the camera is approximately 70 cm. The pulse UV-LED light source and I.I are operated as explained in the previous section. The cooling CCD exposure time is 5 s. As shown in Fig. 3, the RPL has a center wavelength of 635 nm. Thus, the red filter is clearly effective. The images obtained under 100 Gy show the highest luminance. It has been confirmed that 100 Gy results in the longest fluorescence after UV pulse excitation. The images obtained during UV excitation \( (d = 0 \mu s) \) are the brightest. Even under nonirradiation conditions, it is possible to confirm that the RPL detector exhibits the same delay time and results in the collection of images that include fluorescence independent of the \( \gamma \)-rays. Therefore, optimization of the delay time \( d \) is necessary. The S/N ratio and average luminance values of the irradiated ball-shaped RPL detector image and those of the irradiated image are calculated. The results are presented in Fig. 7. The highest S/N ratio is obtained with a delay time \( d = 2 \mu s \), and these conditions are therefore adopted for RPL photography. Furthermore, when the I.I operating time is extended by 1 \( \mu s \), higher-luminance images can be obtained.
However, the S/N ratio may decrease slightly.

5. Dose distribution photography

5-1 Relationship between the captured image and absorbed dose

Figure 8 shows the ball-shaped RPL detectors with different absorbed doses and compares an image captured using a commercially available camera (EOS 70D, Canon Inc., Tokyo, Japan) under white light (Fig. 8(a)) with that captured using the RPL photography device (Fig. 8(b)). Figure 8(c) is the digital-image-processed version of the RPL-captured image luminance. As shown in Fig. 8(b) and (c), differences in the absorbed dose are confirmed by RPL capture. In fact, the ball-shaped RPL detector is irradiated evenly with γ-rays, and it exhibits high luminance in the central section of the detectors. The luminance is low around the periphery of the sphere. The object in this photograph has a curved surface, and maintaining uniform lighting conditions and fluorescent detection efficiency for all object surfaces is difficult.

Figure 9 shows the relationship between the image average luminance and the absorbed dose for ball-shaped RPL detectors with different absorbed doses. The method of calculation is the same as that shown in Fig. 7. We confirm the linearity in the absorbed dose range of 1–100 Gy.

5-2 Spatial Dose Distribution Measurement Tests

In a 60Co irradiation facility, we placed 59 ball-shaped RPL detectors around 60Co sources (6TBq) on a steel floor and investigated the spatial dose distribution. Furthermore, at a distance of approximately 20 cm from the area of the source, 5 cm × 10 cm × 20 cm lead blocks are placed, with their 10 cm × 20 cm surfaces facing down and stacked four-high to partially obstruct the detector. The distance between the source and the surrounding wall is approximately 72 cm at a recently contacted area. Figure 10 shows RPL photographs obtained
after γ-ray irradiation, where ball-shaped RPL detectors were aligned in the same position in the $\text{Co}^{60}$ facility. The position of the lead blocks and $\text{Co}^{60}$ γ-ray source are shown schematically in Fig. 10. The distance between the RPL photography device and the dosimeter was approximately 2 m, and the cooling CCD exposure time was 10 s. Figure 10(a) shows the image captured using a commercially available camera under white light. Figure 10(b) shows the position and shape of the ball-shaped RPL dosimeter, as automatically extracted by digital image processing using the image captured at $d = 0 \mu s^9$. Figure 10(c), which represents an RPL image captured at $d = 2 \mu s$, shows the average calculated luminance values of the dosimeter luminance locations described in Fig. 10(b) and displays these values along with the average luminance based on the pseudo colors obtained from digital processing. As shown in Fig. 10(c), the doses centered around the γ-ray source are distributed radially, and the areas obstructed by the lead are confirmed to exhibit the lowest dose. The difference in the average luminance of the dosimeters located at the same distance from the source is caused by the ununiformity of the UV rays from the pulse UV-LED source.

6. Summary

In this study, we proposed a method of RPL photography using a pulse UV-LED light source and a gated ICCD camera. Because the RPL photography conditions rely on the RPL features of silver-activated phosphate glass, we investigated these RPL features. The fluorescence spectrum due to the UV excitation of the silver-activated phosphate glass showed a broad area with a central wavelength of 635 nm and a fluorescence lifetime of several microseconds. When the pulse UV-LED light-source lighting time was set to 1 ms, the I.I was operated with a delay time of 2 ms. These parameters are known to be valid for RPL measurements. The dosage settings based on these conditions were obtained linearly within the range of 1–100 Gy. Furthermore, in the spatial dose distribution measurement tests, ball-shaped RPL detectors with a diameter of 30 mm were laid out and the spatial dose distribution in high-radiation fields was successfully visualized.

In the future, we plan to make technical improvements so that the developed RPL photography method will be useful in spatial dose distribution measurements within, for example, the Fukushima Daiichi Nuclear Plant. Further issues include making RPL photography devices more compact.
7. **Acknowledgments**

Part of this study was conducted by the Japan Science and Technology Agency, Research results development business (advanced measurement analysis technology/device development program), 2012–2014 “Practical development of a dose measurement method for high radiation fields”, (Team Leader: Takayoshi Yamamoto).

**References**


