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### **IV. 3. High Sensitivity Radiochromic Film Dosimetry Using an Optical Common-mode Rejection and a Reflective-mode Flatbed Color Scanner**

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#### **Introduction**

Radiochromic film (RCF) is a thin, plastic, 2D planar dosimeter offering ease of handling and broadly applied in dosimetry<sup>1-3)</sup>. However, its low sensitivity precludes their application to measuring lower doses accurately. Assuming macroscopic and microscopic non-uniformities of film layers, including the thickness variations in the film's active radiochromic layer and coating, were the main causes of light disturbance (noise) against the lights (signal), resulting in a lowering of actual film sensitivities, we developed an optical common-mode rejection (CMR) that can improve the dosimetric sensitivity limit of radiochromic films by using a spectrophotometer<sup>4)</sup>. The R component is highly sensitive to radiation exposure as two absorption peaks are located at wavelengths of 675 and 617 nm<sup>5)</sup>, while the G component is less sensitive than R component is, owing to the absence of a clear absorption peak in the green waveband. The two light components suffer a common fate, with the exception of wavelength-dependent events, having passed together along common attenuation paths. The ratio of the two components (R:G) is analogous to the 'common-mode rejection' in electronics, where the factors common to both numerator and denominator cancel out. This result indicated that the CMR can compensate the variation in the film's active radiochromic layer by using red and green components.

In this paper, the optical CMR scheme was applied to the R and G component outputs from a flatbed color scanner in reflection mode used to scan a Gafchromic XR type R dosimetry film after irradiation with X-rays. Two types of dose-response curves obtained by the optical CMR scheme using ratios of red/green and the conventional analysis method using red component were produced. With a linear fit in the range from 3.7 mGy to 0.81 Gy, the agreements in both curves between measured and fitted data were compared.

## Materials and methods

The radiochromic film model GafChromic XR type R, produced by ISP (International Specialty Products), was used. The active layer of 15  $\mu\text{m}$  thick is sandwiched between the two substrates of 97  $\mu\text{m}$  polyester, one of which is transparent and the other is opaque (white). XR type R film pieces (2 $\times$ 2 cm square) were exposed to X-ray beams of 100 kV with a 1.0-mm Al filter from an MBR-1520R unit (Hitachi Medico Co.) in the range from 3.7 mGy to 8.1 Gy. The amount of radiation was monitored with a thimble ionization chamber installed inside the unit. It is traceable to the Japanese national standard maintained by the Japan Quality Assurance Organization. The films were scanned before and twenty-four hours after exposure with an Epson ES-10000G flatbed color image scanner (SEIKO EPSON Corporation) with 1200 dpi resolution and 16 bits per color of the digital resolution dpi. The scans were performed in reflection mode using a white lid with no color correction factors or filters. A 2 $\times$ 2 cm square area with uniform response was identified by performing blank scans with the same condition described above and delimited in order to use only this area for digitalization.

For each film, scanning was repeated five consecutive times and acquired images were averaged. The obtained digital data were evaluated using self-written routines in MATLAB 7.3 software (The Mathworks). The digital data before exposure was subtracted pixel-by-pixel from the post-exposure image for each film. The serial images obtained by scanning each film before and after exposure were aligned using fiducial marks. After mathematical operations, the averages and standard deviations of the results were taken for 1 $\times$ 1 cm square (approximately 472 $\times$ 472 pixels) at the center of each film.

The reflectance is obtained as digitalized output of the R, G, B component, when films are scanned by a color scanner in reflection mode. The relationship between reflectance ( $R_f$ ) and optical density (OD) used in film dosimetry can be expressed as follows,

$$\begin{aligned} \text{OD} &= \log_{10}(2^{16}/R_f), \\ \text{net OD} &= \text{OD} - \text{OD}_0 = \log_{10} R_{f_0} - \log_{10} R_f = \log_{10} (R_{f_0}/R_f) \end{aligned} \quad (1)$$

where subscripts denote unirradiated background quantities and 'net' stands for the quantities after removing the background.

The conventional analysis way uses only red component, at which net OD -  $R_d$  is defined as,

$$\text{net OD}_{\text{Rd}} = \log_{10} (\text{Rd}_0/\text{Rd}) \quad (2)$$

In the optical CMR scheme, in which red and green components are used, Rf should be replaced by Rd/Gr, where Rd and Gr are each amount of reflectance lights. Thus, net reduced OD (net ROD<sub>Rd</sub>\_Gr) in the optical CMR scheme is written as,

$$\begin{aligned} \text{ROD}_{\text{Rd\_Gr}} &= \log_{10} (\text{Rd}/\text{Gr}), \\ \text{net ROD}_{\text{Rd\_Gr}} &= \log_{10} ((\text{Rd}_0/\text{Gr}_0)/(\text{Rd}/\text{Gr})) \end{aligned} \quad (3)$$

## Results and discussion

Figure 1 shows the absorption spectra, obtained using a GretagMacbeth SpectroEye reflection spectrometer, for GafChromic XR type R film unirradiated and exposed to 8.1 Gy of X-ray over the range of 380 - 730 nm in 10 nm steps and an example of filter functions for red, green, and blue wavebands on CCD. The results show the absorption spectra produce two pronounced peaks located around at 670 nm and 610 nm, which are lying in the red region of the light spectra and both responsible for the same R output from the color scanner. It also shows that the G output is less sensitive than the R output due to the absence of a clear absorption peak in the green waveband.

The two dose-response curves as a function of delivered dose ranging from 3.7 mGy to 8.1 Gy for 100 kV X-ray beams and from films scanned 24 hrs after exposure are plotted in Fig. 2. Closed triangles represent the net optical density obtained by using red component in Eq. (2) and open circles show the net reduced OD calculated by Rd and Gr components in Eq. (3), respectively. Error bars are shown in the figure as one standard deviation for data of approximately 472×472 pixels. Since these figures indicate that the type R film response is nonlinear, second-order polynomial fits were applied to each of the two curves exhibited. In order to evaluate the validity of the fit, the errors of fitting equations for two types of indices, OD<sub>Rd</sub> and ROD<sub>Rd</sub>\_Gr were analyzed by obtaining residuals defined by Eq. (4).

$$\text{OD}_{\text{residuals}} = \text{OD}_{\text{meas.}} - \text{OD}_{\text{calc.}} \quad (4)$$

where OD<sub>residuals</sub>, OD<sub>meas.</sub>, and OD<sub>calc.</sub> are the residuals, the experimental results (ODs), and the calculated ODs, respectively.

Figure 3 shows the quotients obtained by dividing each residual at measured dose by the standard deviation (error),  $\sigma$  of all residuals on each index. For an index of ROD<sub>Rd</sub>\_Gr, the quotients consistently increase up to 0.81 Gy. The similar tendency is observed in an index of OD<sub>Rd</sub>, though deviation among samples is apparently exhibited.

This consistent tendency indicates that second-order polynomial fits are not appropriate below 0.81 Gy. Then, linear fits were applied to the measured values of both indices in the dose-response ranging from 3.7 mGy to 0.81 Gy. Figure 4 shows the net optical densities of OD - Rd (closed triangles) and ROD\_Rd\_Gr (open circles), demonstrating each regression line and equation without y-intercept. Figures 5(a) and 5(b) show the expanded figures for two indices of OD\_Rd and ROD\_Rd\_Gr. respectively, in the low range less than 0.1 Gy in Fig. 4. Figure 5(a), representing the measured values obtained with a conventional analysis using the red component, exhibits a large discrepancy in measured optical densities among samples and does not show a consistency with a linear fit under 81 mGy. This is consistent to product specification; describing the dose of 0.1 Gy is the lowest detectable dose. However, in Fig. 5(b), the measured optical densities of the same samples obtained with the optical CMR scheme show a good consistency among each other and all values show an improved consistency with a linear fit within one standard deviation of each measured optical densities. These results indicate that the CMR scheme makes it possible to reproduce the measured optical densities and measure the dose in the lower range.

Comprehensive results of this study by using the XR type R films and a reflective-mode flatbed color scanner demonstrated that the optical CMR is a novel method to greatly improve the sensitivity limit by mitigating the effects of RCF film nonuniform response and lowering noises. It can be applied to any type of radiochromic films and RGB color scanners in transmission mode as well.

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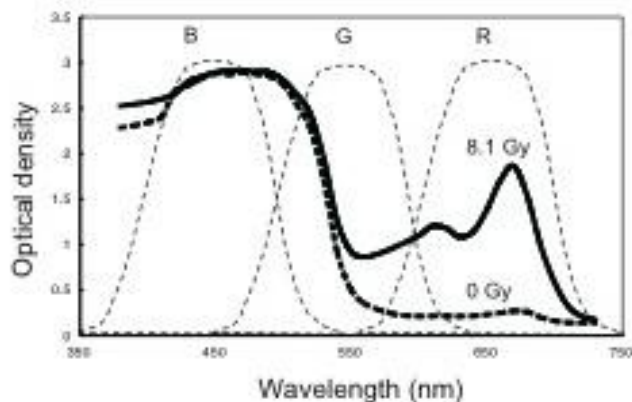


Figure 1. Absorption spectra for GafChromic XR type R film unirradiated and exposed to 8.1 Gy of X-ray over the range of 380 - 730 nm in 10 nm steps and an example of filter functions for red, green, and blue wavebands on CCD.

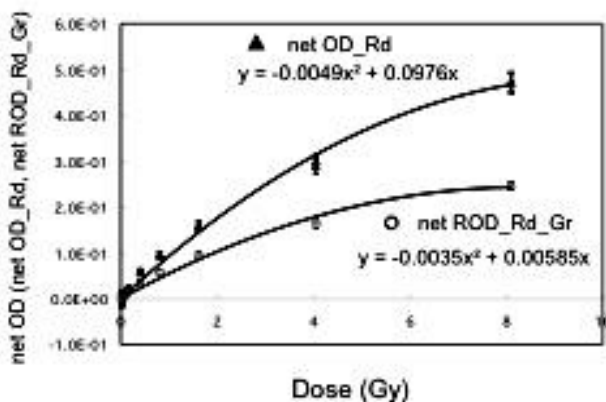


Figure 2. Dose-response curves as a function of delivered dose ranging from 3.7 mGy to 8.1 Gy for 100kV X-ray beam and from films scanned 24 hrs after exposure.

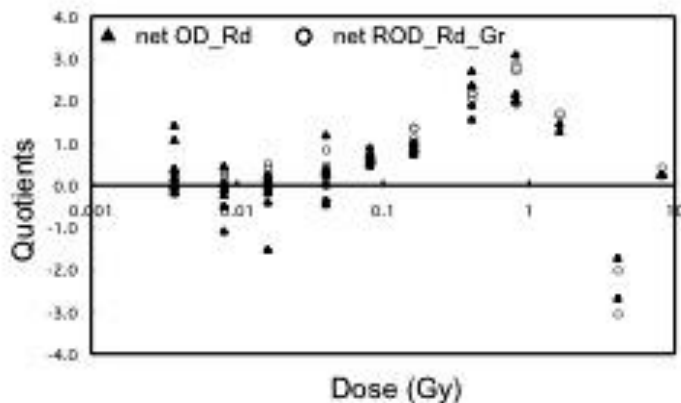


Figure 3. Quotients obtained by dividing each residual at measured dose by the standard deviation (error),  $\sigma$  of all residuals on each index. For both indices of OD\_Rd and ROD\_Rd\_Gr, the quotients consistently increase up to 0.81 Gy.

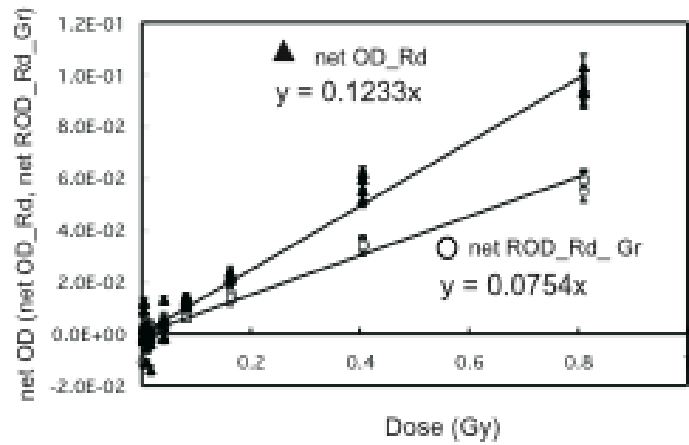


Figure 4. Net optical densities of OD\_Rd (closed triangles) and ROD\_Rd\_Gr (open circles) demonstrate each regression line of linear fits and equation without y-intercept.

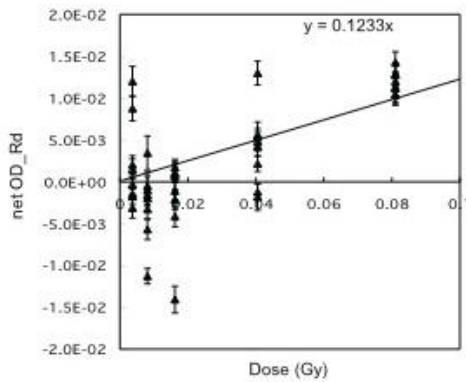


Fig. 5 (a)

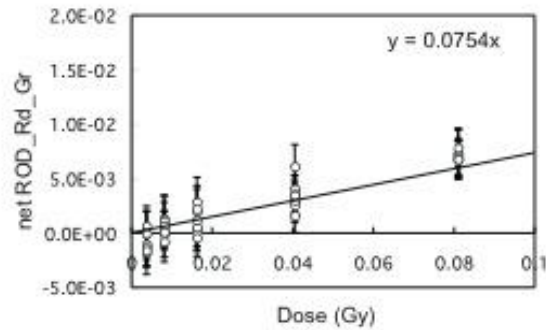


Fig. 5 (b)

Figure 5. Expanded figures in the low range less than 0.1 Gy in Fig. 4. Figure 5(a) represents the measured values for an index of OD\_Rd and exhibits a large discrepancy in measured optical densities among eight samples and does not show a consistency with a linear fit under 81 mGy. Figure 5(b), representing the measured optical densities of eight samples obtained with the optical CMR scheme, shows a good consistency each other and an improved consistency with a linear fit within one standard deviation of each measured optical densities.