Computed Tomography Dosimeter Utilizing a Radiochromic Film and an Optical Common-mode Rejection

Characterization and calibration of the GafChromatic XRCT film

Hiroko Ohuchi*, Mitsuya Abe*

*Graduate School of Pharmaceutical Sciences, Tohoku University, 6-3 Aoba, Aramaki, Aoba-ku, Sendai, 980-8578, Japan.

Sendai Kousei Hospital, 4-15 Hirose-machi, Aoba-ku, Sendai, 980-0873, Japan.

Abstract. Gafchromic XRCT radiochromic film is a self-developing high sensitivity radiochromic film product which can be used for assessment of delivered radiation doses which could match applications such as computed tomography (CT) dosimetry. The film automatically changes color upon irradiation changing from amber to dark greenish-black depending on the level of exposure. The absorption spectra of Gafchromic XRCT radiochromic film as measured with reflectance spectrophotometry have been investigated to analyse the dosimetry characteristics of the film. Results show two main absorption peaks produced from irradiation located at around 630 nm and 580 nm. We employed a commercially available, optical flatbed scanner for digitization of the film and image analysis software to determine the response of the XRCT films to ionizing radiation. The two dose-response curves as a function of delivered dose ranging from 1.069 to 119.7 mGy for tube voltages of 80, 100, and 120 kV X-ray beams and from films scanned 24 hrs after exposure are obtained. One represents the net optical density obtained with the conventional analysis way using only red component and another shows the net reduced OD with the optical CMR scheme, which we developed, using red and green components. The measured ODs obtained with the optical CMR scheme show a good consistency among four samples and all values show an improved consistency with a second-order polynomial fit less than 1 mGy, while those with the conventional analysis exhibited a large discrepancy among four samples and did not show a consistency with a second-order polynomial fit less than 1 mGy. This result combined with its energy independence from 80 kV to 120 kV X-ray energy range provides a unique enhancement in dosimetric measurement capabilities such as the acquisition of high-spatial resolution and calibrated radiation dose profiles over currently available dosimetry films for CT applications.

KEYWORDS: high sensitivity; optical common-mode rejection; color scanner; film dosimetry; radiochromic; computed tomography; radiation dose profile

1. Introduction

Recently there has been a growing concern over doses received by patients during diagnostic computed tomography (CT) examinations and various CT dose reduction schemes have been developed consistent with the established ALARA (as low as reasonably achievable) principle. The need for novel and precise measurements of calibrated dose distributions in diagnostic CT has been increased. For this purpose, the spatial resolution and ease-of-handling properties of radiochromic films (RCFs) make them ideal candidates.

Radiochromic film (RCF) is a thin, plastic, 2D planar dosimeter offering ease of handling and broadly applied in dosimetry for radiotherapy [1-3] and interventional radiology [4-6]. In radiochromic films an organic-based dye is used, which causes a change in their optical properties due to polymerization when exposed to ionizing radiation and the change of color intensity/optical density is a measure of energy deposited. An overview of the properties and investigations are given in a recent review article [7]. The main advantages of radiochromic-film dosimeters are the coupling of rapid full planar acquisition, high-spatial resolution and wide dynamic range of absorbed doses. However, RCFs have large disadvantages as radiation dosimeters, e.g. their low sensitivity to ionizing radiation and non-uniformity of response. These preclude their application to measure lower doses accurately in all types of radiochromic films. Various studies have reported that film sensitivity can be improved by layering multiple sheets of film

* Presenting author, E-mail: hiroko@mail.pharm.tohoku.ac.jp
together [8], using a red acetate filter [9], and wrapping the film with UV phosphor screens [10], however further improvements in sensitivity appear to have reach their limit.

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, HS-14 and MD-55-2, through use of a set of red R and green G color components, by using a spectrophotometer [11] and a Gafchromic XR type R dosimetry film by using a commercially available document scanner [12]. The two light component lights are neighboring wavebands about 100 nm apart and suffer a common fate, with the exception of wavelength-dependent events, having passed together along common attenuation paths. In the HS-14, MD-55-2, XR type R dosimetry film, the R component is highly sensitive to radiation exposure as two absorption peaks [7, 11, 12], 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 ratio of the two components (R:G) is analogous to the 'common-mode rejection' (CMR) in electronics, where the factors common to both numerator and denominator cancel out. These results indicated that the CMR can compensate the variation in the film's active radiochromic layer by using red and green components.

In this work we present a method of measuring reflective mode calibrated radiochromic film response with a flatbed optical scanner, combined with the conventional analysis way using red component and our new data analysis method of an optical CMR scheme. Then, we investigate the dosimetric characteristics of the film when irradiated with kilovoltage CT X-ray radiation and obtain the radiation dose profiles in an Aquilion 64 CT scanner.

2. Materials and methods

2.1 Radiochromic film and irradiation

The radiochromic film model GafChromatic XRCT was used in this study. Two 25-μm-thick active layers, which are separated by a double 5-μm-thick inert interlayer, are sandwiched between the two substrates of 97-μm polyester, one of which is transparent and the other is opaque (white). This film type is designed and manufactured by ISP (International Specialty Products) and is available in a strip of sheet. The strip has a metric scale. The scale runs from -50 mm to +50 mm. The color of film turns from amber to dark greenish-black depending on the level of exposure. To shield the films from the UV light, they were kept in black polyethylene envelope when not in use. The dosimetric characteristics of the XRCT film were determined by cutting sheets of film into small 2 x 2 cm squares and the radiation dose profiles were acquired by using the strip of XRCT film from an Aquilion 64 CT scanner fabricated by Toshiba Medical Systems Co. Due to their sensitivity to dust, scratches, the films were handled with great care, tagged by a layer of clear transparency to hold and support them. Standard precautions, which apply to radiochromic film handling, such as keeping film temperature controlled as outlined in TG-55 [13] were employed.

The XRCT film samples were exposed to CT X-ray radiation in the configuration illustrated in Fig.1. The amount of radiation was measured by using a Radcal 10 x 5-6 thimble chamber of 6 cm³ effective volume (Radcal Co.), which is also shown in Fig.1. It is traceable to the Japanese national standard maintained by the Japan Quality Assurance Organization (JQA) in Tokyo, Japan. The 9-cm-thick Styroform stand with 20 x 20 cm square front face was placed on the patient couch. The center of the top of the stand was marked, then, the couch was moved to bring and adjust the mark to the isocenter of the CT scanner. A 2 x 2 cm square XRCT film sample was placed right above the mark with the axis of the sample parallel to the axis of the CT scanner — i.e. the axis perpendicular to the X-ray beam. The scanner alignment laser was used to ensure proper positioning within the gantry. The tube voltages of 80, 100, and 120 kV were used to investigate the energy dependence. The dose-response of XRCT films in the range from 0.283 to 119.7 mGy was evaluated in each tube voltage of 80, 100, and 120 kV. For each exposure, four film samples were irradiated in the lower range less than 1 mGy, two for the delivered dose above 1 mGy. Each film was irradiated one by one. The angular dependence of
the film response was determined by irradiating the XRCT film samples with 24 mGy of X-rays with a tube voltage of 120 kV. A 2 x 2 cm XRCT film was placed on the stand and the CT X-ray tube was rotated in the range of -90° to 90° in 30° step. The angle, at which the axis of the film sample is perpendicular to the X-ray beam, was set at 0°. For each angle, two samples were irradiated. The radiation dose profiles were obtained by placing the strip of XRCT film in the scanner isocenter with their long axis along the z direction. The film sample was exposed at 120 kV, 300 mA, and 1.5 s exposure time with 1, 2, 4, and 8 mm beam.

2.2 Scanning procedure and image processing

The films were scanned before and twenty-four hours after exposure with an Epson ES-10000G flatbed color image scanner (SEIKO EPSON Corporation) with 300 dpi resolution (84.6 μm/pixel) 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. ES-10000G has Charge Coupled Device (CCD) line sensors and its light source is white xenon cold cathode fluorescent lamp. For color separation, R, G and B a CCD color filter was used. Image splitting produces three separate 65536 intensity levels of R, G or B images corresponding to each color CCD channel.

Figure 1: Setup for irradiating GafChromic XRCT film. The film sample was placed on top of the Styroform stand in the isocenter. The scanner alignment laser was used to ensure proper positioning within the gantry. The amount of radiation was measured by using a Radcal 10 x 5-6 thimble chamber, which is also shown here.

An area with uniform response was identified by performing blank scans with the same condition described above and delimitated in order to use only this area for digitalization. Blank scans (no film), meaning the zero-light transmitted intensity, were repeated five times with a white lid closed in transmission mode. The same number outputs such as 0, 2, and 4 appeared in the square for each color and each scan. No non-uniformity was observed in blank scans for each RGB output.

The obtained digital data were evaluated using self-written routines in MATLAB 7.3 software (The Mathworks, Natick, MA). 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 a metric scale drawn in the XRCT strip. After mathematical operations, the averages and standard deviations of the results were taken for about 1.7 x 1.7 cm square (approximately 200 x 200 pixels) at the center of each film in investigating the dosimetric characteristics of the film. To obtain spectra of the films, the reflectance of the unexposed and irradiated films over the range of 380 - 730 nm in 10 nm steps was obtained using a GretagMacbeth SpectroEye reflection spectrometer (GretagMacbeth, Regensdorf, Switzerland).
2.3 Optical density and mathematical operation using the optical CMR method

The reflectance is obtained as digitalized output of the R, G, B component, when films are scanned by a color scanner in reflection mode. Since the film's active layer is transparent, the reflectance can be processed in the same way as transmittance. In reflectance measurements, the light emitted from the bottom side of the scanner bed transmits the film twice because of the reflection by the lid, then, the length of the optical path becomes effectively double. The amount of the reflectance light, thus, could be twice larger in reflectance measurements than that of the transmittance scanned in transmission measurements, theoretically. The relationship between reflectance (Rf) and optical density (OD) used in film dosimetry can be expressed as follows,

\[
\begin{align*}
\text{OD} &= \log_{10}(2^{16}/\text{Rf}), \\
\text{net OD} &= \text{OD} - \text{OD}_0 = \log_{10} \text{Rf}_0 - \log_{10} \text{Rf} = \log_{10} (\text{Rf}_0/\text{Rf})
\end{align*}
\]

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_Rd is defined as,

\[
\text{net OD}_\text{Rd} = \log_{10} (\text{Rd}_0/\text{Rd})
\]

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_Rd_Gr) in the optical CMR scheme is written as,

\[
\begin{align*}
\text{ROD}_\text{Rd_Gr} &= \log_{10} (\text{Rd}/\text{Gr}), \\
\text{net ROD}_\text{Rd_Gr} &= \log_{10} ((\text{Rd}_0/\text{Gr}_0)/(\text{Rd}/\text{Gr}))
\end{align*}
\]

3. Results and Discussion

Fig. 2 shows the absorption spectra for GafChromic XRCT film unirradiated and exposed to 81.25 mGy produced by a 120 kV X-ray beam 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 630 nm as a main peak and 580 nm as a subpeak). This is consistent with the result obtained by Butson et al. [14], which showed two marked absorption peaks upon irradiation at 636 nm and 585 nm. The main peak is lying in the red region of the light spectra and it responsible for the 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 main absorption peak in the green waveband. The high optical density values observed at the blue waveband, which are not affected by two absorption peaks, are assumed to represent the optical property of polyester substrates in the film.

The two dose-response curves as a function of delivered dose ranging from 1.069 to 119.7 mGy for tube voltages of 80, 100, and 120 kV X-ray beams and from films scanned 24 hrs after exposure are plotted in Fig.3. Closed marks of triangles, squares, and circles represent the net optical density obtained by using red component in Eq. (2) for tube voltages of 80, 100, and 120 kV, respectively. Open marks of triangles, squares, and circles show the net reduced OD calculated by Rd and Gr components in Eq. (3) for each tube voltage as well. Error bars are shown in the figure as one standard deviation for data of approximately 200 x 200 pixels. As shown in Fig.3, there are no sensitivity variations in the range of 80 - 120 kV for both curves of the net optical densities of OD_Rd (closed marks) and the net reduced OD of ROD_Rd_Gr (open marks), indicating its energy independence from this X-ray energy range. Both figures also indicate that the XRCT film response is nonlinear. The net optical densities of OD_Rd demonstrates a continuous increase in all over the range, however, the curve for the net reduced OD seems to reach its maximum over 50 mGy.
Figure 2: Absorption spectra for GalChromic XRCT film unirradiated and exposed to 81.25 mGy produced by a 120 kV X-ray beam 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 3: Dose-response curves as a function of delivered dose ranging from 1.069 to 119.7 mGy for tube voltages of 80, 100, and 120 kV X-ray beams and from films scanned 24 hrs after exposure.

To compare the two dose-response curves as a function of delivered dose between the net optical density of OD_Rd and the net reduced OD of ROD_Rd_Gr under 50 mGy (at which the curve for the doesn't reach its maximum), second-order polynomial fits were applied to each of the two curves and equations without y-intercept were exhibited in Fig 4 (a). Fig 4 (b) shows the expanded figures for two indices of OD_Rd and ROD_Rd_Gr, respectively, in the low range less than 2 Gy in Fig 4 (a). In Fig 4 (b), the measured optical densities obtained with the optical CMR scheme show a good consistency among four samples and all values show an improved consistency with a second-order polynomial fit. These results indicate that the CMR scheme makes it possible to measure the dose in the lower range less than 1 mGy though the dose of 1 mGy is the lowest detectable dose for product specification. However, the curve for the net reduced OD obtained with the optical CMR scheme seems to reach its maximum over 50 mGy. Thus, to obtain maximum measured range from low and high dose, the conventional analysis way using red component and the optical CMR scheme using red and green components should be combined.
Fig. 5 shows an angular response of optical densities of XRCT films for X-rays with a tube voltage of 120 kV in the range of -90° to 90° in 30° step. The maximum variation among individual readings of XRCT films is 3.0% except -90° and 90°. The result revealed that the XRCT film has an almost isotropic efficiency except -90° and 90°. Relatively low responses of the XRCT film are observed at ±90°, because large numbers of incidences might not hit the surface of the thin XRCT film and/or X-rays might be attenuated by the XRCT film itself as they traverse the XRCT film.

**Figure 4:** Net optical density of OD_Rd and the net reduced OD of ROD_Rd_Gr demonstrate each second-order polynomial fit and equation without y-intercept in Fig.4 (a). Fig.4 (b) shows the expanded figures for two indices of OD_Rd and ROD_Rd_Gr. respectively, in the low range less than 2 Gy in Fig.4 (a).

![Graph 1](image1.png)

![Graph 2](image2.png)

**Figure 5:** Angular response of optical densities of XRCT films for X-rays with a tube voltage of 120 kV in the range of -90° to 90° in 30° step. The maximum variation among individual readings of XRCT films is 3.0% except -90° and 90°. The result revealed that the XRCT film has an almost isotropic efficiency except -90° and 90°.

![Graph 3](image3.png)

Fig.6 shows CT radiation profiles collected using the XRCT films with 1, 2, 4, and 8 mm beam and displayed in the net optical density of OD_Rd with an overlay displayed in OD with an overlay of the same profile converted to exposure dose using the experimentally determined relationship between net OD and exposure dose in Fig.4 (a). The both profiles of net OD (closed triangles) and exposure dose (solid lines) show the same shape with 1, 2, 4, and 8 mm beam so that FWHM measured using either OD or exposure results in the same measurement.
Figure 6: CT radiation profiles with 1, 2, 4, and 8 mm beam measured using the XRCT film. (120 kV, 300 mA, and 1.5 s): Net OD\_Rd profiles and their conversion to exposure dose using the relationship between net OD and exposure dose from Fig. 4 (a).

4. Conclusion

Comprehensive results of this study by using the XRCT films and a reflective-mode flatbed color scanner demonstrated that it shows energy independence from 80 kV to 120 kV X-ray energy range in an Aquilion 64 CT scanner. Two types of dose-response curves as a function of delivered dose ranging from 1.069 to 119.7 mGy for tube voltages of 80, 100, and 120 kV X-ray beams were obtained with the optical CMR scheme, in which red and green components were used, and the conventional analysis method using red component, respectively. The measured optical densities obtained with the optical CMR scheme show a good consistency among four samples and all values show an improved consistency with a second-order polynomial fit less than 1 mGy, while those with the conventional analysis exhibited a large discrepancy among four samples and did not show a consistency with a second-order polynomial fit less than 1 mGy. These results indicate that the CMR scheme makes it possible to measure the dose in the lower range less than 1mGy though the dose of 1m Gy is the lowest detectable dose for product specification. However, the curve for the net reduced OD obtained with the optical CMR scheme seems to reach its maximum over 50 mGy. Thus, to obtain maximum measured range from low and high dose, the conventional analysis way using only red component and the optical CMR scheme using red and green components should be combined. An angular response of optical densities of XRCT films for X-rays with a tube voltage of 120 kV in the range of -90° to 90° in 30° step was investigated. The result revealed that the XRCT film has an almost isotropic efficiency except -90° and 90°. Overall results demonstrate that the CT dosimeter utilizing this film combined with the optical CMR scheme provides a unique enhancement in dosimetric measurement capabilities of high-spatial resolution, calibrated radiation dose profiles from CT over currently available dosimetry films for CT applications. CT radiation profiles were obtained by using the XRCT films with 1, 2, 4, and 8 mm beam and displayed in the net optical density of OD\_Rd with an overlay displayed in OD with an overlay of the same profile converted to exposure dose using the experimentally determined relationship between net OD and exposure dose. The both profiles of net OD and exposure dose show the same shape with 1, 2, 4, and 8 mm beam so that FWHM measured using either OD or exposure results in the same measurement.

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