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Article

Measurements of Radiochromic Films (EBT3 and EBT-XD) Using Three Portable Colorimeters

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Featured Application: The recently proposed method for on-site radiation dosimetry by using portable colorimeter and radiochromic film can be applied to at least six combinations of two Gafchromic films (EBT3 and EBT-XD) and three portable colorimeters.

Abstract: The authors recently proposed a method for on-site dosimetry by a combination of radiochromic film and portable colorimeter. To test and expand the applicability of this method, dosimetric properties of radiochromic reactions were examined for six combinations of two popular Gafchromic films (EBT3 and EBT-XD) and three commercially-available portable colorimeters (nix pro2, nix spectro2 and Spectro1 Pro; abbreviated to "NixP", "NixS" and "SpoP", respectively). EBT3 and EBT-XD were irradiated with 160 kV X-rays at 0.3 to 40Gy and 1 to 80 Gy, respectively, and the radiation-induced color levels of RGB and CMMK components were measured with the three colorimeters. Angle dependence was examined by reading at 15° intervals. As results, it was judged that all combinations would work effectively as tools for on-site dosimetry. NixP and NixS showed advantages that they were applicable to a wider dose range for both films, while Spo1 worked better in a lower dose range. On the other hand, Spo1 had an advantageous feature of no angular dependence in reading films, while NixP and NixS showed significant angle-dependent changes. These differences were presumed to attribute to the different geometries of LED light emission; it came from all directions (ring-shape source) in Spo1, 4 directions in NixP, and 8 directions in NixS. These findings would expand the applicability of the proposed on-site dosimetry method to various occasions.

Keywords: radiochromic; gafchromic film; EBT3; EBT-XD; portable colorimeter; angle dependence; X-rays

1. Introduction

Radiographic film has a superior characteristic of undergoing a visible color change directly after exposure to radiation without chemical processing for the development of the image by a dye creation triggered by radiation exposure. The frst, commercially available product of radiochromic film appeared in the late 1980s for industrial use [1]. While this initial, polydiacetylene-based product called 'Gafchromic' (International Specialty Products, Wayne, NJ, USA) had a good dose-response feature, it had some issues related to sensitivity, uniformity and reproducibility in color development [2–4]. Continuous efforts to improve the dosimetric properties have solved those problems in subsequently developed models (HD-810, MD-55, HS and EBT series) [4–9] by achieving higher spatial resolution, nearer tissue equivalence, weaker energy dependence, and consistent dose responses to different quality radiations. The recent EBT model is relatively insensitive to visible light, which has offered ease of handling under normal indoor light conditions [8,9]. With these advantages and its reasonable cost, Gafchromic EBT films have been gaining the popularity for QA of external radiotherapy beams. Radiochromic films have been widely used for two-dimensional dose verification and quality assurance (QA) of radiation beams in external radiotherapy using photons, electrons and protons [5–7,10–34].

The advanced features of the recently developed radiochromic films have good potentials for application to many fields other than verification of delivering radiation doses in industry and research. As one of such potential applications, robust, light-insensitive radiochromic films are expected to be effectively used for individual monitoring of occupational radiation exposure of workers who routinely handle high-level radiation sources or who are in charge of the response to nuclear/radiological emergency. In these occasions, the ability of a sensitive radiochromic film to immediately detect an accidental high-dose exposure from the color change visible with the naked eye would be helpful for earlier recognition of the occurrence of a radiological accident and prevention of unnoticed excessive exposure, and then it would enable us to save the lives of highly exposed casualties by taking necessary medical actions without delays.

Though a real-time monitoring can be made with an electronic personal dosimeter, such electronic devices have count-loss problems at high dose-rate fields and can hardly work in the common situation of a high-dose radiological accident. While this count-loss prob-lem can be averted with passive dosimeters or some artificial/natural materials that can stably hold radiation-induced free radicals over a wide dose range [35–38], these techniques need large, non-portable equipment to read the thermally/optically stimulated luminescence or electron spin/paramagnetic resonance signals from the samples, which makes it difficult to per-form a prompt, on-site dose assessment. Some approaches using biological samples such as tooth enamel and peripheral blood lymphocyte need several days for processing the samples including the elaborate dose calibration [36,37].

With these thoughts, the authors proposed a novel method using a combination of a Gafchromic film and a portable dosimeter for on-site dosimetry [39]. This method could solve the issue of elaborate process for image acquisition using a flatbed scanner and subsequent analyses using an image processing software [5,9,27], which was promising for wide application to various occasions where on-site dosimetry would be needed. In the present study, the authors try to expand the applicability of this method by testing its effectiveness with other combinations of radiochromic films and portable colorimeters that are commercially available at present.

2. Materials and Methods

2.1. Materials for Dosimetry

As radiochromic materials, two Gafchromic films, EBT3 and EBT-XD (ISP, Wayne, NJ, USA) were employed in the present study. While both films are currently popular as recent products of the EBT series which appeared in 2004. The newest EBT-XD film has some better features than EBT3 in view of delivering beam dosimetry in radiation therapy [9,27]. The physical structures of both products are nearly the same; both films have thin active layer (28 μm in EBT3 and 25 μm in EBT-XD) sandwiched with 125 μm-thick polyester substrates [40,41]; the active layer is made of the crystals of lithium-10,12-pentacosdiynoate (LiPCDA) compound with 1 to 2 μm in diameter, marker dye, and other stabilizers and additives [9,27]. A notable difference is the applicable dose range; the optimal dose range of EBT3 is 0.1 to 10 Gy and dynamic dose range is 0.1 to 20 Gy, while EBT-XD is 0.4 to 40 Gy and 0.1 to 60 Gy, respec-tively. The LiPCDA crystals of EBT-XD are shorter in length (2 to 4 μm) than that of EBT3 (15 to 25 μm) [9,27]; the small-size active compounds are considered to work well for reducing light scattering and polarization, leading to fewer lateral response artifacts, the so-called 'orientation effect' which is characterized by a change in the measured color intensity of a scanned film depending on its orientation on the scanner [7,27,42,43].

The color intensities of Gafchromic films were measured by using portable colorimeters with an intention of achieving a simple, on-site dosimetry that should be beneficial for the prompt response to a possible radiological accident. Three commercially available portable colorimeters were employed: "nix pro 2" (Nix Sensor Ltd., Ontario, Canada; ab-breviated to "NixP" hereafter), "nix spectro 2" (Nix Sensor Ltd.; abbreviated to "NixS"), and "Spectro1 Pro", Variable, Inc., Tennessee, USA; abbreviated to "SpoP"). These products contain rechargeable lithi-um-ion batteries and can perform more than 100 scans per single charge.

A phograph of these three colorimeters is shown in Figure 1. As seen, NixP and NixS have hexagon shape and SpoP is cylindrical. They measure the color intensities of any flat material while cutting the ambient light, and the data of color intensity measured as RGB and CMYK components in a few seconds and are trans-ferred via Bluetooth to a smartphone installed with the exclusive application, and imme-diately displayed on its screen. These data can be saved into the smartphone and exported for further analyses.

Figure 1. The sensors of three portable colorimeters employed in the present study. From the left, nix pro 2 (Nix Sensor Ltd.; abbreviated to "NixP"), nix spectro 2 (Nix Sensor Ltd.; "NixS"), and Spectro 1 Pro (Variable Inc.; "SpoP"). The upper photograph (a) was taken from the above and the lower one (b) taken from the bottom.

It should be noted that, since the aperture size of any portable colorimeter for detect-ing the reflected light from a sample surface is more than 5 mm in diameter (Figure 1b), the conventional method using a flatbed scanner [5,9,20,28,44] is needed for precise two-dimensional dosimetry.

The high performance of these portable colorimeters in reading color intensities has been well validated in previous studies for the determination of soil compositions [45–47] and evaluation of beef freshness [48–50]. Their practical features such as the small size, light weight, easiness to handle and relatively low price are preferable for application to on-site dosimetry. Particularly, the good portability fits the aim of the present study, as anyone can easily carry this device in their pocket to prepare for a possible, unexpected opportunity of radiological emergency.

2.2. Irradiation and Film Analyses

Both Gafchromic films (EBT3 and EBT-XD) were irradiated with 160 kV X-rays generated in a commercial X-ray irradiator ("CP-160", Faxitron, Wheeling, IL, USA). Each film was exposed to a different range of dose with consideration of the dynamic dose range; EBT3 was irradiated at 0.3, 0.6, 0.9, 1.2, 1.6, 2, 3, 4, 5, 6, 8, 13, 20, 30, 40 Gy and EBT-XD at 1, 2, 4, 7, 10, 15, 20, 25, 30, 40, 60, 80 Gy. The dose rate of the static X-ray beam was adjusted by changing the distance between the source and the film so that the irradiation time would be longer than 2 min in every case. The field diameter was more than 5 cm even at the shortest distance.

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At a sufficient post-irradiation time (few hours or more) when the radiation-induced color was stabilized, the color intensities of an irradiated film was placed on a Kent paper (thick white paper commonly used for drawing) and measured with the portable colorimeters (NixP, NixS and SpoP). The data of color intensities as RGB (red, green and blue) and CMYK (cyan, magenta, yellow and black) components were acquired by using an exclusive application on the smartphone as RGB color components: RGB, red, green and blue. In reading the films, was placed under the EBT-XD film (Figure 2a).

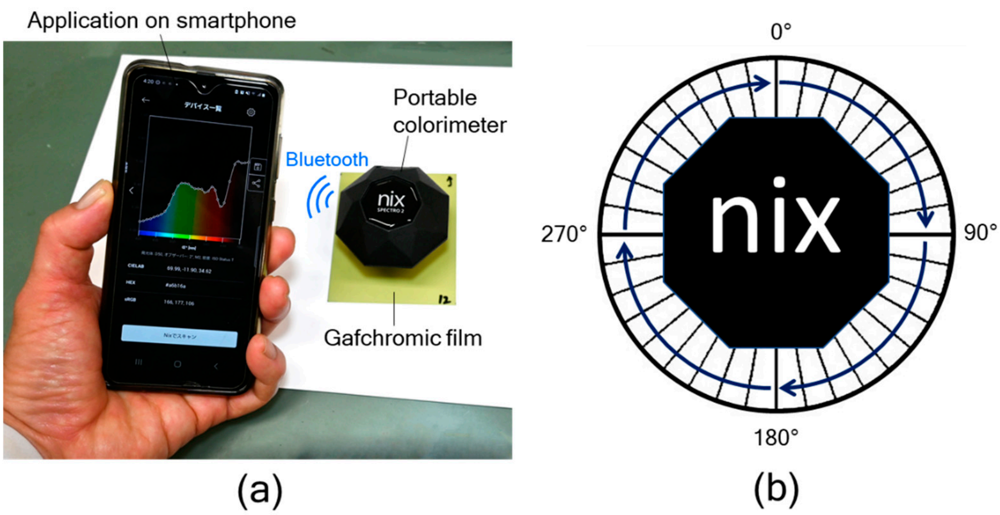

Figure 2. A scene of measurement with a portable colorimeter (a) and the definition of angles (b); angle dependence was examined with each sensor being rotated at 15° intervals.

There are artifacts associated with the color digitization of Gafchromic films scanned with flatbed scanners, which are known as 'orientation effect' and 'lateral response artifact', which is characterized by a change in response as a function of the orientation of the film on the scanner bed [7,9,27,42,43,51–53]. Thus, the dependence of color intensity measurements on the angle in measurement was also examined by being rotated at 15° intervals in a clockwise direction (Figure 2b). Statistical analyses of the measured data and productions of plot graphs including regression curves were made using commercial data analysis software (IGOR Pro, WaveMetrics, Inc., Portland, OR, USA).

3. Results and Discussions

3.1. Dose responses of radiochromic reactions

In the field of radiotherapy, the color intensity of a Gafchromic film has been generally evaluated with the next optical density change (*netOD*) which is calculated as a logarithm of the ratio of a pixel's color-channel value of the film before irradiation and that after irradiation [9,28,54]. However, it was judged by the authors that this approach using *netOD* (i.e., calculation with logarithmic functions) was too complex to use for the urgent task of on-site dosimetry in an emergency situation. Therefore, the radiation-induced change in color intensity (ΔI) was simply calculated here from the readings obtained with a portable colorimeter as follows.

For RGB component:

$$\Delta I = I(0) - I(D) \quad (1)$$

For CMYK component:

$$\Delta I = I(D) - I(0) \quad (2)$$

where $I(D)$ is the measured intensity of the respective color channel at dose D; $I(0)$ means the color intensity measured before irradiation. Because the film coloration (darkening) caused by radiochromic reaction generally decreases the color intensities of the former and generally increases those of the latter, ΔI was calculated in the opposite way for the RGB and CMYK components, so that major color components would generally present positive values.

Figures 3 and 4 show the dose responses of color intensities of EBT3 and EBT-XD, respectively. The blue component was less sensitive in every case and became negative at lower dose range. The yellow component showed peculiar radiochromic reactions which was nearly opposite with those of other components (cyan, magenta and black). Accordingly, these two components were judged to be unsuitable for use in dosimetry. The red and green components presented advantages of higher sensitivity compared to the RGB component which is a mixture of three components (red, blue and green).

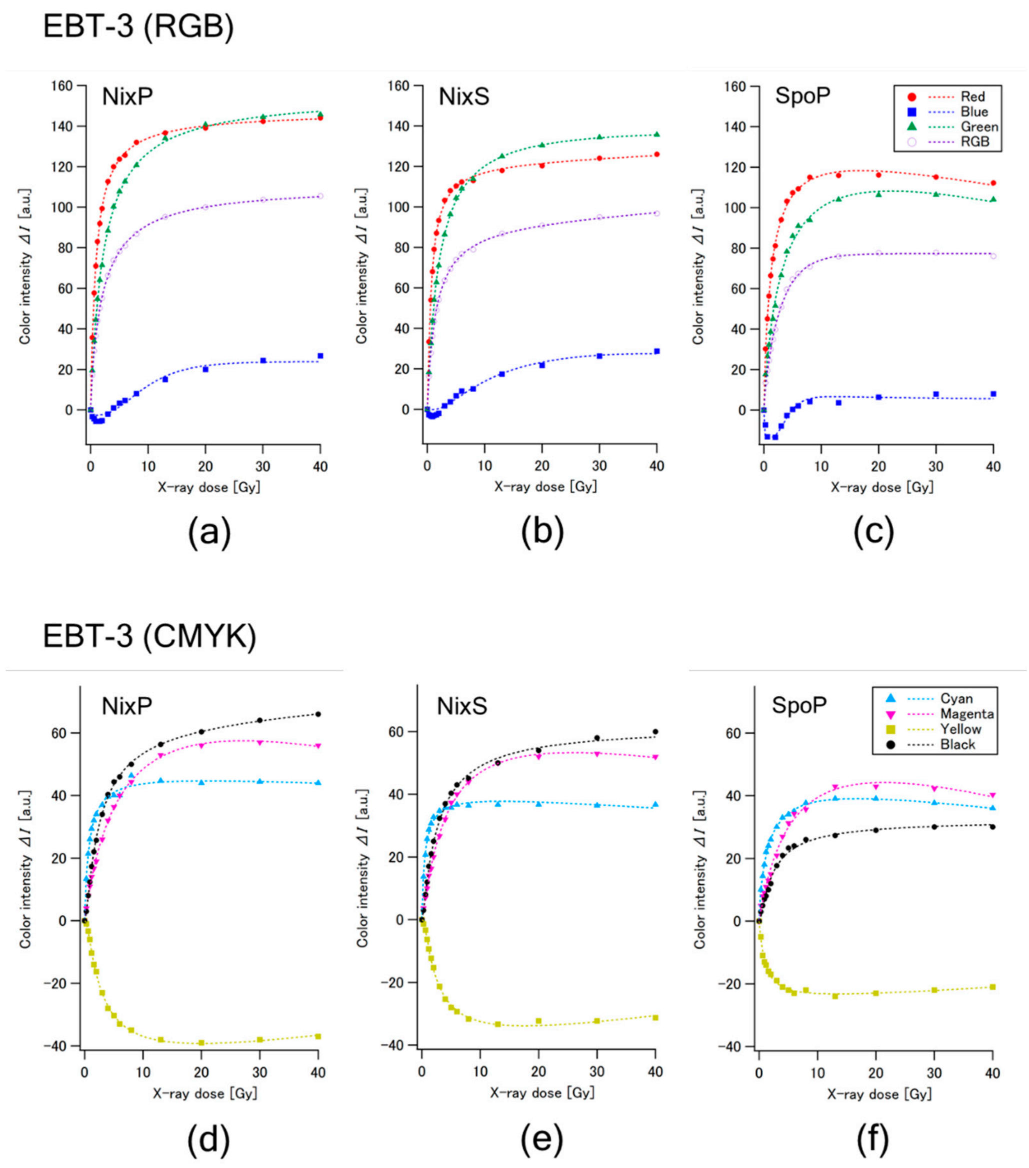

Figure 3. Dose responses of the color intensities of Gafchromic EBT3 film irradiated with 160 kV X-rays at up to 40 Gy in regard to the RGB components (above) and CMYK color components (below) measured with three portable colorimeters: NixP (a,d), NixS (b,e) and SpoP (c,f) at the angle of 0°.

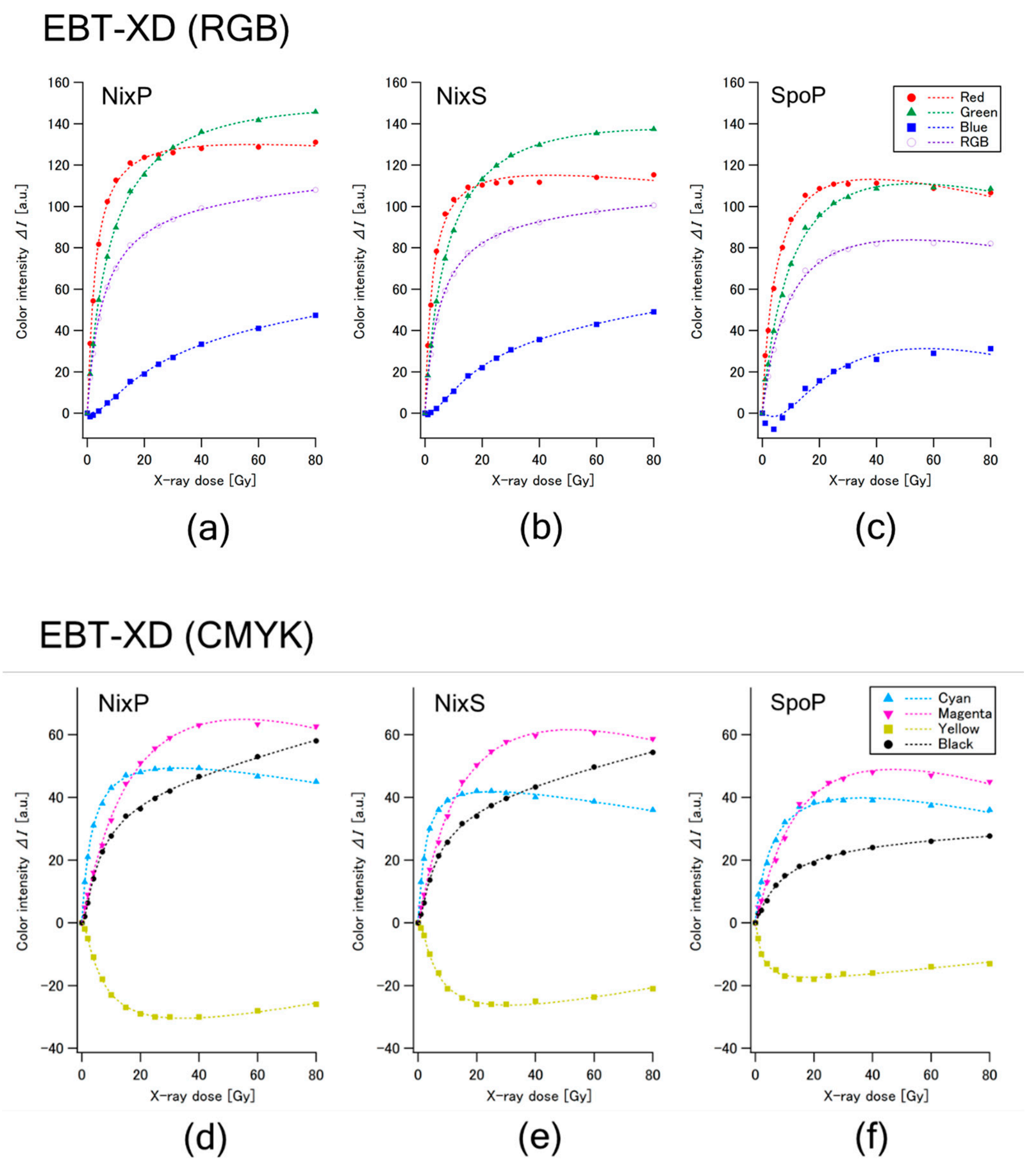

Figure 4. Dose responses of the color intensities of Gafchromic EBT-XD film irradiated with 160 kV X-rays at up to 80 Gy in regard to the RGB components (above) and CMYK color components (below) measured with three portable colorimeters: NixP (a,d), NixS (b,e) and SpoP (c,f) at the angle of 0°.

As to EBT3, the red and green components showed comparable, simply increased dose responses in NixP and NixS. The red component increased more steeply than the green component, while the green component continued increasing at higher dose range. On the other hand, both components of SpoP decreased at higher dose ranges (>10 Gy for the red component and >20 Gy for the green component). The cyan component reached almost constant values at several to 10 Gy and the magenta component decreased gradually at higher dose ranges (>10 to 30 Gy). The black component simply increased with dose in all colorimeters; its sensitivity was the highest among those of the CMYK components in NixP and NixS, while it was lower than those of the cyan and magenta components in SpoP.

The dose responses of EBT-XD were similar with those of EBT3, while some different characteristics were observed. It should be noted that, unlike EBT3, the color intensities of the black component were lower always than those of the magenta component over the investigated dose range (up to 80 Gy) in any colorimeters, while it simply increased with increasing dose.

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For the discussion of applicability to on-site dosimetry, the relationship between the color intensity (ΔI) of each Gafchromic film as explanatory variable and the absorbed doses of 160 kV X-rays as objective variable was investigated within their optimal dose ranges. The experimental data were approximated in empirical ways with a regression curve of the sum of a linear term and an exponential term as follows:

$$\Delta I = a \times \Delta I + b \times e^{c \times \Delta I} \quad (2)$$

where a, b and c are the fitting parameters that are determined through regression analyses. As seen in Figure 5, the regression curves of Eq.3 well fitted the experimental data in all cases. It was confirmed that the curves of NixP and NixS were identical while the curve of SpoP was much steeper. These results indicate that SpoP is suitable for a narrower, lower dose range, compared to NixP and NixS. Values of three fitting parameters (a, b and c in Eq.3) obtained for the color-dose relationship of each combination of radiochromic film (EBT3 or EBT-XD) and portable colorimeter (NixP, NixS, or SpoP) are summarized in Table 1. It was confirmed that the parameter values of SpoP were notably different from those of other two colorimeters (NixP or NixS), as expected from the curve shapes shown in Figure 5.

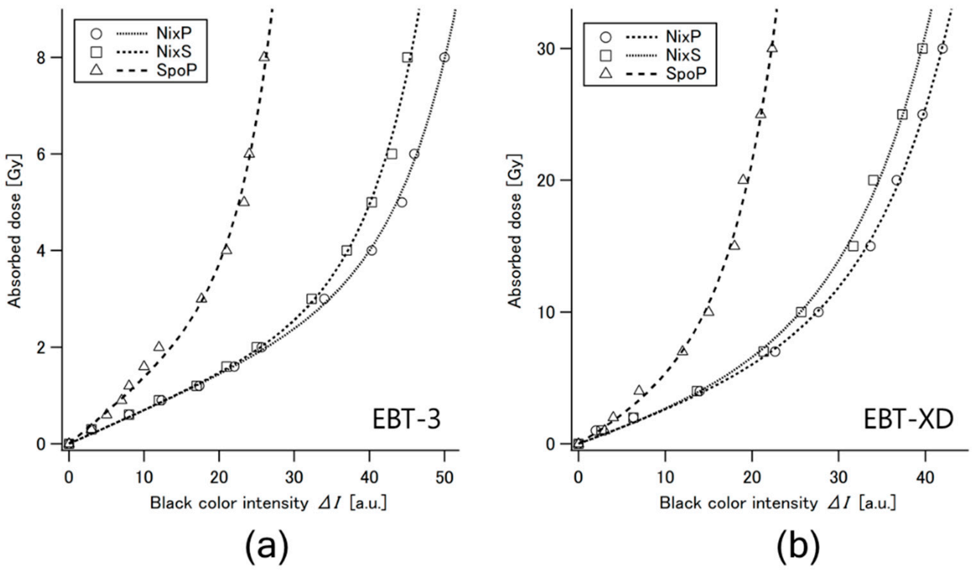

Figure 5. Comparison of the relationships between the color intensities of the black (K) component measured with three colorimeters for EBT3 (a) and EBT-XD (b) irradiated with 160 kV X-rays in the ranges of up to 8 Gy and 30 Gy, respectively.

Table 1. Fitting parameter values in the regression curve (Eq.3:D=a×ΔI+b× exp(c×ΔI)) obtained for the color-dose relationships of six combinations: two radiochromic films (EBT3 and EBT-XD) and three portable colorimeter (NixP, NixS and SpoP).

Radiochromic film	Portable colorimeter	Parameter value		
		a	*b*	*c*
EBT3	NixP	0.0673	0.00859	0.126
	NixS	0.0676	0.00728	0.143
	SpoP	0.125	0.0179	0.213
EBT-XD	NixP	0.224	0.173	0.114
	NixS	0.200	0.365	0.104
	SpoP	0.333	0.377	0.185

3.2. Angle Dependence and Dose Response

Figure 6 shows the color intensities of the black (K) component measured with three colorimeters being rotated at 15° intervals after irradiation with 160 kV X-rays at four dose levels each: 2, 4, 8 and 20 Gy for EBT3 and 4, 10, 40 and 80 Gy for EBT-XD. The color intensity (ΔI) were calculated with Eq.2 as a difference of $I(D)$ measured at each angle and $I(0)$ at the angle 0°.

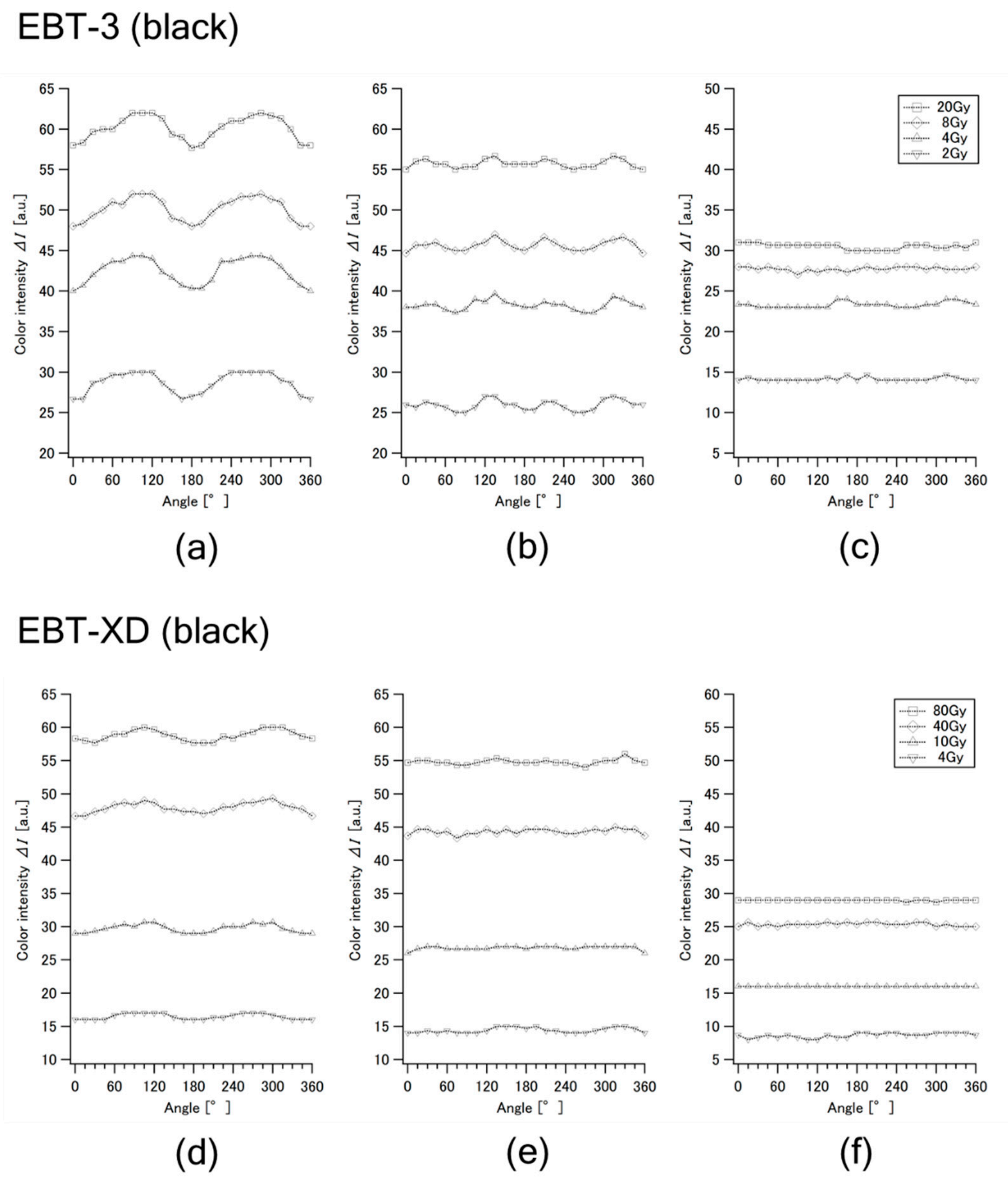

Figure 6. Angle dependences of the black (K) component color intensities of Gafchromic EBT3 (above) and EBT-XD (below) measured at 15°intervals with three colorimeters: NixP (a,d), NixS (b,e) and SpoP (c,f) after irradiation with 160 kV X-rays at 0 (control), 2, 4, 8 and 20 Gy.

As seen in the figure, three colorimeters showed considerably different patterns of angle dependence. NixP showed the largest angle dependence, and it became smaller in NixS, the same company's product. Their color intensities showed systematic, wave-like angle-dependent changes with certain cycles: 180° for NixP and 90° for NixS; the results of NixP showed good reproducibility was seen in comparison of the previous study [39]. The absolute variation ranges were nearly the same regardless of dose levels; consequently, the relative errors became higher at lower doses according to the reduced color intensities. On the other hand, no angle dependence was seen in SpoP.

The angle dependences of the color readings of Gafchromic films, known as 'orientation effects' or 'lateral response artifacts', were reported in previous studies using flatbed scanners for film

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readings [7,9,27,42,43,51–53]. As these effects are caused by the anisotropic light scattering on the surface of a Gafchromic film, the authors assumed that the observed differences of angle dependence among three colorimeters shown in Figure 6 were attributable to the different patterns of LED light emission for reading films. To confirm this assumption, photographs of the bottom side of each colorimeter were taken in continuous shooting mode during the process of color reading. Selected scenes are shown in Figure 7. As expected, NixP had the smallest number (four) of LET light sources and NixS had doubled (eight) ones. It was found that SpoP provided seamless light emission from a ring-shape (360°) source. Such geometric differences of LET light sources were considered to have attributed to the observed difference in angle dependences (Figure 6).

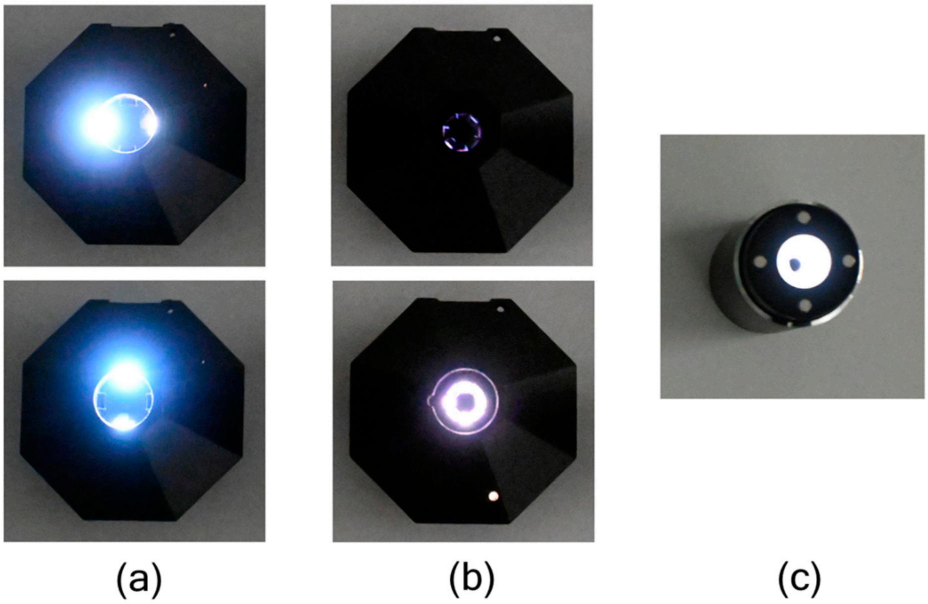

Figure 7. Photographs of the LED light emissions from three portable colorimeters: (a) NixP, (b) NixS and (c) SpoP.

4. Conclusions

In the present study, the applicability of a recently proposed method for on-site dosimetry by a combination of radiochromic film and portable colorimeter was examined for six combinations of two Gafchromic films (EBT3 and EBT-XD) and three commercially-available portable colorimeters (nix pro2: NixP, nix spectro2: NixS and spectro1 pro: SpoP). Though different patterns of dose response and angle dependence were observed, any combination was expected to work for the aim of on-site dosimetry in radiological emergency situations. When it is needed to cover a wider dose range, NixP and NixS would be more suitable than SpoP of which the applicable dose range is narrower. On the other hand, Spo1 has an advantageous feature of no angle dependence in film reading, which can simplify the dosimetry process.

The findings presented in this study indicate that we could conduct a simpler, practical radiation dosimetry on site by carrying a radiochromic material and portable colorimeter. It is expected that its feature of simple and rapid dose quantification would be preferably used for QAs of radiation sources used in medicine, industry and research. The authors will continue to explore this potential by investigating the applicability of other radiochromic materials and other color-reading devices to establish the most suitable system for on-site dosimetry through clarification of the effectiveness and limitation of each method.

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