Analysis of Post-exposure Density Growth in Radiochromic Film with Respect to the Radiation Dose

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Film dosimetry/Radiochromic film/GafChromic EBT film/Post-irradiation coloration effect/Post-exposure density growth.

The post-exposure density growth (PEDG) is one of the characteristics of radiochromic film (RCF). In film dosimetry using RCF and a flatbed scanner, pixel values read out from the RCF are converted to dose (hereafter, film dose) by using a calibration curve. The aim of this study is to analyze the relationship between the pixel value read out from the RCF and the PEDG, and that between the film dose converted from the RCF and the PEDG. The film (GAFCHROMIC EBT) was irradiated with 10-MV X-rays in an ascending 11-dose-step arrangement. The pixel values of the irradiated EBT film were measured at arbitrary hours using an Epson flatbed scanner. In this study, the reference time was 24 h after irradiation, and all dose conversions from the pixel values read out from the EBT film were made using a calibration curve for 24 h after irradiation. For delivered doses of 33 and 348 cGy, the measured pixel values at 0.1 and 16 h after irradiation represented ranges of –9.6% to –0.7% and –3.9% to –0.3%, respectively, of the reference value. The relative changes between the pixel values read out from the EBT film at each elapsed time and that at the reference time decreased with increasing delivered dose. However, the difference range for all the film doses had a width of approximately –10% of the reference value at elapsed times from 0.1 to 16 h, and it showed no dependence on the delivered dose.

INTRODUCTION

To evaluate a planned dose in radiotherapy, radiotherapy facilities verify the absolute dose by methods such as ionization chamber measurement and dose distribution techniques, e.g., film measurement. A radiographic film (consisting mainly of silver bromide) and a radiochromic film (RCF, consisting mainly of diacetylene monomer) are employed for film measurement. Compared to a radiographic film, an RCF has a relatively small dependence on radiation energy.11 When an RCF is irradiated, polymerization of the diacetylene monomer begins within 1 μs,21 and the convergence of the change requires 24 h. Post-exposure density growth (PEDG) is one of the characteristics of the RCF.3–7) In an analysis of the PEDG on an RCF, Martina Fuss et al.31 reported that for a delivered dose of 100 cGy, the film’s optical density measured at 2 h and 4 h after irradiation was –3% and –2%, respectively, of that measured 24 h after irradiation. In the same way, Cheung et al.69 showed that for a delivered dose of 200 cGy, the optical density measured 6 h after irradiation was ~1% of that measured at 24 h after irradiation. This suggests that the PEDG depends on the irradiated dose, they did not present specific evidence for this dependence.

In film dosimetry using an RCF in combination with a flatbed scanner, the pixel value of the RCF is generally converted to the dose (hereafter, the film dose) on the basis of the exponential change between the pixel value and the known delivered dose (hereafter, the calibration curve). In areas of a low delivered dose, the pixel value (or optical density) exhibits a gradual increase. Compared to the values in the appropriate dose range, the pixel values increase almost linearly. In areas of a high delivered dose, the pixel values exhibit a sharp increase. Therefore, in these situations, the
PEDG may have a different influence on the pixel value read out from the RCF and the film dose converted from the pixel value of the RCF.

The aim of this study is to analyze the relationship between the pixel value read out from the RCF and the PEDG, and that between the film dose converted from the RCF and the PEDG.

**MATERIALS AND METHODS**

A Varian linear accelerator, Clinac2100C (Varian Medical Systems, Palo Alto, CA, USA) provided two photon beams with nominal acceleration potentials of 4 MV and 10 MV. All measurements were carried out with 10-MV photons. In this study, the 10-MV X-ray was chosen because the RCF has little dependence on radiation energy.\(^5,8\) Because an asymmetric field was used, the Y2 jaw was reduced step-by-step (11 steps in all). The dose was delivered to the RCF in 11 steps in an ascending order; each step was 2 cm \(\times\) 10 cm in size. Under these conditions, the RCF could accommodate 11 dose areas (2 cm \(\times\) 10 cm each). The monitor unit (MU) value for each field is shown in Table 1, and the irradiated film is shown in Fig. 1. In this study, as the delivery doses for the analysis of PEDG on the EBT film, we chose almost the same 11 dose levels as those in Bouchard H. \(et\ al.\)\(^9\)

A dose was assessed at the central point of each dose area. A GAFCHROMIC\(^6\) EBT film (International Specialty Products, NJ, USA, Lot # 47277-03I) was employed in this study as the RCF (hereafter, EBT film). For dose delivery, the EBT film was placed in a solid water phantom (Gammex RMI, Tennessee, USA, 40 cm \(\times\) 40 cm \(\times\) 30 cm), at a position 10 cm from the top surface of the phantom, with the plane of the film perpendicular to the central axis of the beam. The source–film distance was 100 cm. In this study, in order to determine the relative sensitivity of the radiation dose, ion-chamber measurements (W30001, PTW-Freiburg, Freiburg, Germany, and Ramtec 1000 Plus, Toyo Medic, Tokyo, Japan) were conducted at the central point of each dose area by the same geometric arrangement as that for the EBT film exposure.

**Data acquisition for analysis of the PEDG**

The irradiated EBT film was scanned with an Epson flatbed scanner (ES-10000G, Seiko Epson Corporation, Nagano, Japan) in a 48-bit color mode (using the red channel) at a resolution of 150 dpi without the application of any image processing features (contrast enhancement, color correction, etc.).\(^5\) These images then were converted with a 3 \(\times\) 3 median filter to reduce the noise. When the film density was zero, the pixel value from the flatbed scanner was defined as zero. For this reason, the pixel value was ascending with an increasing film density. The pixel value for the PEDG analysis was read out from the EBT film at 11 dose assessment points. The assessment points were almost the same size as the ion chamber. The EBT film was scanned every hour from approximately immediately after irradiation to 8 h after irradiation and at 22, 24, and 48 h after irradiation. Therefore, the film was scanned 12 times. For measurements using the flatbed scanner, a time lag of approximately 6 min from the irradiation time was required to bring the films to the scanner. Thus, the hour immediately after irradiation determined that the film was obtained at 0.1 h (6 min) after irradiation, as mentioned in Cheung \(et\ al.\)\(^6\). In addition, for the reference time in this study, we chose 24 h

![Fig. 1. Irradiated EBT film. Long horizontal and vertical lines cross shows a center of the field. Because an asymmetric field was used, the Y2 jaw was reduced step by step (11 steps in all). The dose was delivered to the EBT film in 11 steps in ascending order; each step was 2 cm \(\times\) 10 cm in size. Irradiated dose corresponding to each step is shown.](image-url)
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and all doses were converted from the pixel value read out from the EBT film by using the calibration curve at 24 h after irradiation.

In film dosimetry using an EBT film and a flatbed scanner, the pixel value read out from the film was influenced by the scanner’s flatness and noise. Therefore, we corrected for the scanner flatness by subtracting the image before irradiation from the image after irradiation. To correct for the scanner noise, the film was scanned successively five times, and the average of the last three scans was used for further analysis. Moreover, the pixel value read out from the EBT film depended on the direction of the charge-coupled device (CCD) array. Therefore, to avoid differences due to the pixel value’s dependence on the direction of the CCD array, all scans were conducted in the same landscape orientation (main scanning direction) at the same position on the flatbed scanner. In addition, the density growth of the EBT film was influenced by the temperature of the film and ambient light on the film. To avoid the influence of temperature on the EBT film, we used a discontinuous scan and maintained the room temperature at almost 26°C. To reduce any influence of ambient light, the EBT film was set on the scanner until 48 h after irradiation. Moreover, we protected the scanner from ambient light except during readout while scanning the EBT film.

RESULTS

The pixel values for each post-irradiation elapsed time and each delivered dose are shown in Fig. 2. The pixel values increased sharply from 0.1 to 2 h after irradiation and then showed a gradual increase. Further, the relative change in the pixel value due to PEDG was approximately 1% from 24 h to 48 h after irradiation, not shown in Figs. 2 and 3. The relative changes between the pixel values at the reference time and those at each post-irradiation elapsed time are shown in Table 2. The pixel value difference (%) was calculated by the following equation:

\[
\text{difference} (\%) = \left( \frac{PV_t}{PV_0} - 1 \right) \times 100
\]

where \( PV_0 \) is the pixel value at the reference time (\( t = 0 \)) and \( PV_t \) is the pixel value at each post-irradiation elapsed time (\( t = t \)). For delivered doses of 33 and 348 cGy, the pixel values at 0.1 and 16 h after irradiation ranged from –9.6% to –0.7% and from –3.9% to –0.3%, respectively, of the reference value. The range of difference between the pixel value read out from the EBT film at each elapsed time and the reference time decreased with an increase in the delivered dose.

The film doses for each post-irradiation elapsed time for each delivered dose are shown in Fig. 3. The film dose showed an increase similar to that of the pixel value of the EBT film depending on the elapsed time. The relative changes between the film dose at each elapsed time and that at the reference time are shown in Table 2. The film dose difference (%) was calculated by using the following equation:

\[
\text{difference} (\%) = \left( \frac{FD_t}{FD_0} - 1 \right) \times 100
\]

where \( FD_0 \) is the film dose at the reference time (\( t = 0 \)) and \( FD_t \) is the film dose at each post-irradiation elapsed time (\( t = t \)).

For delivered doses of 33 and 348 cGy, the film doses at 0.1 to 16 h after irradiation ranged from –11.8% to –0.9%.
and from –10.4% to –0.8%, respectively, of the reference value. The relative change in all the film doses showed a range of approximately –10% at elapsed times from 0.1 to 16 h and showed no dependence on the delivered dose.

**DISCUSSION**

In this study, we analyzed the relationship between the pixel value read out from the RCF and the PEDG, and between the film dose from RCF and the PEDG. The range of the difference between the pixel values at each elapsed time and those at the reference time clearly became narrower at a delivered dose of 348 cGy than at a delivered dose of 33 cGy (Table 2). The pixel value at a lower delivered dose was smaller than at a higher delivered dose. Hence, the relative changes in the pixel value due to PEDG became large. After the EBT film was irradiated, the diacetylene monomers were transformed into a polymer. This transformation required several hours. As a result of this transformation, the pixel value of the film might have increased. Moreover, the increase in the pixel value for a low delivered dose might be because many diacetylene monomers exist in areas of the low delivered dose during the transition from monomer to polymer diacetylene in the EBT film.

The relative changes in the film dose at each elapsed time compared with those at the reference time were similar to the pixel values (Fig. 3). However, for the delivered dose of 33 cGy to 348 cGy at 2 h after irradiation, the difference (%) in the film dose was within approximately 1% (Table 2) difference of the relative changes in the pixel value. As a result of this, when the base of the pixel value increased exponentially with the delivered dose, the increase in the film dose at low dose delivery was less than the pixel value, and the increase in the film dose at high dose delivery was more than the pixel value. Therefore, the variation of pixel value due to PEDG might offset the gradient of the calibration curve for dose conversion depending on each delivered dose in the dose-conversion process of the pixel value for the EBT film.

**Fig. 3.** Delivered dose plotted as the film dose from the EBT film for each post-irradiation readout time. Film dose is indicated by symbols, and the regression curve of the logarithm of the film dose is plotted as a solid line (R2 = 0.9284–0.9924).

**Table 2.** Differences between measured pixel values and film doses at 0.1 to 16 h after irradiation and those at the reference time.

<table>
<thead>
<tr>
<th>Post irradiation elapsed Time (h)</th>
<th>Delivery dose</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>33 cGy</td>
</tr>
<tr>
<td>Pixel value</td>
<td>Film Dose</td>
</tr>
<tr>
<td>0</td>
<td>–9.6%</td>
</tr>
<tr>
<td>2</td>
<td>–4.4%</td>
</tr>
<tr>
<td>4</td>
<td>–3.1%</td>
</tr>
<tr>
<td>6</td>
<td>–2.4%</td>
</tr>
<tr>
<td>10</td>
<td>–1.5%</td>
</tr>
<tr>
<td>16</td>
<td>–0.7%</td>
</tr>
</tbody>
</table>
In this study, the film dose for a delivered dose of 102 cGy was ~3.1% of that at 24 h after irradiation at an elapsed time of 4 h. That for a delivered dose of 211 cGy was ~2.5% of that at 24 h after irradiation at an elapsed time of 6 h. The relative changes in film dose between the reference time and each elapsed time were larger than the relative changes in pixel value. Therefore, when evaluating an absolute dose, the verification of dose distribution using the EBT film might require the consideration of the elapsed time. In a previous report, the relative changes in the pixel value of the EBT film reported by Fuss et al. and Cheung et al. were similar to our results. Moreover, these researchers reported that a relative change in the pixel value due to the PEDG was a little after 4 h or 6 h post-irradiation. However, our result shows that the difference between the film dose at the reference time and that at each post-irradiation elapsed time was approximately the same for all delivered doses (Table 2). Therefore, the evaluation of the relative dose by verifying the dose distribution using the EBT film might be only slightly influenced by the PEDG and may not require the consideration of the elapsed time.

The Gafchromic EBT film model was introduced as a more sensitive and more uniform alternative to the MD-55 and HS Gafchromic film model. Recently, a Gafchromic EBT2 film was released as the newest Gafchromic EBT film. The active layer of the EBT2 film contains the same radiation-sensitive component as that used in the EBT film. In addition, Slobodan et al. reported that the two film models experience the same dose change in terms of net absorbance and that the sensitivity of the latest EBT-2 model Gafchromic film is slightly lower than that of its predecessor. Therefore, we considered that the PEDG of the EBT2 film might be similar to the PEDG of the EBT film.

In conclusions, the pixel values read out from an EBT film increased because of the PEDG, which depended on the delivered dose, but the relative changes produced in the film dose reading by the PEDG did not depend on the dose level at which the film was irradiated. In the verification of the dose distribution using an EBT film and a flatbed scanner, the PEDG had little influence on the evaluation of the relative dose. Therefore, in an evaluation of the relative dose by this type of verification, the PEDG has little effect and the elapsed time need not be considered. However, when the EBT film was used in the evaluation of the absolute dose, the post-irradiation elapsed time before the readout of the EBT film was required to correspond with the reference time.

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REFERENCES


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