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NOTE

Intra-irradiation changes in the signal of polymer-based dosimeter (GAFCHROMIC EBT) due to dose rate variations

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Abstract
The effect of dose rate on the real-time change in optical density (ΔOD) of a GAFCHROMIC® EBT film is quantified using a previously reported optical readout approach. A range of doses (5–1000 cGy) and dose rates (16–520 cGy min^{-1}) are used, and a statistically significant difference between ΔOD of films exposed at different dose rates occurs within approximately one order of magnitude change in the dose rate. A small increase in per cent standard deviation of measured ΔOD values is also observed when the entire dose rate range was used, but in all cases combining all ΔOD values produces per cent standard deviation of <4.5%. Thus, whether the dose rate effect is clinically significant depends on the specific application of EBT and the desired accuracy.

1. Introduction

In recent years, use of radiation-induced polymerization materials for the measurement of dose has been gaining importance (Maryanski *et al* 1996, Low *et al* 1999, Berg *et al* 2001, Wuu *et al* 2003, Oldham *et al* 2003, Chiu-Tsao *et al* 2004, Hirata *et al* 2005). While many of the current polymer systems are utilized for two- or three-dimensional dose representation, their characteristics offer a potential for a successful implementation in point-based measurements. Radiochromic materials commercially available in GAFCHROMIC® films (International Specialty Products, Wayne, NJ), which polymerize upon irradiation, have also been shown to respond quickly enough to see the effects during irradiation or in real time (Rink *et al* 2005a, 2005b). These radiochromic media are able to provide a sufficient signal from a sub-cubic millimetre volume (Rink *et al* 2005a, 2005b), and can be made relatively energy independent, as was done with the GAFCHROMIC® EBT (Chiu-Tsao *et al* 2005, Rink *et al* 2007). Ultimately, all of these characteristics may allow the use of these polymer systems in real-time dose measurements on or within the patient during diagnosis, treatment and

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monitoring of a patient's pathologies. However, these polymer systems are known to have post-exposure development (Klassen *et al* 1997, Ali *et al* 2003, Rink *et al* 2005a, 2005b) due to the non-instantaneous polymerization reaction. For this reason, variations in the real-time change in optical density (ΔOD), which is used as an indicator of delivered dose, are expected with fluctuating dose rates (and thus the total time taken to deliver a given dose). The impact of this dependence on dose rate needs to be quantified in order to properly assess the suitability of these radiochromic materials for a real-time dosimetry. The signal measured for a MD-55 film was shown to depend on the dose rate for doses above 1 Gy (Rink *et al* 2005a). For the EBT film, it is expected that the dose rate dependence is going to be less significant than that of its predecessor since previous results suggest that polymerization reactions in the EBT film occur faster than in the MD-55 film (Rink *et al* 2005b). This note quantifies the dependence of real-time ΔOD of the EBT film on the rate of dose delivery.

2. Methods and materials

1 cm × 1 cm pieces of GAFCHROMIC® EBT (Lot 35322-003I) film were placed into the film holder within a 30 cm × 30 cm × 4 cm phantom (Rink *et al* 2007), such that the centre of the film was located at a 1.5 cm depth, and the plane of the film is perpendicular to the top surface of the phantom and along the central axis of the irradiating beam. The phantom was placed onto a 30 cm × 30 cm × 6 cm slab of solid water™. A range of doses (5–1000 cGy dose to water at the centre of film) was then delivered at various dose rates (16–520 cGy min^{-1}) using a 100 cm SAD (98.5 cm SSD) setup, 10 cm × 10 cm field and 6 MV x-rays from a linear accelerator (Elekta Synergy®).

The details of the delivery and collection optical fibres are described elsewhere (Rink *et al* 2007). In brief, a 50/125 μm (core/cladding diameter) optical fibre delivered interrogation light from the 630 nm light emitting diode (LED5 23RED, 17 nm full-width half-maximum, LED Light Inc., Carson City, NV) perpendicularly to the film. A 1.50/1.55 mm fibre on the other side of the film collected the transmitted light and delivered it to the spectrophotometer (SD2000, Ocean Optics Inc., Dunedin, FL). Both delivery and collection fibres were located at a 1.5 cm depth within the phantom, parallel to the top surface and perpendicular to the EBT film.

The spectra of transmitted light were obtained for approximately 10 s prior to the exposure, during the exposure and for several minutes after the exposure at roughly one to two spectra per second. Using Matlab 7.1 for all data processing and analysis, the absorbance was calculated at each wavelength using equation (1):

$$\Delta A(\lambda) = \log_{10} \frac{(I_{\mathrm{R}}(\lambda) - I_{\mathrm{D}}(\lambda))}{(I_{\mathrm{S}}(\lambda) - I_{\mathrm{D}}(\lambda))} \tag{1}$$

where I_{D} is the dark spectrum, I_{R} is the reference spectrum (light transmitted through film prior to irradiation) and I_{S} is the sample spectrum at every measurement prior, during and after irradiation. Change in optical density for each collected spectrum was then calculated using a 630–640 nm wavelength range centred on the main absorbance peak using equation (2):

$$\Delta OD = \frac{1}{\lambda_n - \lambda_1} \times \sum_{i=1}^{n-1} \left(\frac{\Delta A_i + \Delta A_{i+1}}{2} \right) (\lambda_{i+1} - \lambda_i) \tag{2}$$

where ΔA_i is the absorbance calculated at the wavelength λ_i within the 10 nm range (Rink *et al* 2005a, 2005b). The ΔOD was then plotted as a function of time. Straight lines were fitted to pre-exposure and post-exposure data; a third order polynomial was fitted to the data obtained during exposure. Using the intercepts between these lines, and subtracting the ΔOD before

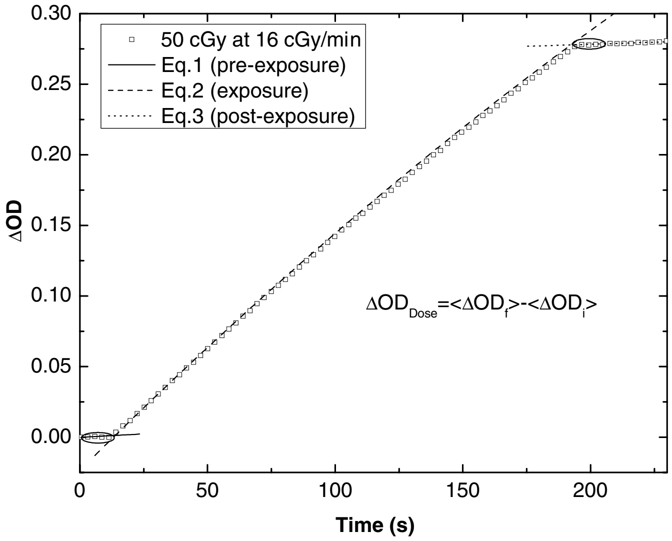

Figure 1. Change in OD versus time for a 50 cGy irradiation at 16 cGy min^{-1}. The ΔOD for this dose and dose rate is calculated as the difference between the ΔOD at the end of exposure and that prior to exposure. The same approach is used for other doses and dose rates.

from the ΔOD at the end of exposure (an average of five points each time), the real-time ΔOD for the given dose was calculated as illustrated in figure 1 (Rink *et al* 2005a).

For most of the doses and dose rates, five measurements were made using five different 1 cm × 1 cm pieces of the EBT film from the same sheet. The exception is in the cases where only three or four measurements were made for the following doses and dose rates: 5 cGy delivered at 130 and 260 cGy min^{-1}, 10 cGy delivered at 260 and 390 cGy min^{-1} and 25 cGy delivered at 520 cGy min^{-1}. In these cases only three or four measurements were made. No data for 5 cGy at 390 and 520 cGy min^{-1} or 10 cGy at 520 cGy min^{-1} was available. This was due to a very short irradiation time and not enough data points available during irradiation to do a line of best fit to calculate ΔOD (as described above). An average ΔOD, or ⟨ΔOD⟩, and standard deviation, σ_{OD}, for each dose and dose rate were calculated using equations (3) and (4), where n is the total number of measurements using different pieces of film. These were then normalized to 1 Gy in order to condense the scale for easier comparison, and plotted for each dose as a function of the dose rate.

$$\langle \Delta \mathrm{OD} \rangle = \frac{\sum_i^n \Delta\, \mathrm{OD}_i}{n} \tag{3}$$

$$\sigma_{\mathrm{OD}} = \sqrt{\frac{\sum_i^n (\Delta \mathrm{OD}_i - \langle \Delta \mathrm{OD} \rangle)^2}{(n-1)}}. \tag{4}$$

The *average per cent standard deviation* for each dose was then calculated across all dose rates, and reported as $\langle \%\sigma_{\mathrm{OD}} \rangle$. For example, for 100 cGy the per cent standard deviations of ΔOD at each dose rate used are 1.5%, 1.5%, 1.7%, 2.0%, 1.3%, 1.4% and 1.3%. The average per cent standard deviation, $\langle \%\sigma_{\mathrm{OD}} \rangle$, for 100 cGy is then 1.5%. To calculate the *overall per cent standard deviation* for a given dose using all dose rates, all of the data irrespective of the dose rate used were averaged, and the per cent standard deviation is reported as $\%\sigma_{\mathrm{OD}}$. This number incorporates the deviations in ΔOD arising from using different dose rates, and is

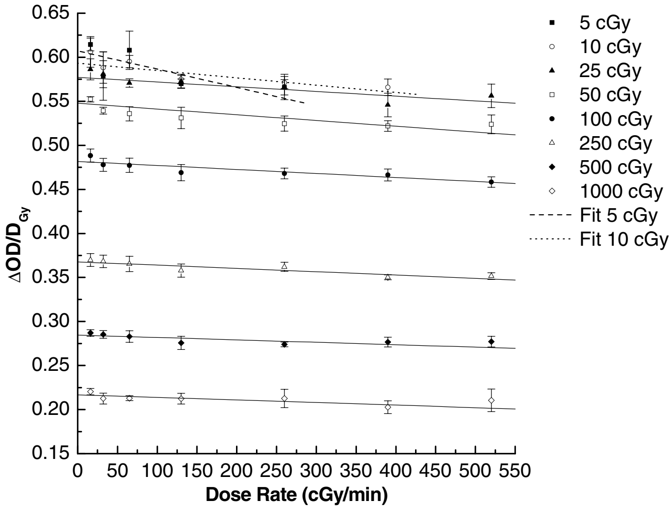

Figure 2. The average sensitivity $\Delta\mathrm{OD}/D_{\mathrm{Gy}}$ as a function of dose rate, for various doses (error bars are $\pm 1\sigma_{\mathrm{OD}}/D_{\mathrm{Gy}}$, where σ_{OD} is one standard deviation for the ΔOD obtained for that dose and given dose rate and D_{Gy} is the delivered dose). The lines of best fit are shown on the graph. Because of the overlap between some of these, the lines of best fit for 5 cGy and 10 cGy doses are marked as dashed lines for clarity.

always larger than $\langle \%\sigma_{\mathrm{OD}} \rangle$. The difference between the two, $\%\sigma_{\mathrm{OD}} - \langle \%\sigma_{\mathrm{OD}} \rangle$, denoted as Δ, is the *average increase in per cent standard deviation* when the dose rate is varied between 16 cGy min^{-1} and 520 cGy min^{-1} instead of keeping it constant.

3. Results and discussion

Average ΔOD normalized to 1 Gy, denoted as $\Delta\mathrm{OD}/D_{\mathrm{Gy}}$, is plotted versus dose rate for various doses (figure 2). First it can be seen that the $\Delta\mathrm{OD}/D_{\mathrm{Gy}}$ decreases with dose, dropping from ~0.6/Gy for 5–10 cGy to just over 0.2/Gy for 1000 cGy. This is due to previously reported nonlinearity of the EBT film with dose (Chiu-Tsao *et al* 2005, Rink *et al* 2005b, Zeidan *et al* 2006). It can also be seen that as the dose rate increases, the $\Delta\mathrm{OD}/D_{\mathrm{Gy}}$ for a given dose decreases and vice versa. This behaviour can be explained by the fact that at low dose rates, the polymerization reactions initiated at the beginning of irradiation have had more time to develop, and hence the ΔOD and $\Delta\mathrm{OD}/D_{\mathrm{Gy}}$ associated with the formed polymers are higher than if the doses were delivered at a high dose rate, and thus over a shorter irradiation time. Although the decrease due to the higher dose rate appears relatively minor, a careful analysis of the data is warranted in order to estimate the importance of this increase in ΔOD. The linear fits to the decrease in $\Delta\mathrm{OD}/D_{\mathrm{Gy}}$ with dose rate are also plotted, and the coefficients of these lines of best fit are shown in table 1. The intercept, y, is the $\Delta\mathrm{OD}/D_{\mathrm{Gy}}$ value approached as dose rate approaches zero (in other words, as the time for a given dose approaches infinity). The idea that as time approaches infinity, the ΔOD for a given dose converges to a given value has been reported previously (Ali *et al* 2005) for various fractionation patterns. Our data support that, since a fractionation pattern can be thought of as a dose rate variation pattern, just on a longer time scale.

The slope, m, of the lines of best fit appears to decrease with increasing dose. However, with the exception of the data for 5 cGy, it does so proportionally with the intercept and the

Table 1. Coefficients of equations of best fit characterizing $\Delta\mathrm{OD}/D_{\mathrm{Gy}}$ as a function of the dose rate ($\dot{D}$). N/A denotes data that are not available. y denotes the $\Delta\mathrm{OD}/D_{\mathrm{Gy}}$ as $t \to \infty$, regardless of the dose rate used for irradiation.

Dose (cGy)	Equation of best fit line: ($\Delta OD/D_{\mathrm{Gy}} = y + m \times \dot{D}$) y (1/Gy)	m ($\times 10^{-3}$) (min Gy^{-2})	% decrease in ΔOD from 16 to 520 cGy min^{-1} rate	Fit of data in figure 1 to line of best fit (R^2)
5	0.607 ± 0.006	-21 ± 4.5	N/A	0.697
10	0.593 ± 0.006	-8.3 ± 3.0	N/A	0.673
25	0.577 ± 0.005	-5.3 ± 2.5	4.5	0.680
50	0.548 ± 0.002	-6.5 ± 1.4	6.0	0.717
100	0.482 ± 0.004	-4.5 ± 1.4	4.7	0.843
250	0.368 ± 0.004	-3.7 ± 1.1	5.1	0.792
500	0.285 ± 0.002	-2.7 ± 1.1	4.8	0.604
1000	0.217 ± 0.002	-2.9 ± 1.6	6.7	0.526

overall sensitivity of the film. Thus deducing that the dose rate fluctuations have a smaller effect on larger doses from these data alone would be erroneous. If there were no fluctuations associated with the ΔOD readout for a given dose, then the per cent decrease in $\Delta\mathrm{OD}/D_{\mathrm{Gy}}$ and in ΔOD caused by increasing the dose rate from 16 cGy min^{-1} to 520 cGy min^{-1} calculated using the best-fit lines seems rather substantial. As shown in table 1, it ranges between 4.5 and 6.7%, with no obvious dose-level trend. However, the film is known to vary in sensitivity with a deviation of ±1.5% to ±4% depending on dose (Zeidan *et al* 2006). Also, small fluctuations in the light source output and spectrophotometer (measured combined standard deviation of 0.1% over a period of 5 h) exist and the linear accelerator output has a maximum ±2% variation. Thus, the ΔOD measurements are not error free, and the important question is whether the error introduced due to the fluctuating dose rate is a significant portion of the overall error associated with the ΔOD measurement.

To evaluate whether the dose rate has a statistically significant effect on the ΔOD measurements, an F-test (Milton and Arnold 1990) was performed for each dose and different combinations of dose rates, starting with only two groups (16 and 32 cGy min^{-1}), and ending with seven groups (16 to 520 cGy min^{-1}) if data were available. This test compares the difference between the mean ΔOD values of groups with respect to the standard deviation of each group, in order to detect whether the difference between groups is significant compared to the associated uncertainty in the measurement. If the difference between means of groups is deemed to be statistically significant, then dose rate has an effect on the ΔOD measurement. Since as many as five pieces of film (taken randomly from a single large piece of EBT) were used at each dose and dose rate to obtain these average ΔOD and σ_{OD} values, the uncertainty associated with the ΔOD measurement will include film non-uniformity, variability of output of the linear accelerator between different times that the measurements were performed, and light and spectrophotometer fluctuations. If $p < 0.05$, the difference between the sets of measurements is taken to be statistically significant, and thus dose rate fluctuations have a significant effect on the ΔOD measurement. For 5 cGy, varying the dose rate (even between 16 cGy min^{-1} and 32 cGy min^{-1}) introduced significant difference in ΔOD beyond normal deviation. For all other doses, varying the dose rate from 16 cGy min^{-1} to 390 cGy min^{-1} (or 520 cGy min^{-1}) introduced a significant change in ΔOD. The general trend is that $p < 0.05$ levels are seen when dose rate difference is eightfold or more for a given dose. For example, there is a statistically significant difference between ΔOD values obtained at 16 and

Table 2. Average per cent standard deviation ($\langle\%\sigma_{\mathrm{OD}}\rangle$) for each dose, combined per cent standard deviation ($\%\sigma_{\mathrm{OD}}$) of all ΔOD values across the entire dose range and the difference between the two (Δ) for each dose delivered.

	Dose (cGy)							
	5	10	25	50	100	250	500	1000
$\langle\%\sigma_{\mathrm{OD}}\rangle$	2.4	1.8	2.0	1.4	1.5	1.7	1.9	3.3
$\%\sigma_{\mathrm{OD}}$	4.4	3.1	3.0	2.4	2.4	2.6	2.5	4.4
Δ	2.0	1.3	1.0	1.0	0.9	0.9	0.6	1.1

130 cGy min^{-1}, or between 520 and 65 cGy min^{-1}, but not between 520 and 390 cGy min^{-1}, or 16 and 65 cGy min^{-1}. This seems to be irrespective of the dose delivered to the film.

Per cent standard deviations of ΔOD were calculated for a given dose at specific dose rates, and the average of these are shown as $\langle\%\sigma_{\mathrm{OD}}\rangle$ in table 2. Overall per cent standard deviation is also reported for each dose. A small increase in per cent standard deviation is observed when ΔOD values obtained with various dose rates across the entire range tested are combined. This further illustrates the dependence of the measured ΔOD on the range of dose rates used. For all doses, except 5 and 10 cGy, the average increase in the per cent standard deviation, denoted as Δ, is $\sim$1%. For all doses examined in the 5 to 1000 cGy range, the $\%\sigma_{\mathrm{OD}}$ calculated using ΔOD values obtained with the entire 16 to 520 cGy min^{-1} range is 4.4% or less.

4. Conclusion

Real-time measurements of ΔOD of GAFCHROMIC® EBT films irradiated to doses in the 5 cGy to 1000 cGy range showed a small dose rate dependence when an eightfold difference in dose rate was introduced. Combining all ΔOD measurements for a given dose irrespective of dose rate used within the 16–520 cGy min^{-1} range introduced a dose rate dependent uncertainty of $\sim$1%. For all doses, the per cent standard deviation of the ΔOD values using all the dose rates within the tested range was <4.5%. Therefore, although varying dose rate by an order of magnitude has a statistically significant effect on the real-time ΔOD, the measurement can still be performed with an uncertainty of 4.5% of less, which can be satisfactory for many applications of the EBT film.

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