Energy dependence of response of new high sensitivity radiochromic films for megavoltage and kilovoltage radiation energies

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The purpose of this paper is to evaluate the energy dependence of the response of two new high sensitivity models of radiochromic films EBT and XR-QA. We determined the dose response curves of these films for four different radiation sources, namely, 6 MV photon beams (6 MVX), Ir-192, I-125, and Pd-103. The first type (EBT) is designed for intensity modulated radiation therapy (IMRT) dosimetry, and the second type (XR-QA) is designed for kilovoltage dosimetry. All films were scanned using red (665 nm) and green (520 nm) light sources in a charge-coupled device-based densitometer. The dose response curves [net optical density (NOD) versus dose] were plotted and compared for different radiation energies and light sources. Contrary to the early GAFCHROMIC film types (such as models XR, HS, MD55-2, and HD810), the net optical densities of both EBT and XR-QA were higher with a green (520 nm) than those with a red (665 nm) light source due to the different absorption spectrum of the new radiochromic emulsion. Both film types yield measurable optical densities for doses below 2 Gy. EBT film response is nearly independent of radiation energy, within the uncertainty of measurement. The NOD values of EBT film at 1 and 2 Gy are 0.13 and 0.25 for green, and 0.1 and 0.17 for red, respectively. In contrast, the XR-QA film sensitivity varies with radiation energy. The doses required to produce NOD of 0.5 are 6.9, 5.4, 0.7, and 0.9 Gy with green light and 19, 13, 1.7, and 1.5 Gy with red light, for 6 MVX, Ir-192, I -125, and Pd-103, respectively. EBT film was found to have minimal photon energy dependence of response for the energies tested and is suitable for dosimetry of radiation with a wide energy spectrum, including primary and scattered radiation. XR-QA film is promising for kilovoltage sources with a narrow energy spectra. The new high sensitivity radiochromic films are promising tools in radiation dosimetry.
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Key words: radiochromic film, film sensitivity, absorption spectrum, energy response, light source

I. INTRODUCTION

Radiochromic films have been used extensively for radiation dosimetry in conventional radiation therapy, including external beam, brachytherapy, and radiosurgery.[1–4] With the recent development of intravascular brachytherapy, radiochromic film dosimetry has emerged as one of two major dosimetry tools together with Monte Carlo simulations.[5–12]

Earlier types of radiochromic films include GAFCHROMIC models HD810, MD55-1, MD55-2, HS, XR-T, and XR-R. The models HD810, MD55-1, MD55-2, and HS were based on the same radiochromic emulsion, are listed in order of increasing sensitivity.[13–17] Models XR-T and XR-R, containing high Z materials in the emulsion chemical, were designed for use in the kilovoltage range.[4,16,18] The film sensitivity of these early models has been found to depend on energy in the range covering megavoltage and kilovoltage radiation modalities.[16,17,19,20]

The absorption spectrum of these early models of radiochromic films consists of a major absorption peak at about 670 nm.[16,21–24] The selection of light source in a densitometer to optimize the film sensitivity has been in favor of red light.[1,22,24–29] Evaluation of densitometers with green and blue light source,[16] as well as broad band spectrum,[1,30,31] for use in radiochromic film dosimetry has also been reported.

Two new types of radiochromic films, EBT and XR-QA, were recently introduced by International Specialty Products (ISP, Wayne, NJ). The first type (EBT) is designed for intensity modulated radiation therapy (IMRT) dosimetry. In the megavoltage radiation energy range, this new model can be five to ten times more sensitive than HS and MD55-2, depending on the wavelength of the light sources in the densitometer used for scanning.[32–36] In addition, the major peak in the absorption spectrum is close to 635 nm, shifted from 670 nm for the early models.[33–35] (See Fig. 1.) Evaluation of the feasibility of EBT film for IMRT dosimetry has been recently reported.[34–37]

Although the original design idea for EBT film was for megavoltage radiation dosimetry, it is important to (1) compare the dosimetric characteristics of EBT film at megavoltage and kilovoltage energies of primary and scattered radiation and (2) explore its potential application to low energy photon sources. In this paper, we present our study of dose response curves of EBT film for four different radiation sources, namely, 6 MV photon beams (6MVX), Ir-192 (370 keV), I-125 (28 keV), and Pd-103 (21 keV). Compar-

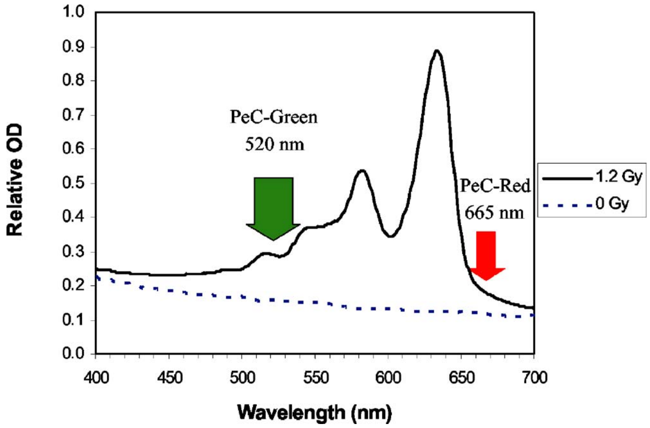

FIG. 1. Absorption spectra of new high sensitivity radiochromic EBT film. The absorption spectra for XR-QA films are the same. (Courtesy of David Lewis, ISP.) The upper solid and lower dotted curves are for doses of 1.2 and 0 Gy, respectively. The wide (left) and narrow (right) arrows indicate the wavelengths of green (referred to as PeC-Green, 520 nm) and red (referred to as PeC-Red, 665 nm) light sources used with the CCD-based densitometer for scanning the films.

ing these four response curves, we observed minimal energy dependence of response for this wide range from megavoltage to kilovoltage radiation energies.

The second type of new film (XR-QA) is designed for kilovoltage dosimetry. It contains high Z materials[33] and is expected to be much more sensitive to low energy photon radiation compared with megavoltage beams. It is important to determine the energy dependence of the response. Hence, we carried out a parallel investigation of the dose response characteristics of XR-QA film for 6MVX, Ir-192, I-125, and Pd-103.

The modified absorption spectrum (Fig. 1) in EBT and XR-QA films would affect the relative film sensitivity scanned using different light sources. In this study, we scanned the EBT and XR-QA films using green (520 nm) and red light (665 nm) of a charge-coupled device (CCD)-based densitometer, and compared the film sensitivities.

II. MATERIALS AND METHOD

A. Film irradiation

Four different radiation sources, namely, 6 MV photon beams (6MVX), Ir-192, I-125, and Pd-103 were used to irradiate the two new types of radiochromic films, EBT and XR-QA. Prototype EBT films of lot no. 33303-X2PERP and XR-QA films of lot no. 33303-016IP2100 from ISP were evaluated. Small film pieces, in size 2 cm $\times$ 2 cm, were cut from the film sheets of about 10 cm $\times$ 10 cm. A set of 13 to 18 film pieces was individually irradiated by each radiation source with different doses. A background (unirradiated) film was kept in each set of exposed films described below.

A Clinac 2100C (Varian, Palo Alto, CA) was used for the 6 MV photon beam (6MVX) irradiation. One film piece of model EBT and one of XR-QA, were positioned horizontally side by side near the beam's central axis in a solid water phantom (RMI model 457, Gammex, Middleton, WI), 30 cm $\times$ 30 cm $\times$ 20 cm, at a depth of 1.5 cm placed at 100 cm source to surface distance (SSD). The radiation field size was 10 cm $\times$ 10 cm at the isocenter. The dose output (in cGy) to water was calibrated following the TG21 protocol using an ion chamber which was calibrated by an Accredited Dose Calibration Lab (ADCL). The dose rate to water was 6 Gy min^{-1}. There were 16 irradiated films in this set, receiving doses from 0.2 to 30 Gy.

An Ir-192 HDR v2 source (model 105.002) in a microSelectron from Nucletron Corporation (Columbia, MD) was positioned at the center of a solid water phantom (30 cm $\times$ 30 cm $\times$ 20 cm) for film irradiation. One film piece of each type, EBT and XR-QA, was positioned at about 1.1 cm from the source center, below and above the source, respectively. The two films were exposed simultaneously. At the time of irradiation, the source strength was 7.5 Ci, based on decay from the calibration using an HDR1000 well ionization chamber (Standard Imaging, Middleton, WI), which was calibrated by an ADCL. Dose to water at the film center was calculated using the source strength, distance from the source center to film emulsion layer, exposure time, and TG43 parameters[38] obtained by Daskalov *et al.*[39] The dose rate to water was 4.5 Gy min^{-1} and the exposure times ranged from 5 s to 5 min. With varying exposure times, doses to water from 0.37 to 22 Gy were delivered to the center of 15 film pieces of each type.

We used an I-125 seed (model 2301, Best Medical International, Springfield, VA) and a Pd-103 seed (Best model 2335) to irradiate the films positioned at about 5 mm from the seed center, above or below the seed. The seed strengths were traceable to the National Institute of Standards and Technology standard, and also checked with our in-house well chamber, Capintec model CRC15. The seed was positioned at the center of a solid water phantom, 30 cm $\times$ 30 cm $\times$ 20 cm for film exposure. One I-125 seed with initial source strength of 6 U (5 mCi) was used to irradiate the entire series of films sequentially during a three week period. The dose rates to water, ranging from 13 to 25 cGy h^{-1}, were calculated using the source strength (incorporating decay), distance between the film emulsion layer and seed center, and TG43 parameters recommended by the TG43U1 report.[40] The doses to water were from 0.16 to 20 Gy for 12 EBT films and from 0.06 to 10 Gy for 14 XR-QA films.

For the Pd-103 irradiation, one Pd-103 seed[41,42] was used for the entire series of film exposures in a time period of two months, with the initial and final seed strengths being 2.6 and 0.26 U (2 and 0.2 mCi), respectively. The dose rates to water were calculated using the source strength (with decay factor incorporated), distance between the seed center and film center, and TG43 parameters obtained by Meigooni *et al.*[41] The initial and final dose rates were 7 and 0.6 cGy h^{-1}, respectively, in the two month period. The exposure times ranged from 0.3 to 500 h (20 days). The doses to water ranged from 0.006 to 6 Gy for 17 XR-QA films and 0.13 to 22 Gy for 14 EBT films.

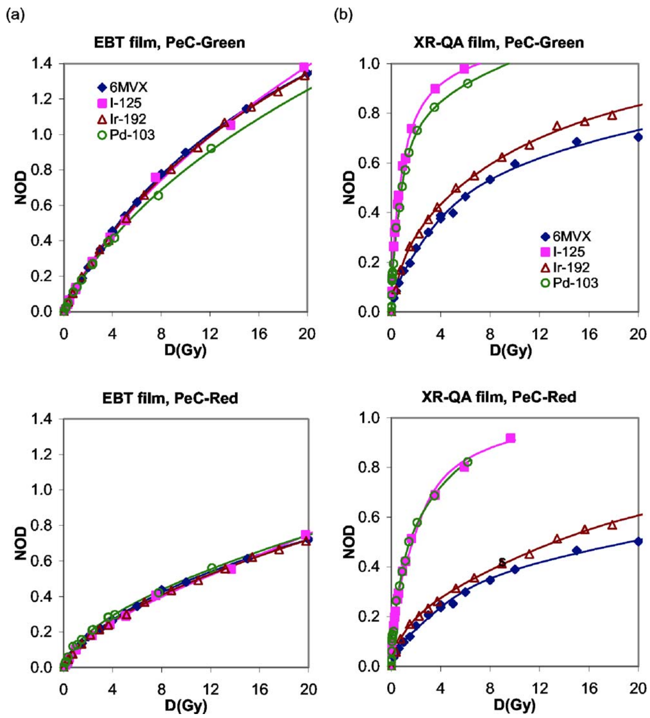

FIG. 2. Dose response curves for (a) EBT films and (b) XR-QA films, scanned using green light (PeC-Green, upper) and red light (PeC-Red, lower), irradiated by 6 MVX (closed diamond), I-125 (closed square), Ir-192 (open triangle), and Pd-103 (open circle). The solid lines are fitted curves.

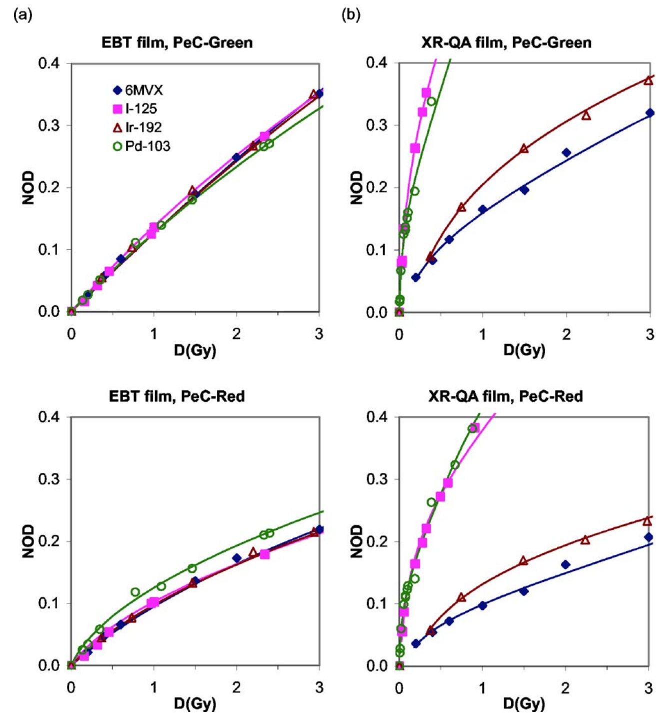

FIG. 3. Dose response curves in zoom-in scale for (a) EBT films and (b) XR-QA films, scanned using green light (PeC-Green, upper) and red light (PeC-Red, lower), irradiated by 6 MVX (closed diamond), I-125 (closed square), Ir-192 (open triangle), and Pd-103 (open circle). The solid lines are fitted curves.

B. Film scanning

All films were scanned using red [665 nm, full width at half maximum (FWHM) 10 nm] and green (520 nm, FWHM 20 nm) light sources in a CCD-based densitometer [model CCD100, Photoelectron Corporation (PeC), Lexington, MA] at least five days after the completion of irradiation. Film pieces grouped within an area of $10\ \text{cm} \times 10\ \text{cm}$ were scanned together. The pixel resolution was 0.2×0.2 mm. The readings of optical densities (OD) were acquired and processed using LABVIEW-based software from PeC.

For each film piece irradiated by Ir-192, I-125, and Pd-103, an average reading over a small area of 1 mm $\times 1$ mm (5×5 pixels) at the film center was obtained using the PeC software. For the background films and the films irradiated by 6MVX, an average reading over an area of $5\ \text{mm} \times 5$ mm of each film was obtained.

For each film type (EBT or XR-QA) and light source (red or green) used for scanning, the optical density readings of the four unirradiated films in the four sets of films were compared. The average of these four readings was obtained. The individual background OD readings of the four unirradiated films were all within 2% from the average OD value. The net optical density (NOD) of each irradiated film was obtained by subtracting the average background OD.

III. RESULTS

A. Dose response curves

The dose response curve of each type of radiochromic films irradiated by a given radiation source was obtained by plotting NOD values against corresponding doses using green or red light source. These curves for EBT and XR-QA films are shown in Figs. 2(a) and 2(b), respectively. Contrary to the early GAFCHROMIC film models (such as models XR, HS, MD55-2, and HD810), the values using the green or red light source against corresponding delivered doses of both EBT and XR-QA were higher with the green (520 nm) than those with the red (665 nm) light source, because of different absorption spectra (Fig. 1) of the new radiochromic emulsion. To closely examine the dose range within 3 Gy, we also display the response curves in a zoomed-in scale in Fig. 3. All the curves are nonlinear. The slope (film sensitivity in NOD/Gy) decreases with increasing dose monotonically. Such a decrease in slope is more pronounced for the XR-QA film compared with the EBT film studied in this work.

The EBT film response is nearly independent of radiation energy, within the uncertainty of measurement. The EBT film sensitivities are very close for 6MVX, Ir-192, and I-125. Compared with these three radiation sources, the sensitivity of EBT film to Pd-103 is slightly higher with red light and slightly lower with green light. When averaged over all four radiation energies, the NOD values at 1 and 2 Gy are 0.13 and 0.25 for green, and 0.1 and 0.17 for red, respectively. For a given light source used in scanning, the doses for a NOD of 0.5 or 0.1 are similar for all four radiation sources. (See Table I.)

The XR-QA film sensitivity decreases with increasing radiation energy, as expected from the original design idea.[33]

TABLE I. (a) Values of NOD/D(Gy) at 1 Gy for XR-QA and EBT films, irradiated by 6 MV photon beams, Ir-192, I-125, and Pd-103, read using red and green light sources. (b) Values of D(Gy) for NOD=0.5. (c) Values of D(Gy) for NOD=0.1.

(a)

Values of NOD/Gy at $D=1$ Gy

Film type	Light source	Radiation modality			
		6 MVX	Ir-192	I-125	Pd-103
XR-QA	PeC-Green	0.16	0.21	0.60	0.55
	PeC-Red	0.10	0.13	0.38	0.41
EBT	PeC-Green	0.13	0.13	0.14	0.13
	PeC-Red	0.09	0.10	0.10	0.13

(b)

D(Gy) for NOD=0.5

Film type	Light source	Radiation modality			
		6 MVX	Ir-192	I-125	Pd-103
XR-QA	PeC-Green	6.9	5.4	0.7	0.9
	PeC-Red	19	13	1.7	1.5
EBT	PeC-Green	4.5	4.6	4.7	5.2
	PeC-Red	11	11	11	10

(c)

D(Gy) for NOD=0.1

Film type	Light source	Radiation modality			
		6 MVX	Ir-192	I-125	Pd-103
XR-QA	PeC-Green	0.47	0.41	0.04	0.04
	PeC-Red	1.0	0.67	0.07	0.06
EBT	PeC-Green	0.79	0.78	0.71	0.77
	PeC-Red	1.1	1.0	0.96	0.71

The curves for I-125 and Pd-103 are close to each other. The Ir-192 and 6MVX curves are in a separate group, not far from each other. The doses required to produce NOD of 0.5 are 6.9, 5.4, 0.7, and 0.9 Gy with green light and 19, 13, 1.7, and 1.5 Gy with red light, for 6MVX, Ir-192, I-125, and Pd-103, respectively. Since NOD is not linear with dose, it would be important to also note the difference in doses required to produce NOD of 0.1 for the four radiation sources and two light sources. These are displayed in Table 1.

For comparison, we also list the values of NOD/D(Gy) at $D=1$ Gy for XR-QA and EBT films, irradiated by 6 MV photon beams, Ir-192, I-125, and Pd-103, read using red and green light sources. (See Table I.) Both film types yield reliably measurable optical densities for the doses below 2 Gy.

B. Uncertainty analysis

Uncertainty in delivered dose values was determined for each radiation source. The 6 MV photon beam doses were based on calibration using an ADCL calibrated ion chamber with 2% uncertainty.

The combined uncertainty in delivered dose values for Ir-192, I-125, or Pd-103 sources was obtained by summing the quadratures of the uncertainties in (1) the distance between the source center and film emulsion layer, (2) source air kerma strength, (3) dose rate constant, (4) radial dose function, (5) equatorial anisotropy, and (6) exposure times. The maximum dose uncertainties were estimated as 9% for both I-125 and Pd-103, and 8% for Ir-192.

The uncertainty in net optical density values was estimated as 5.4%, which was obtained by combining in quadratures of the uncertainties in film uniformity (5%) and densitometer readings (2%). Therefore, the maximum uncertainty in film sensitivity [NOD/D(Gy)] was estimated as 10.4%, 10.4%, 9.8%, and 5.7% for Pd-103, I-125, Ir-192, and 6MVX, respectively.

IV. DISCUSSION AND CONCLUSION

Due to the low source strengths of the Pd-103 and I-125 seeds used in the film irradiation, the dose rates were between 0.6 and 7 cGy h^{-1}, much lower than the dose rate of a few Gy min^{-1} from Ir-192 and 6MVX. It is not known if there may be any effect of very long exposure times (up to 20 days for Pd-103). It has not been confirmed if there is any dose rate effect on the film response, although there are some reports of such studies for some early models.[43,44]

Due to the limited supply of the prototype films available for this study, the film exposures were not repeated for reproducibility check. The above mentioned uncertainties were not statistical.

Variation in film sensitivity from lot to lot may also be non-negligible. This study was carried out using prototype lots of EBT and XR-QA films. The results reported here should serve as a guide for future studies. Users are advised to establish calibration curves for each lot of films, even of the same type.

EBT film has minimal photon energy dependence of response and may be suitable for dosimetry of photon radiation sources with wide energy spectrum, including primary and scattered radiation. Such minimal energy response may make such types of films a strong candidate for dosimetry of radiation with heterogeneous energy spectra, such as IMRT (Refs. 35 and 37) and electronic brachytherapy.[45] Given the high sensitivity of XR-QA films to kilovoltage radiation sources, they may have potential applications in brachytherapy dosimetry of low energy radiation sources, and CT, mammography and fluoroscopy dosimetry in diagnostic radiology. Both film types yield measurable optical densities for doses below 2 Gy. The new high sensitivity radiochromic films are promising tools in radiation dosimetry.

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