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Characterisation of delaminated GAFCHROMIC[™] EBT3 films in clinical photon, proton and ¹⁹²Ir brachytherapy source

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Abstract. This paper aims to assess the dose-response characteristics of delaminated GAFCHROMICTM EBT3 films for radiotherapy beams. Delaminated EBT3 films were produced by peeling off the top polyester substrate of original EBT3 using surgical precision forceps. The films were irradiated to 500 cGy with photon beams of 6 MV and 10 MV, while proton and ¹⁹²Ir exposures were conducted at nominal energies of 150 MeV and 0.38 MeV respectively. Digitisations were made using a flatbed scanner in Red-channel for optimum sensitivity. Analyses of data fitting, reading reproducibility, film integrity and energy dependency were then implemented for comparison with original EBT3 films. Results of R^2 in each curve suggested that the selected non-linear function appropriately fits the data with low reduced chi-square. However, the delaminated films experience integrity degradation of up to 13% due to active layer distress, affecting the reading reproducibility with values extending to 1.0%. Plus, the mean relative response ratio of energy dependency for delaminated EBT3 in photon irradiations was observed at 0.97, which is inferior to their original counterpart. In summary, the delaminated EBT3 yields comparable dose-response behaviour despite integrity deterioration. It is important to factor film delamination uncertainties into existing uncertainty budget as it is instrumental in reading dose-response deviations. Accurate evaluation together with reliable fabrication processes could make delaminated EBT3 attractive in specific applications including α -particles dosimetry and ultraviolet radiation monitoring.

1. Introduction

Radiochromic films (RCFs) are powerful chemical based 2-D dosimeter in medical radiation physics. The active compound of RCFs polymerises and darkens permanently upon irradiation and is translated in optical density (OD) unit for relative dosimetry. GAFCHROMIC[™] EBT3 films (Ashland

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Specialty Ingredients, Bridgewater, NJ, USA) were known as the third generation of EBT RCF series. As a successor to the EBT2 model, EBT3 RFCs were made to improve the shortcomings of asymmetrical design and susceptibility towards Newton's Rings. Its appeal for being weakly dependent on beam energies and submergible in aqueous solution makes it suitable for a myriad of application in the clinical and industrial setting.

Recent areas of research involving EBT3 films were gaining attention with the introduction of delaminated EBT3 films (also known as peeled-off or unlaminated EBT3). The structural configuration of both original and delaminated EBT3 films is depicted in Figure 1. The chief purpose of removing the top polyester substrate is to eliminate any potential scattering or attenuation found in standard-issued radiochromic films [1, 2]. A limited number of reports had been published regarding the uses of delaminated RCFs: alpha-particle emitters dosimetry in radiopharmaceuticals [3], detection of short-wave ultraviolet radiation (UVC) [4], quantification of physical dose enhancement by short ranged photoelectrons and Auger electrons [5] and characterisation of heavy particle radiotherapy beams such as ¹²C ions [6]. Since this RCF is only made available through special requests from the manufacturer and costs almost double the price of an original RCF, film delamination techniques were introduced as an inexpensive solution to fabricate such films. There have been a few methods of film delamination mentioned in the literature. Mukherjee et al. [3] used a surgical scalpel to split the polyester sheath, Lee et al. [7] on the other hand used a stationery cutter knife while Ng et al. [8] proposed a novel method of 'spontaneous peeling' involving immersion of silicone-sealed RCFs into deionised water for 19 days. Although the authors reported no or minimal performance degradation, they had failed to appropriately address the level of distress occurred during the delamination process. Therefore, this study set out to compare the dose-response curves of original versus delaminated EBT3 films and to quantitatively estimate the effects of film delamination distress onto film integrity, reading reproducibility and energy dependency using a flatbed colour scanner system.



Figure 1. The structural configuration of (a) original and (b) delaminated EBT3 film.

2. Materials and Methods

2.1. Film dosimeters

GAFCHROMICTM EBT3 films (Lot #: 05011702) with sheet dimensions of 20.3 cm x 25.4 cm were taken out from the refrigerator and allowed to warm in room ambient temperature for an hour before being cut into separate pieces of 1.0 cm x 1.2 cm. Since the matte polyester substrate of EBT3 is weakly bound to the active compound layer and prone to separation during cutting, the top substrate was then peeled carefully using surgical precision forceps, henceforth referred to as delaminated EBT3 films. Handlings of both laminated and delaminated RCFs were in line with the American Association of Physicists in Medicine (AAPM) Radiation Therapy Committee Task Group 55 guidelines [9].

2.2. Irradiations

Photon irradiations were conducted using PRIMUS[™] Linear Accelerator (Siemens Medical Systems, Concord, CA, USA), while gamma-ray irradiations were achieved using a High Dose Rate (HDR) ¹⁹²Ir-loaded brachytherapy unit (microSelectron[®] HDR-V3; Nucletron Corp, Columbia, MD, USA) at Hospital USM. Measurements of proton beam (Mitsubishi Electric, Hyogo, Japan) were performed at Hyogo Ion Beam Medical Centre. Phantoms used for all irradiations were correct in dimensions for a

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stable investigational setting. The samples were then administered with 10 radiation dose levels of 50 cGy to 500 cGy, in sequences of 50 cGy. Detailed descriptions of the set-ups for this experiment were tabulated in Table 1.

Beam type	Energy	Field size (cm ²)	Source-to-surface distance; SSD (cm)	Measurement depth (cm)
Photon	6 MV 10 MV	10 x 10	100	1.5 2.5
Proton	150 MeV	20 x 20	100	6.0
¹⁹² Ir source	0.38 MeV	1 x 1	n/a	1.0

Table 1. Overview of irradiation set-up.

2.3. Digitisation

Scanning was accomplished 72 hours post-exposure. All films were digitised with Epson[®] Expression[®] 10000XL (Epson Seiko Corp., Nagano, Japan) flatbed colour scanner in transmission mode. The film pieces were handled with latex gloves and the laminated sides were clean swabbed using 70% ethanol-soaked cotton buds before scanning to reduce potential systematic error. Default digitisation parameters listed by Tagiling *et al.* [10] was adopted inside the TWAIN-equipped PTW FilmScan software version 2.8 (PTW-Freiburg, Freiburg, Germany). The films were then placed on the central axis region of the scanner bed in landscape orientation after three empty scans, and the final images were saved in a tagged image file format (.tiff) for analysis.

2.4. Dose-response analysis

Pixel values of reflected intensities (I) were extracted using FilmCal software version 2.4 (PTW-Freiburg, Freiburg, Germany). To confirm exposure homogeneity, three samplings of the equally sized region of interest (ROI) were applied to each film image. Change in optical density (*netOD*) and its uncertainty (film reproducibility; σ_{netOD}) was defined as follows in Equation (1) and (2):

$$netOD = OD_{irr} - OD_{non-irr} = \log_{10} \left(\frac{I_{non-irr}}{I_{irr}} \right)$$
(1)

$$\sigma_{netOD} = \frac{1}{\ln(10)} \left(\left(\frac{\sigma_{I_{non-irr}}}{I_{non-irr}} \right)^2 + \left(\frac{\sigma_{I_{irr}}}{I_{irr}} \right)^2 \right)^{\frac{1}{2}}$$
(2)

 $I_{\text{non-irr}}$ is the averaged pixel value in non-irradiated film pieces and I_{irr} relates to the averaged pixel value of irradiated film pieces, while $\sigma_{I_{\text{non-irr}}}$ and $\sigma_{I_{\text{irr}}}$ are the standard deviations of $I_{\text{non-irr}}$ and I_{irr} .

Two possible fitting functions were considered for the best fit in both films:

$$D = B \cdot netOD + C \cdot netOD^2 \tag{3.1}$$

$$D = B \cdot netOD + C \cdot netOD^3 \tag{3.2}$$

B and *C* are known as fitting parameters. Devic *et al.* [11] included the exponentiation of *netOD* in the fitting function as a consideration of non-linear saturation for RCFs at high doses. On this wise, 2.0 and 3.0 were chosen as the exponent value of Equation (3.1) and (3.2) to resemble second-order and third-order polynomials, which were reported to give sufficiently accurate curve fit [12]. Data plotting

were accomplished using OriginPro 2018 software package (OriginLab, Northampton, Massachusetts, USA) and was optimised using the Orthogonal Distance Regression (ODR) algorithm feature.

To quantify the integrity of delaminated EBT3 films hence determining its performance, relative *netOD* difference percentage in each dose point D was calculated using the following Equation (4):

$$R_{\text{film-diff}} = \left(\frac{\left|netOD_{D, \text{ ori}} - netOD_{D, \text{ delam}}\right|}{netOD_{D, \text{ ori}}}\right) \cdot 100 \tag{4}$$

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 $netOD_{D, ori}$ and $netOD_{D, delam}$ stands for netOD values derived from original and delaminated films respectively at dose D. The anticipated errors between two photon energies in delaminated EBT3 films were thereby computed from the established dose-response curves using the relative response ratio of energy dependency formula (k), with 6 MV as the reference beam quality energy:

$$k_{6 \text{ MV}}^{10 \text{ MV}} = \frac{f_{D, 10 \text{ MV}}}{f_{D, 6 \text{ MV}}}$$
(5)

The labels $f_{D, 6 \text{ MV}}$ and $f_{D, 10 \text{ MV}}$ in Equation (5) represent the values of *netOD* at dose *D* for fitting functions of 6 MV and 10 MV photon beams.

3. Result and Discussion

It is noteworthy to mention that there are no observable differences of delaminated EBT3 films scanning compared to the original films scanning other than its delicate handling and scanning-side dependence. Figure 2 displays the dose-response curves of original and delaminated EBT3 films for photon, proton and ¹⁹²Ir radiotherapy source. The fitting comparison was conducted in the Redchannel analysis because of the maximum sensitivity provided and its suitability for doses of clinical interests below 800 cGy. Results of the coefficient of determination (R²) and its adjusted value (adj-R²) for both fitting functions were equal to 1 in all beam qualities. Table 2 presents the final indicator for goodness-of-fit in terms of reduced chi-square (\tilde{x}^2). Values of \tilde{x}^2 were lower for Equation (3.1) in both original and delaminated EBT3 films upon fitting, indicating a similar non-linear response. Researchers had tested different exponent values to fit *netOD* data in RCF dosimetry [13, 14]. It is reasoned that the various values of exponent were a result of different protocol, RCF and densitometer combination, in which to suit each experimental condition.

Table 2. Fitting analysis values according to reduced chi-square (\tilde{x}^2) .

	Exponent	Photon	Photon	Proton	¹⁹² Ir
Film type		6 MV	10 MV	150 MeV	0.38 MeV
		\tilde{x}^2	$\tilde{\chi}^2$	\widetilde{x}^2	\tilde{x}^2
EDT2 (0	2	2.15	1.41	31.19	27.68
EB15 (Original)	3	7.18	4.40	75.95	72.64
	2	1.01	1.93	1.11	2.39
EB13 (Delaminated)	3	2.12	3.67	1.95	4.14

netOD uncertainties for original EBT3 films were found to be low in all testing with values of up to 0.3% each. However, the uncertainties for delaminated EBT3 films were higher due to the increased noise signal and varied across the experiments due to the varying levels of distress exerted on the

active layer of each individual film pieces. For example, the averaged σ_{netOD} in 10 MV photon beam was within 0.6% while the averaged σ_{netOD} in 150 MeV proton beam was reaching 1.0%, showing poor film reproducibility in relation to the original films. On whole, the delamination process had affected the films' integrity and introduced a mean relative *netOD* film difference of 4.8% with deviations ranging between 1% and 13.0%.

The relative response ratio for each dose point in original films irradiated with photon beams exhibited low energy dependence with a nearly uniform trend (mean k : 0.99) in comparison to the irregular trend shown in delaminated films (mean k : 0.97). These findings further implied the idea of active layer damage as the cause of the energy response shift. Among the examples of active layer damage may include fingerprints, scratches, moisture/grease and loss of active layer material. Nevertheless, there are alternative dosimetry techniques that could be adopted as measures to improve the reading accuracy for delaminated RCFs. For instance, in a study by Marcos *et al.* [15] for measurements of ultra-superficial doses using delaminated EBT3 RCFs, it was recommended for users to impose a multi-channel RCF calibration as opposed to single-channel RCF calibration to curb the non-uniformities on the uncovered active layer. 2-D adaptive Wiener filter technique was also found to be substantial in minimising the high noise signal caused by film imperfections [11].



Figure 2. Dose-response comparison of original vs. delaminated GAFCHROMICTM EBT3 for (a) Photon 6 MV, (b) Photon 10 MV, (c) Proton 150 MeV, and (d) HDR ¹⁹²Ir source. A total of 264 RCFs were employed, with each dose points comprised of triplicate measurements.

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4. Conclusion

Current findings in this work had demonstrated that the performance of delaminated EBT3 films degrades in opposition to its original form due to the active layer perturbation, which in turn caused poor film reproducibility and more energy dependency. Yet the dose-response behaviour in delaminated films is comparable to the original EBT3 films in terms of its non-linearity. Exploration of new delamination approaches was suggested to produce more reliable and robust delaminated films for prospect usages in dosimetry, on top of stricter RCF handling and better calibration procedures.

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