Technical Note: On GAFChromic EBT-XD film and the lateral response artifact

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Purpose: The new radiochromic film, GAFChromic EBT-XD, contains the same active material, lithium-10,12-pentacosadiynoate, as GAFChromic EBT3, but the crystalline form is different. This work investigates the effect of this change on the well-known lateral response artifact when EBT-XD film is digitized on a flatbed scanner.

Methods: The dose response of a single production lot of EBT-XD was characterized by scanning an unexposed film plus a set of films exposed to doses between 2.5 and 50 Gy using 6 MV photons. To characterize the lateral response artifact, the authors used the unexposed film plus a subset of samples exposed to doses between 20 and 50 Gy. Digital images of these films were acquired at seven discrete lateral locations perpendicular to the scan direction on three Epson 10000XL scanners. Using measurements at the discrete lateral positions, the scanner responses were determined as a function of the lateral position of the film. From the data for each scanner, a set of coefficients were derived whereby measured response values could be corrected to remove the effects of the lateral response artifact. The EBT-XD data were analyzed as in their previous work and compared to results reported for EBT3 in that paper.

Results: For films scanned in the same orientation and having equal responses, the authors found that the lateral response artifact for EBT-XD and EBT3 films was remarkably similar. For both films, the artifact increases with increased net response. However, as EBT-XD is less sensitive than EBT3, a greater exposure dose is required to reach the same net response. On this basis, the lower sensitivity of EBT-XD relative to EBT3 results in less net response change for equal exposure and a reduction in the impact of the lateral response artifact.

Conclusions: The shape of the crystalline active component in EBT-XD and EBT3 does not affect the fundamental existence of the lateral response artifact when the films are digitized on flatbed scanners. Owing its lower sensitivity, EBT-XD film requires higher dose to reach the same response as EBT3, resulting in lesser impact of the lateral response artifact. For doses >10 Gy, the slopes of the EBT-XD red and green channel dose response curves are greater than the corresponding ones for EBT3. For these two reasons, the authors prefer EBT-XD for doses exceeding about 10 Gy. © 2016 American Association of Physicists in Medicine. [<http://dx.doi.org/10.1118/1.4939226>]

Key words: radiochromic film dosimetry, QA, IMRT, radiotherapy, lateral response

1. INTRODUCTION

We recently became aware of the introduction of GAFChromic EBT-XD film. While this radiochromic film (RCF) contains the same active component, lithium-10,12-pentacosadiynoate (LiPCDA) as GAFChromic EBT3, it has been designed to have lower sensitivity, and owing to the greater contrast in dose response at equal exposures, it is claimed to be better suited for measurements where doses exceed 10 Gy.¹ The principal difference between the two films is the size and shape of the crystals of the active component. In EBT3, the needle-like particles are about 1–2 μm in diameter and 15–20 μm in length, while the particles in EBT-XD have a similar diameter but are only about 2–4 μm long. The aspect ratio (width:length) of the particles in the two films is about 1:10 and 1:2. At the time the films are coated, the dynamics

of the coating process induces preferential alignment of the long axis of the particles parallel to the fluid flow. This is somewhat modified by the action of Brownian motion—the random motion of particles suspended in a fluid—in the few seconds before the coating is dried. Nevertheless, the sharp differences in the sizes of the particles in the two films result in a contrast between their properties. The larger particles in EBT3 are less affected by Brownian motion and tend to maintain their alignment of particles with the long axis parallel to the coating direction. However, the smaller particles in EBT-XD film are more affected and tend toward a more random alignment in the dried film.

Upon exposure, the LiPCDA in both films polymerizes to form a colored polymer. Since the EBT3 film exhibits preferential alignment of the LiPCDA particles and chromophores of this type polarize transmitted light,² it is believed that the

shape of the particles in EBT3 influences the lateral response artifact (LRA) of this film. On a flatbed scanner, the polarized transmitted light is guided to the CCD detector by a series of mirrors and a lens. At the lateral center of the scan area, rays are incident normal to the plane of the mirrors, but the angle of incidence increases as the distance from the center increases. As the rays transmitted by EBT3 pass through the optical system, the reflectivities of the mirrors are influenced by the angle of incidence of the polarized light. The consequence is that for equal transmission through films placed at the lateral center and side of the scanner, the detected signal is greater at the center and diminishes toward the side of the scanner. Also, the geometry of the optical system in flatbed scanners results in an increase in the path-length of light through the film toward the lateral edges of the scanner. By the Beer–Lambert Law, this causes transmission to decrease with increasing distance from the center of the scanner, reinforcing the effects caused by polarization.

Owing to the smaller aspect ratio of the particles in EBT-XD, the fluid flow dynamics during coating have less effect on particle alignment. There is an expectation that this will reduce transmitted light polarization relative to EBT3, and for films containing the same amount of polymerized chromophore, the LRA will be reduced. One goal of this work has been to evaluate whether the smaller particles will fundamentally reduce LRA, hopefully to the extent where it could be ignored.

The LRA, exhibited when RCF is digitized on a CCD scanner, has been the subject of recent studies with detailed evaluation of the relationship between the measured response and the lateral location on the scanner.^{3,4} Both papers included descriptions and demonstration of protocols to calibrate scanners and correct for the effect, which stems from the polarization of light transmitted by the film and its consequent interaction with the system of mirrors in the optical train of the scanners.

In RCF dosimetry, it is common to scan film with a CCD scanner, usually a RGB flatbed scanner. The measured responses depend on the position of the film on the scanner, its orientation, and the dose. The lateral position of the film refers to its location measured in the direction perpendicular to the scan direction. The LRA in RCF images from flatbed scanners was pointed out by numerous researchers.^{4–11} Response differences due to lateral film position are small near the center of the scanner, but the measured optical density of a film increases substantially toward the lateral edges of the scan frame. For EBT-XD exposed to 10 and 40 Gy, we measured optical density increases in the red color channel of about 8% and 11%, respectively, between the center and the edge of the scanner. In the green and blue channels, these differences were much smaller. While the effect of LRA is mitigated using multichannel dosimetry,³ errors are potentially significant when films are not laterally centered on the scanner, when the exposed areas-of-interest extend to the lateral edges of the scan window or when the doses are very high, e.g., >10 Gy.

The fundamental causes are twofold. First, RCF scatters a portion of transmitted light. This causes an edge effect due to differences in illumination of the film at the center and edges

of the field. Second, the LRA stems from the polarization of scanner illumination transmitted through RCF.^{12,13} To reach the detector, the transmitted light is reflected from mirrors in the optical path. Owing to the dependence of reflectivity on the angle of incidence on the mirrors, there is less light reaching the detector from film located near the edge of the scan area than from film located in the center of the scan window. Furthermore, as we have observed from the polarized light microscopy of crystals of the active component, the polarization of the transmitted light becomes greater as the film progressively darkens with increased radiation dose. As a result, the magnitude of the response artifact is dependent upon the lateral position of the film on the scan window as well as the dose.

Several approaches have been proposed to correct for the LRA.^{3–11,14} In general, they involved the measurement of some number of films exposed to a range of doses in an attempt to characterize the behavior of the scanner for a single color channel. However, none of the approaches attempts the characterization of a RGB scanner in all three color channels, as is needed to preserve the inherent advantage of triple-channel dosimetry, which is to separate the dose-dependent and dose-independent responses of a RCF image and eliminate the variation of active layer thickness as an error source in dose measurement. It is critical to characterize the LRA in each color channel if the ability to perform accurate triple-channel dosimetry is to be preserved.¹⁵

2. MATERIALS AND METHODS

In this work with EBT-XD film, we employed similar methods used in our prior investigation of the LRA of EBT3 film.⁴

2.A. Film and exposures

A LRA calibration film set composed of an unexposed film plus films exposed to 20, 30, 40, and 50 Gy was scanned at seven discrete lateral locations at a spatial resolution of 50 dpi. The calibration film set came from a single production lot of EBT-XD (01081501) cut into rectangular 4×7 cm² pieces with the long dimension parallel to the long dimension of the original 20.3×25.4 cm² sheets. Samples were exposed at a depth of 5 cm on a Varian Trilogy at the center of a 20×20 cm² open field using 6 MV photons. The output of the Trilogy was calibrated per AAPM TG-51 protocol using an ion chamber calibrated by an ADCL. The dose to water at $d_{\max}$ was set at 1 cGy/MU at 100 cm SAD in water phantom. As described in Sec. 2.B, digital images were obtained in RGB color mode with all color corrections turned off.

Data were acquired with films in both portrait and landscape orientations. By the former, we mean that films were oriented, so the long dimension of the original 20.3×25.5 cm² film sheet was parallel to the scan direction. Landscape orientation applies when the short dimension of the original sheet is parallel to the scan direction. Measurements acquired from this film serve as reference values by means of which the responses in all scans can be brought to a common basis.

To correct for LRA, we used a correction method for each color channel X in which the measured response of a film exposed to dose D and positioned at lateral position L can be related to the response at the center, C , of the scanner,

$$\text{Response}(C,D,X) = A_{L,X} + B_{L,X} \cdot \text{Response}(L,D,X), \quad (1)$$

where the coefficients, $A_{L,X}$ and $B_{L,X}$ are correction coefficients at the given lateral position L . Both $A_{L,X}$ and $B_{L,X}$ are determined from measurements of pairs of films exposed to widely different doses. For convenience, one of those doses was zero. Note that scanner response is a value proportional to light intensity measured at a specific location. In this work, we used the native 16-bit pixel values (0–65 535) provided by the EPSON SCAN software.

To define a calibration function for EBT-XD, a set of films was exposed, using the previously described conditions, to seven doses between 2.5 and 50 Gy. With the addition of an unexposed film, the samples were scanned at the lateral center location of the scanner. Finally, to aid in the demonstration of the LRA correction method, we exposed a $15 \times 15 \text{ cm}^2$ field at the center of several $20.3 \times 25.4 \text{ cm}^2$ EBT-XD films using doses of 10, 20, and 40 Gy and the conditions previously described. These films were scanned at the lateral center location and also at locations where one edge of the film was at the lateral limit of the scan window.

2.B. Tools and software used in this work

In the current work, we collected data using three Epson 10000XL scanners and a single production lot, 01081501, of EBT-XD film. We refer to the scanners as 10000XL #1, 10000XL #2, and 10000XL MSKCC. Paper scales were attached across the scanner to assist in accurately placing films at the desired lateral locations. A 4 mm, clear glass sheet was used atop the films to conform them to the plane of the scanner's glass window. The scanners were operated through EPSON SCAN 3.9 software and image measurements were obtained using FilmQAPro™ 2014 (Ashland, NJ). The films exposed to the $15 \times 15 \text{ cm}^2$ open field were scanned in portrait orientation at the lateral center of the scanner and also at the positions where one edge of the film touched the edge of the scan window. In these cases, the center of the film was close to lateral positions $\pm 5.3 \text{ cm}$.

2.C. Procedure to obtain data for lateral response correction

The process involved creating a set $4 \times 7 \text{ cm}^2$ films exposed to 20, 30, 40, and 50 Gy, plus an unexposed film. Samples were cut from a single $20.3 \times 25.4 \text{ cm}^2$ sheet with the long dimension parallel to the long side of the sheet making it obvious how to orient the small films for scanning. To ease handling, paper templates were cut with openings of $3.5 \times 6 \text{ cm}^2$ behind which the films were taped. The windows in the templates were oriented as needed for portrait and landscape scans. To aid placement of films for scanning, two paper scales marked to indicate lateral locations of -129 , -86 , -43 , 0 ,

43 , 86 , and 129 mm were taped to the scanner's glass window. Position 0 mm was located at the lateral center of the scan window. In addition, a $2 \times 15 \text{ cm}^2$ piece of unexposed EBT-XD was taped at a fixed location on the scanner to serve as a control, or reference film. When included in the scan frame, measurements from this film provide the means for compensating for interscan response variation. A 4 mm glass sheet the same size as the scanner's glass window was placed on top of the films to ensure they were flat and equidistant from the light source.

To avoid the influence of postexposure response changes, films were exposed within about 30 min, while, on a given scanner, a set of scans was obtained within 20 min and at least one week after exposure. Prior to acquiring a set of images, the scanner's light source was warmed up by performing 10 preview scans. Images were collected in positive film transmission mode at a spatial resolution of 50 dpi and a response depth of 16-bits/channel (48 bit RGB color) with all the color correction features in the EPSON SCAN software turned off.

Measurements of film images were made with the FilmQAPro application using a uniform $3 \times 5 \text{ cm}^2$ area-of-interest to record the red, green, and blue responses of the calibration films and a standard $1.5 \times 12 \text{ cm}^2$ area on the control films. Response values were exported to an Excel worksheet, and using the control film measurements, the values of the calibration set were adjusted to compensate for scan-to-scan variability.

The tabulated response values of the unexposed film and the film exposed to the highest dose (50 Gy) were substituted into the relationship in Eq. (1), where $\text{Response}(C,D,X)$ is the response value measured at the central location, C ($y = 0$) for color channel X at dose D and $\text{Response}(L,D,X)$ is the response value of the same film measured at lateral position $y = L$ to determine the values of coefficients $A_{L,X}$ and $B_{L,X}$ for the seven lateral positions at which the films were scanned. The process was repeated for films exposed to doses of 20, 30, and 40 Gy. Values of the coefficients reported in the results section are the average from film measurements at the four doses.

2.D. Correcting an image for the lateral response artifact

At 50 dpi resolution, a full-frame RGB image on a 10000XL scanner consists of 610×860 pixels with response values for each color channel. The lateral direction on the scanner is composed of 610 pixels. The values of the determined coefficients $A_{L,X}$ and $B_{L,X}$ for each color channel of a full-frame image on a particular scanner were set up in an Excel worksheet. A raw image (50 dpi) to be corrected was imported to a second worksheet and the correction coefficients were applied to the RGB response values for pixels at the corresponding lateral location to calculate an image corrected for the effects of LRA. The detailed procedure is described in our previous publication.⁴

2.E. Validation of the LRA methodology

To validate the LRA methodology, we applied the corrections to images of films $20.3 \times 25.4 \text{ cm}^2$ exposed to a

Fig. 1. [(a) and (b)] Correction coefficients as a function of lateral position for 10000XL MSKCC.

15 × 15 cm² open field at doses of 10, 20, and 40 Gy. Each film was scanned in two orientations, e.g., 20.3 cm edge parallel to scan (landscape orientation) and 25.4 cm edge parallel to scan (portrait orientation). Dose maps were calculated using calibration data for film scanned in the corresponding orientation. For films scanned in portrait orientation, the dose maps were calculated for images with and without correction for LRA. In the dose maps from landscape orientation scans, the in-line direction (parallel to the scan direction) is parallel to the 20.3 cm side of the film and dose profile in this direction is unaffected by LRA and provides an appropriate comparison with dose profiles in the lateral direction from films scanned in portrait orientation. After correction for LRA, the lateral dose profile from the portrait orientation scan should be identical to the longitudinal dose profile from the landscape orientation scan.

3. RESULTS

Figures 1(a) and 1(b) compare the lateral correction coefficients $A_{0,L}$ and $B_{0,L}$ for EBT-XD and EBT3 as a function of lateral position for all three color channels on the 10000XL

MSKCC scanner. Films were scanned in portrait orientation. Results for EBT3 are from our previous publication.⁴

Our results showed similar qualitative behavior in landscape orientation, but the correction coefficients are quantitatively different. For this reason, the coefficients for film scanned in one orientation should not be applied to correct the responses for film scanned in a different orientation.

In Figs. 2(a) and 2(b), we show the correction coefficients, $A_{0,L}$ and $B_{0,L}$, for the red color channel for 10000XL #1, #2, and MSKCC as a function of lateral location. We chose not to illustrate the coefficients we measured for the green and blue channels. While there is a broad similarity, there are characteristic differences indicating that the properties of the scanners are unique.

The differences between the coefficients for the red color channel for these scanners make it evident that in most circumstances, the characterization of one scanner could not be applied in the case of second. A similar situation applies to the coefficients for green and blue channels. However, as long as the behavior of a specific scanner has been characterized and correction coefficients for all color channels have been applied to a film image, the effect of LRA can be remedied.

Fig. 2. [(a) and (b)] Correction coefficients for the red color channel of three 10000XL scanners.

FIG. 3. [(a) and (b)] Lateral profiles across open field before and after correction for LRA.

Figures 3(a) and 3(b) show dose profiles, calculated using FilmQAPro software and the triple-channel dosimetry method,¹⁵ before and after correction for LRA. The profiles run in the lateral direction across a 15×15 cm² open field exposed on EBT-XD and scanned at one the extreme lateral position on 10000XL MSKCC. In this instance, the left edge of the film is at the extreme location with the left edge of the exposed area about 2 cm from the edge of the scan window.

In Figs. 4(a) and 4(b), the dose response curves for EBT-XD obtained using the MSKCC scanner are compared to those for EBT3 acquired on the same scanner in our previous study.⁴

4. DISCUSSION

Numerous strategies for dealing with the nonuniform lateral response of flatbed scanners in RCF dosimetry have been reported.^{4-11,14} In the current work, we continued to employ the approach described in our recent publication⁴ on EBT3 film to characterize the LRA of the recently introduced EBT-XD film to compare and contrast the performance of the two films and to demonstrate correction of response values to correct the LRA of EBT-XD.

4.A. LRA correction coefficients: Comparison between EBT-XD and EBT3

One scanner in this study, 10000XL MSKCC, was used with EBT3 film (lot A02181401) in our previous work. It was identified as MSKCC 10000XL.⁴ Figures 1(a) and 1(b) show the correction coefficients for EBT-XD determined in this work compared to those for EBT3. There is a remarkable similarity and it appears as though the coefficients determined for the films might be used interchangeably. To test this, we calculated corrected response values over the range of measured responses for the two films and found that agreement was always within 0.5% and in 90% of instances the agreement was within 0.25%. While the similarity of the films on this scanner is apparent, we advise against any reliance that our finding can be extended to another scanner. Correspondence between the two films must be checked for each scanner.

While the LRA of EBT-XD and EBT3 are essentially identical, it must be clearly stated that this applies to the specific conditions where response values are equal, not to the situation of equal dose to the two films. In Figs. 4(a) and 4(b), our measurements show EBT-XD film to be about four times less sensitive than EBT3. That is, to reach the response values shown by EBT3 film exposed to 10 Gy, an EBT-XD

FIG. 4. [(a) and (b)] Dose response of EBT-XD and EBT3 films.

film would require an exposure dose of about 40 Gy. Note that we restrict the comparison to the red and green responses since these channels contain mainly “dose information” as opposed to “thickness/uniformity information” in the blue channel.¹⁶ For two reasons, the choice of EBT-XD would be a superior for dose measurements >10 Gy. First, the slopes of the response functions for the EBT-XD red and green channels are greater than the corresponding functions for EBT3 at doses >10 Gy. For the red channel of EBT-XD at 10 and 20 Gy, the slopes are >50% and >100% greater respectively than for EBT3. For the green channel at 10 Gy, the slopes of the EBT-XD and EBT3 response functions are equal, while at 20 Gy the slope of the EBT-XD response function is 50% greater. For this reason, EBT-XD should provide more favorable dose uncertainty at doses exceeding 10 Gy. Second, for films exposed to equal doses, the effect of LRA for EBT-XD will be reduced by a factor of about 3 compared to EBT3.

Referring to Figs. 1(a) and 1(b), the strong dependence of the $A_{0,L}$ correction coefficient for the red color channel demonstrates the strong the LRA shown by EBT-XD on the 10000XL #1 scanner. It is apparent that for this film, the net red responses (i.e., the response change due to exposure) are “too high” close to the lateral edges of the scan area. Similar qualitative behavior applies to responses in the green and blue color channels, but the LRA close to the lateral edges of the scanner is much weaker. A brief comparison with the behavior reported for EBT3 on 10000XL scanners shows strong similarity for the two films.

4.B. Dependency of correction coefficients on scanners

In Figs. 2(a) and 2(b), we show that for EBT-XD digitized on three 10000XL scanners, the correction coefficients $A_{0,L}$ and $B_{0,L}$ for the red color channel exhibit the same general characteristics as a function of lateral location. Again this is similar to our observations in the EBT3 study. However, as with EBT3, the differences indicate that the corrections for EBT-XD are unique to each scanner and should not be applied interchangeably. For brevity, we have chosen not to illustrate the coefficients we measured for EBT-XD in the green and blue channels, since the values are again similar scanner-to-scanner, but the quantitative differences show the unique properties of each scanner.

4.C. LRA correction example

To demonstrate the correction of LRA for an EBT-XD film image, we exposed films to a 15×15 cm² open field and scanned them in portrait orientation as described in Sec. 2.B. Using a calibration function for EBT-XD film at the central lateral position in this orientation [Fig. 4(a)], we calculated dose maps of the open fields before and after correcting the image for LRA using the relationship in Eq. (1) to convert measured responses in channel X at lateral position L to the equivalent response at the central location C . The result in Fig. 3(a), for a dose of 20 Gy, shows the extreme effect of LRA

where the left edge of the film was at the edge of the scanner. The rising effect of the increase in net response values further from the center of the scanner is obvious, despite the mitigation of LRA claimed for triple-channel dosimetry.¹⁵ However, after applying corrections, the influence of LRA was almost completely removed as shown in Fig. 3(b). The maximum deviations from the reference measurement (EPIDose) at the same off-axis distance (−7.3 cm relative to the center of the radiation field) before and after the lateral response correction are 24% and 5%, respectively. At this off-axis distance, the dose gradient is large and the superior spatial resolution of film may provide a better representation of the actual dose profile. We could adjust the kernel in the EPIDose physics model slightly wider to make it match the profile of the EBT3 film better in this case.

Two other factors could influence the film profile after correction for the LRA. First, the seven discrete lateral locations at which we made discrete measurements of the LRA were on a rather coarse grid, separated by 4.3 cm. Second, the coefficients at intermediate locations were obtained by linear interpolation. At present, we have not explored fitting the correction coefficients to a smooth function dependent on lateral location as reported by Poppinga.³ As a final check, we scanned the open field film and calibration films in landscape orientation, calculated a dose map of the open field and measured the profile in the direction parallel to the scan where the dose values are unaffected by LRA. This profile and the lateral profile of the film in portrait orientation corrected for the effects of LRA were almost indistinguishable. Similar results were observed for the open field exposures at 10 and 40 Gy.

5. CONCLUSION

Considering EBT-XD and EBT3 film images exhibiting equal response values, we find the LRA for the two products to be substantially indistinguishable. Since the aspect ratio of the particles in the two films is distinctly different, our findings dismiss the prior belief of one of us (DL was formerly responsible for development of the EBT3 product) that the LRA is a function of the needle-like shape of the active component and any preferred orientation of the needle axis parallel to the coating direction.

We also conclude that for EBT-XD and EBT3 with equal exposure, the effect of LRA is markedly less for the former, making it preferred to EBT3 for doses >10 Gy. Nevertheless, a previously published protocol for correcting the LRA in EBT3 film images is applicable to EBT-XD film, and the calibration factors regulating the correction of the measured responses of the two film types appear to be interchangeable.

Despite the preference of using EBT-XD over EBT3 to reduce the impact of LRA at higher doses, it would be wrong to assume that LRA can be ignored. The LRA is a fundamental feature of the digitization of these films on flatbed scanners and their like. When uncorrected, LRA increases measurement uncertainty with increasing dose, especially when the large size of the exposed area on a film makes it inevitable that portions of the field will be located a considerable distance

from the lateral center of the scanner. The user needs to assess the potential impact of LRA on their measurements and justify whether it is negligible and can be ignored.

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