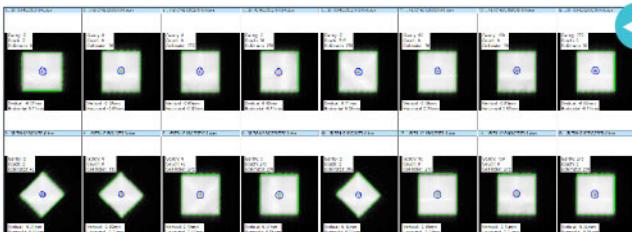


OPTIMIZE YOUR SRS/SBRT QA

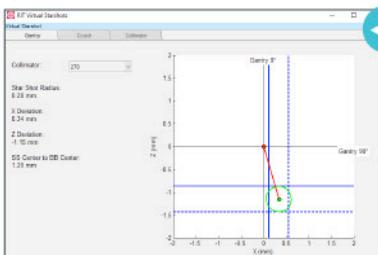
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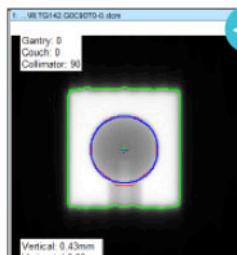


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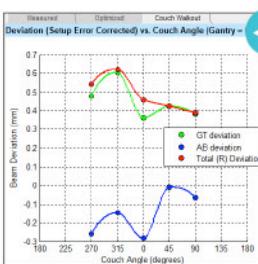


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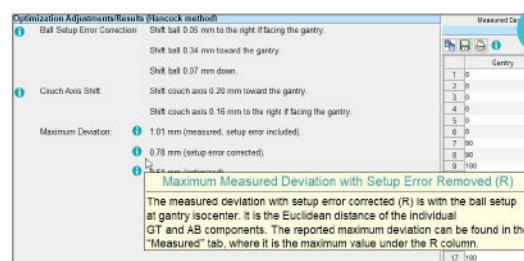
Patents: US 9192784, JP 6009705, CA 2918045, and other international patents pending.



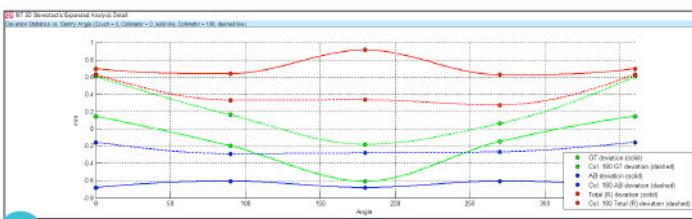
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Correcting lateral response artifacts from flatbed scanners for radiochromic film dosimetry

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Purpose: A known factor affecting the accuracy of radiochromic film dosimetry is the lateral response artifact (LRA) induced by nonuniform response of a flatbed scanner in the direction perpendicular to the scan direction. This work reports a practical solution to eliminate such artifacts for all forms of dose QA.

Methods: EBT3 films from a single production lot (02181401) cut into rectangular $4 \times 5 \text{ cm}^2$ pieces, with the long dimension parallel to the long dimension of the original $20.3 \times 25.4 \text{ cm}^2$ sheets, were exposed at a depth of 5 cm on a Varian Trilogy at the center of a $20 \times 20 \text{ cm}^2$ open field at seven doses between 50 and 1600 cGy using 6 MV photons. These films together with an unexposed film from the same production lot were lined one next to the other on an Epson 10000XL or 11000XL scanner in portrait orientation with their long dimension parallel to the scan direction. Scanned images were then obtained with the line of films positioned at seven discrete lateral locations perpendicular to the scan direction. The process was repeated in landscape orientation and on three other Epson scanners. Data were also collected for three additional production lots of EBT3 film (11051302, 03031401, and 03171403). From measurements at the various lateral positions, the scanner response was determined as a function of the lateral position of the scanned film. For a given color channel X , the response at any lateral position L is related to the response at the center, C , of the scanner by $\text{Response}(C,D,X) = A_{L,X} + B_{L,X} \cdot \text{Response}(L,D,X)$, where D is dose and the coefficients $A_{L,X}$ and $B_{L,X}$ are determined from the film measurements at the center of the scanner and six other discrete lateral positions. The values at intermediate lateral positions were obtained by linear interpolation. The coefficients were determined for the red, green, and blue color channels, preserving the ability to apply triple-channel dosimetry once corrections were applied to compensate for the lateral position response artifact. To validate this method, corrections were applied to several films that were exposed to $15 \times 15 \text{ cm}^2$ open fields and large IMRT and VMAT fields and scanned at the extreme edges of the scan window in addition to the central location. Calibration and response data were used to generate dose maps and perform gamma analysis using single- or triple-channel dosimetry with FilmQAPro 2014 software.

Results: The authors' study found that calibration curves at the different lateral positions could be correlated by a simple two-point rescaling using the response for unexposed film as well as the response of film exposed at high doses between 800 and 1600 cGy. The coefficients $A_{L,X}$ and $B_{L,X}$ for each color channel X were found to be independent of dose at each lateral location L . This made it possible to apply the relationship $\text{Response}(C,D,X) = A_{L,X} + B_{L,X} \cdot \text{Response}(L,D,X)$, to the raw film responses, permitting correction of the response values at any lateral position to an equivalent response, as if that part of the film was located at the center of the scanner. This correction method was validated for several films exposed to open as well as large IMRT and VMAT fields.

Conclusions: The work reported elaborates on the process using the correction procedures to eliminate the lateral response artifact and demonstrates improvements in the accuracy of radiochromic film dosimetry for radiation therapy quality assurance applications. © 2015 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution 3.0 Unported License. [<http://dx.doi.org/10.1111/1.4903758>]

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

1. INTRODUCTION

In radiochromic film dosimetry, it is common to scan film with a CCD scanner, usually a red, green, and blue (RGB) flatbed scanner. The measured responses depend on the position

of the film on the scanner and the dose. The lateral position of the film refers to its location measured in the direction perpendicular to the scan direction. The lateral response artifact (LRA) in radiochromic film images from flatbed scanners was first pointed out by the researchers in 2008.^{1,2} Response

differences due to lateral film position are inconsequential near the center of the scanner, but the measured optical density of a given film increases significantly toward the lateral edges of the scan frame. Furthermore, at a given lateral position, the response differences increase with increasing dose and the differences are particularly acute in the red color channel. While the effect 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., >1000 cGy.

The fundamental causes are twofold. First, radiochromic film scatters a portion of transmitted light. This causes a small edge effect due to differences in illumination of the film at the center and edges of the field. Second, and most acutely, the LRA stems from the polarization of scanner illumination transmitted through Gafchromic film.⁴ 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, the polarization of the transmitted light becomes greater as the film progressively darkens with increased radiation dose.⁵ 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.

A number of approaches have been proposed to correct for the lateral response artifact.^{6–9} In general, they involve 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 an RGB scanner in all three color channels, thus preserving the inherent advantage of triple-channel dosimetry which is to separate the dose-dependent and dose-independent responses of a radiochromic film 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.

A further problem with previous work is that the effect of other response artifacts has not been fully addressed in making measurements. For instance, the inherent variability of the scanner as well as the effect of environmental conditions such as temperature can affect the measured responses for film. Also our experience has been that film response is sensitive to the flatness of the film on the scan window. This is the result of the Callier effect,¹⁰ (i.e., differences in light scattering when film is closer or further away from the light source in the scanner). Without control of these factors, measurement errors can seriously interfere with any attempt to accurately correct for LRA.

Triple-channel dosimetry is a particular advantage offered by Gafchromic films and it is well recognized that flatbed color scanners offer better usability than white-light scanners with these films. Measurements from the red color channel show greater sensitivity at lower doses, while the signal from the green or blue channels provides extension of the dynamic

range of the film to higher doses.^{11–13} Multichannel dosimetry has been shown to have significant advantages over single channel dosimetry by its better dosimetric accuracy.^{3,14,15} In recent publications, Lewis *et al.*¹⁶ raised and Chan *et al.*¹⁷ confirmed the possibility of an investigator publishing a dose-response calibration curve for a given production lot of EBT2 or EBT3 radiochromic film for use, under specified conditions, by a second user at another facility. The requirements for the second user include the use of an Epson flatbed scanner and the adoption of a particular methodology, the “One-scan” protocol,¹⁶ involving the scanning of two reference films together with the QA film to be measured.

In this paper, we report a practical solution to eliminate LRA induced by flatbed scanners in radiochromic film dosimetry for IMRT and VMAT dose QA, especially for the triple-channel dosimetry method. We have found that the correction coefficients needed to compensate for LRA are independent of the production lot of EBT3, implying that a single determination is sufficient for any one scanner.

2. MATERIALS AND METHODS

In this work, we used a Cartesian coordinate system with the origin at the lateral center of the scan window and the start of the scan with *x* and *y* running parallel and perpendicular to the scan direction, respectively. For the purpose of correcting LRA, we define lateral position *L* as the position along the line *y* = *L*. By definition, the center axis of the scan window is along the *x*-axis at lateral position zero (*y* = 0) and the value of *L* can be positive or negative. For Epson 10000XL/11000XL scanner users, we provide the following to further explain our method and results. Figure 1 shows the schematic diagram of the coordinate axes *x* and *y* and the film orientations on the scan window for the group of calibration films. Standing in front of the scanner, the lid opens away from the user with the hinges along the back edge. The scan direction is then from the user’s left to right parallel to the *x*-axis. The lateral position on the scanner is thus measured front-to-back relative

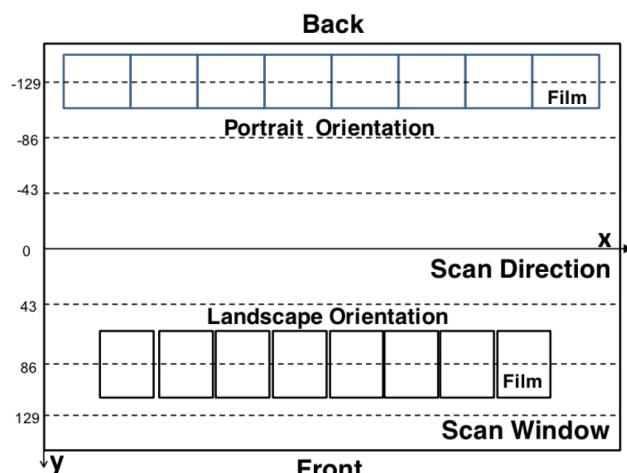


Fig. 1. Schematic diagram of the coordinate axes *x* and *y*, and the film orientations on the scan window for the group of calibration films.

to the central axis ($y = 0$). Negative L is toward the back of the scanner, positive L toward the front. Our convention is to use the “detector’s eye” perspective. The detector’s eye view represents the image presented to the user by Epson Scan software. When the software displays a 10000XL (or 11000XL) image in its native form, the origin is at the middle of the left side of the image with the x -axis horizontal and the y -axis vertical.

To solve the lateral response issue, we have developed 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 is 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 is usually 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.

2.A. Tools and software used in this work

The tools used in this work include three Epson 10000XL and one 11000XL scanners, guillotine type paper cutter, scissors, scalpel or razor blade, $20.3 \times 25.4 \text{ cm}^2$ sheets of EBT3 film (lot 02181401, 11051302, 03031401, and 03171403), paper, adhesive tape, 4 mm thick glass sheet of the same size as the scan window, ruler, and fine felt-tip marker. The software involved includes FilmQAPro™ 2014, Epson Scan Software, and Microsoft Excel. The glass sheet was used to ensure that films were flat and in a plane parallel to the glass window in the scanner.

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

The essential element is to measure a set of calibration films at a number of discrete lateral locations across the scan window using a single scan for each location. To do this, we cut $20.3 \times 25.4 \text{ cm}^2$ sheets of film (from a given production lot) into $10.2 \times 12.7 \text{ cm}^2$ pieces. In the center of each piece, we marked a $4 \times 5 \text{ cm}^2$ area taking care to preserve the relationship of these small rectangular areas to the original $20.3 \times 25.4 \text{ cm}^2$ sheet. This made it easy to know how small and large pieces of film should be oriented for scanning. The $10.2 \times 12.7 \text{ cm}^2$ films were exposed at a depth of 5 cm in a water-equivalent phantom at the center of a $20 \times 20 \text{ cm}^2$ open field at seven doses between 50 and 1600 cGy using 6 MV photons from a linear accelerator (Varian Trilogy). 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. An unirradiated film (zero dose) of the same production lot was kept together with the seven exposed films in a group. To make it easy to

handle film for scanning, the $4 \times 5 \text{ cm}^2$ areas were cut out and using adhesive tape the eight film pieces were mounted in-line, parallel to the 5 cm edge on the film, on a paper template in which open areas of about $3.5 \times 4.5 \text{ cm}^2$ had been cut. Care was taken to avoid the adhesive tape encroaching upon the open window area. Paper scales were attached to the scan window of the scanner close to the start and end of the scan. This facilitated positioning the set of films for scanning in portrait orientation at specific lateral locations. We used the following lateral positions in our work: -129, -86, -43, 0, 43, 86, and 129 mm. A schematic diagram for the placement of the set of calibration films scanned in portrait orientation at a lateral location, e.g., $L = -129 \text{ mm}$, is shown in Fig. 1. Finally, one or more control films were attached in fixed locations on the scanner. Pieces of unexposed or exposed EBT3 film are suitable for this purpose and provide a means for compensating for interscan response variability.

In our work, the film exposures spanned about 30 min and at least 40 h elapsed before films were scanned ensuring that any effects of postexposure change were negligible.¹⁶ Prior to scanning, the light source in the scanner was warmed up by conducting ten preview scans before digitizing the calibration films at the various lateral locations. A piece of 4 mm glass sheet was placed on top of the films to ensure all samples were flat and equidistant from the light source. This glass sheet also covered the optical calibration window, the area about $2 \times 31 \text{ cm}^2$ where the scan starts and where the intensity of the light source is briefly calibrated before each scan. 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 color) with all color correction features in the Epson Scan software turned off. Using the film images at the various lateral locations, the FilmQAPro application was used to acquire the response values for RGB channels of each calibration film measured within a uniform area-of-interest about $3 \times 4 \text{ cm}^2$. In addition, the response values within a standard area of the control films were measured. Response values were exported to an Excel worksheet and based on the values measured for each particular control film, the response values of the calibration films in that same image 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 (1600 cGy) were then 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 the coefficients $A_{L,X}$ and $B_{L,X}$ for the seven lateral positions at which the films were scanned. The set of values of $A_{L,X}$ and $B_{L,X}$ determined this way were then substituted back into Eq. (1) to see if they can be applied to the data for the six intermediate doses between 0 and 1600 cGy at a specific lateral position L for color channel X . Having determined the values of the coefficients at the seven discrete locations, the values at intermediate lateral locations were obtained by linear interpolation. The procedure described above was repeated with the calibration films scanned in landscape orientation as shown in Fig. 1.

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

On an Epson 10000XL/11000XL scanner, a full-frame RGB digital film image at 50 dpi consists of 610×860 pixels with response values for each color channel. The lateral direction (y -axis) coincides with the short dimension of an image spanning 610 pixels. The values of the determined coefficients $A_{L,X}$ and $B_{L,X}$ for each color channel of a full-frame image were set up in an Excel worksheet. The matrix of values represents an array of correction coefficients for application to compensate the raw response of a scanned image for the effect of LRA. We restricted our work to images at 50 dpi, the same spatial resolution as the correction matrix. To apply a correction for LRA, it is necessary to know the lateral location of the image relative to the correction matrix. This is trivial for a full-frame image, but for a partial-frame image the lateral location of one edge of the image must be known. When the Epson Scan software is operated through the FilmQAPro dosimetry application, the position of any partial-frame image is always recorded and available. Once an RGB image with the same spatial resolution as the correction matrix had been exported to an Excel spreadsheet, a pixel-by-pixel adjustment of response values was made using the correction matrix and the refined image was imported back into the FilmQAPro application for further analysis.

As a matter of practice, the as-scanned full-frame (610 \times 860 pixel) images were cropped before applying the correction matrix. Without this, the image files were too large to be handled in Microsoft Excel. As a consequence, the uncorrected and corrected images are of different sizes creating an apparent anomaly in the profile plots [e.g., Figs. 8(c) and 8(d)] of pairs of uncorrected/corrected images from the FilmQAPro application. However, the differences should not be interpreted as indicating that the profiles are at different locations across the exposed field.

2.D. Determine correction coefficients for four film production lots and four scanners

An investigation was made to determine if correction of the lateral response artifact can be made using the correction matrix derived from measurements made on different lots of EBT3 film. To that end samples from three additional production lots 11051302, 03031401, and 03171403 (i.e., in addition to lot 02181401 previously described) were obtained and a series of exposures were made over a range of doses from 0 to 1600 cGy. As shown previously, these calibration films were scanned at 50 dpi at the same seven discrete lateral locations of Ashland 10000XL #1 scanner. A control film was used to assess the scan-to-scan variability and corrections to the responses were made to compensate for the observed differences. Data from the films exposed to zero and 1600 cGy were then used to calculate the correction coefficients A and B for each color channel and each film lot at the seven discrete locations. The above described procedure was also performed for the EBT3 film lot 02181401 for three 10000XL and one 11000XL scanners to study the dependency of the correction coefficients on scanners. The 11000XL is Epson's replacement for the

10000XL discontinued in early 2013. Epson's published specifications for these two scanner models are identical.

2.E. Validation of the LRA methodology

In order to validate the LRA methodology, we applied the corrections to several films that were exposed to a 15×15 cm 2 open field, a head and neck IMRT plan, and a lung SBRT VMAT plan. Dose profiles were plotted and Gamma analysis of the IMRT and VMAT cases was performed, comparing single-channel and triple-channel dosimetry before and after the LRA correction.

2.E.1. 15×15 cm 2 open field

A 20.3×25.4 cm 2 film, exposed to a central dose of about 200 cGy in a 15×15 cm 2 open field, 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). Calibration data for the film production lot were obtained in both orientations and the dose profile in the lateral direction for portrait orientation was compared with the dose profile in the scan direction for landscape orientation. In this way, the same profile on the film was being measured, but the doses (triple-channel dosimetry was applied) were calculated from response data obtained by scanning in the appropriate corresponding orientation. To emphasize LRA, the film was also scanned in portrait orientation in the extreme lateral positions to the front and back of the scan window. Again the lateral profiles were obtained from the dose maps before and after applying corrections for LRA.

2.E.2. Clinical head and neck IMRT case

A seven-field H&N IMRT plan was used with maximum dose of 172 cGy in the plane of interest. The exposed area was about 20×20 cm 2 , extending to the edges of a 20.3×25.4 cm 2 sheet of film (lot #02181401). Much of the film close to the edges was exposed to doses more than 100 cGy. This example provides for a good demonstration of LRA and its correction because many of the dose values near the edge of this film were $>50\%$ of the maximum value. Doses of this magnitude, when artificially increased by LRA, would tend to fail in a gamma value assessment based on the global maximum. By contrast, a plan with a smaller exposed area, or much lower peripheral doses (relative to the maximum) would provide a weaker test, since the lateral response artifact tends to be small near the center of a scanner and/or for low doses. These conditions tend to render the differences invisible even with evaluation criteria of 2%/2 mm, let alone the commonly used values of 3%/3 mm that have drawn recent criticism.^{18–21} This is shown by using the seven-field IMRT film described, together with reference films (exposures zero and 200 cGy) to obtain images on the four scanners. All films were scanned in portrait orientation in the central location, i.e., the centers of the exposed areas were located at lateral position ($y = 0$). Calibration functions were established by scanning the same set of calibration films on each scanner. Dose maps and dose consistency maps were

calculated with and without correcting the measured responses for lateral position on the scanner.

Prior to exposure of the IMRT film, it had been marked with pin-pricks to indicate its placement relative to the in-line and transverse axes of the treatment system. Use was made of these marks by employing the FilmQAPro software to automatically align the dose maps with the treatment plan. While the highest passing rates in a gamma test evaluation might not be provided in this manner, this automated alignment provides an objective way of evaluating the performance on each scanner.

2.E.3. Clinical lung SBRT VMAT case

A VMAT lung treatment with maximum dose 890 cGy was used for these measurements and analyses. Film from one production lot, 02181401, was exposed with the plan. Calibration films from the same production lot were used to establish a calibration function for the central, reference position. The exposed VMAT film was placed at the lateral center position and scanned in portrait orientation with two reference films (0 and 800 cGy exposures) at 50 dpi using Ashland 10000XL #1 scanner. However, while the reference films were always scanned at the central location, the VMAT application film was also positioned to the extreme back of the scan window. In this location, the center of the VMAT field was about 5 cm from the back of edge of the scanner. In addition to compensating for LRA by applying the correction matrix for the 02181401 film lot, corrected images were also calculated using correction coefficients obtained for three other production lots (11051302, 03031401, and 03171403).

3. RESULTS

3.A. Dependency of correction coefficient on lateral positions

The calibration curves in Fig. 2 depict the fitting of dose-response data for the red color channel measured for EBT3 film (lot 02181401) at various lateral positions on Ashland Epson 10000XL #1 scanner and scanned in portrait orientation. To avoid ambiguity, as the lateral artifact is approximately symmetric, only responses at the center and back side of the scan window are shown. The LRA is very obvious with the net responses (i.e., the response change due to exposure) being “too high” close to the lateral limits of the available scan area. Note also that the magnitude of the artifact increases with dose. The situation in the green and blue color channels is similar except that the response artifact is notably less pronounced.

Dose and response values can be correlated using an asymptotic function such as

$$R(D) = a + \frac{b}{c - D}, \quad (2)$$

where D is dose, $R(D)$ is response, and a , b , and c are coefficients to be determined.

The values of $A_{L,X}$ and $B_{L,X}$ determined based on the responses of the two films exposed with 0 and 1600 cGy were found to be also applicable to the films with the six intermediate

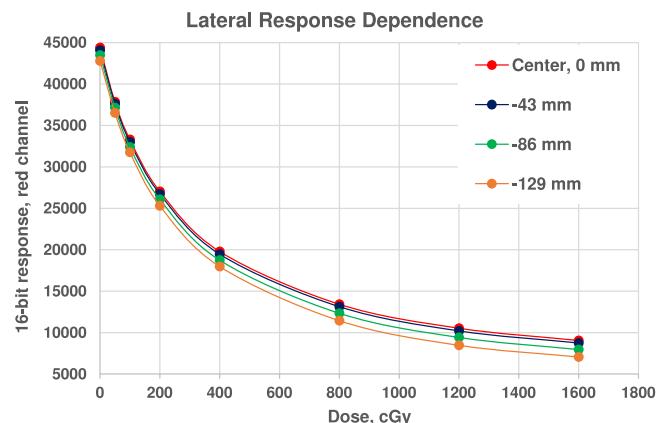


FIG. 2. Dose-response curves at different lateral positions for red color channel for EBT3 film (lot 02181401) scanned with Ashland 10000XL #1 scanner.

doses. In other words, the coefficients $A_{L,X}$ and $B_{L,X}$ were found to be substantially independent of dose for a specific lateral location L and given color channel X . The relationship between the values of the coefficients A and B for the red, green, blue color channels, and lateral position L is shown in Figs. 3(a) and 3(b).

By applying coefficients A and B for specific lateral positions to response values at the corresponding locations, a compensation for the lateral response artifact can be made. An example depicting a plot of the corrected response values for the calibration films is shown in Fig. 4. For any dose, the maximum variance of the corrected values is <0.4% and in most cases <0.2%. From repeated measurements of single films, we established that the standard deviation for measurement of a single film was about 0.17% and concluded that the close correspondence of corrected values is within our measurement uncertainty.

3.B. Dependency of correction coefficients on film production lots

In this section, we present results to show that correction for the lateral response artifact is independent of the production lot of EBT3 film. The values of the coefficients for the red color channel are plotted in Figs. 5(a) and 5(b).

As a test, corrected response values for doses between zero and 1600 cGy were calculated using the coefficients for the four film lots and all seven discrete lateral locations. The results showed good consistency. For the same raw (uncorrected) response value measured at the same lateral location, the corrected response values using the four sets of correction coefficients were in a tight band around the average. As evidenced by the histogram in Fig. 6, in more than 97% of cases, the corrected response values determined using the correction coefficients for the four lots were within 0.4% of one another.

Re-scanning and measurement of a single film showed the variability of response measurement was about 0.17% and we believe that the differences in the corrected response values for the four film lots are most likely due to measurement

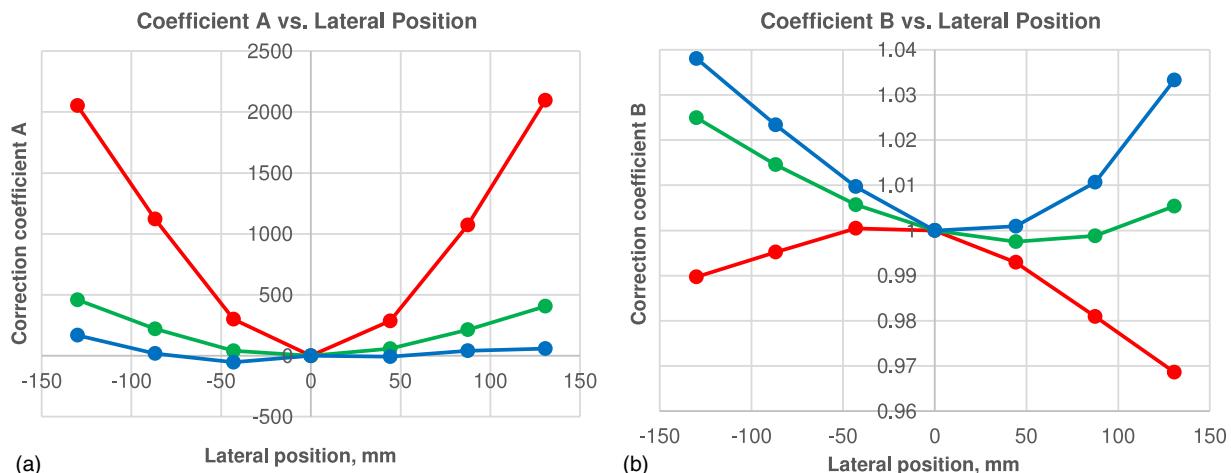


Fig. 3. (a) and (b) Values of coefficients A and B for the red, green, and blue color channels for EBT3 film (lot 02181401) scanned with Ashland 10000XL #1 scanner.

uncertainty. Measurements from additional film production lots would be advisable to confirm this expectation.

Parallel results were obtained for the responses from the green and blue color channels. The magnitude of the corrections to the green channel responses is much less than for the red color channel. The corrections in the blue color channel are smaller again.

3.C. Dependency of correction coefficients on scanners

Figures 7(a) and 7(b) depict the values of coefficients A and B for the red color channel for EBT3 lot 02181401 on four different scanners—three Epson 10000XL and an Epson 11000XL.

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.

3.D. 15 × 15 cm² open field

The profiles are shown in Figs. 8(a) and 8(b), respectively. Measurements parallel to the scan direction [Fig. 8(b)] provide an accurate representation of the actual dose profile as the responses along this path are being measured with the same parts of the CCD sensor array and the transmitted signal is being transported through the same parts of the optical system. The effect of LRA is evident from the disparity between the doses in the color channels toward the edge of the field when measuring perpendicular to the scan [Fig. 8(a)]. Using single, red channel dosimetry, the dose profile perpendicular to the scan direction is shown in Fig. 8(c). The marked asymmetry is not unusual for a scanner of this type, but the results demonstrate that triple-channel dosimetry mitigates, yet does not eliminate LRA. After applying the correction matrix to the raw response data, the dose maps were recalculated. Figures 8(d) and 8(e) show how the LRA corrections have repaired the over-response and channel-to-channel consistency of the profiles in the lateral direction.

Again the lateral profiles were obtained from the dose maps before and after applying corrections for LRA as shown in Figs. 8(f) and 8(g), respectively. The close similarity between the corrected lateral profiles [Fig. 8(g)] and the scan-direction profiles [Fig. 8(b)] establishes the validity of the correction procedure. The increased noise on the lateral profiles probably reflects the small variability between individual elements in the CCD sensor that run in this direction. Small residual differences between the dose values in the three-color channels are probably due to a combination of measurement uncertainty and the use of linear interpolation between discrete lateral locations rather than a smooth fitting function. Figures 8(a)–8(g) are the screenshots from the FilmQAPro application. In reference to the profile path data appearing in the header of each figure, please note the explanation provided at the end of Sec. 2.C. The information on the position of the dose profiles in

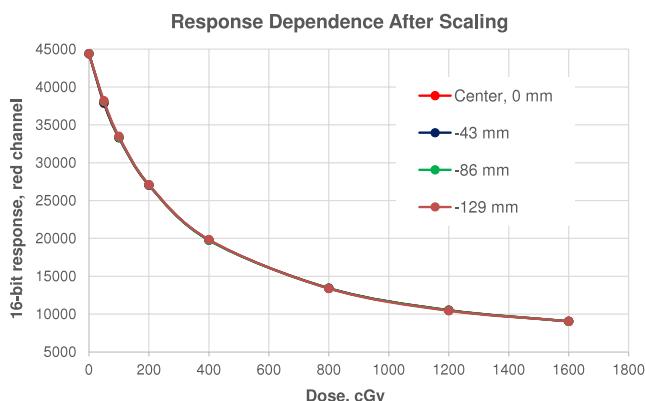


Fig. 4. Corrected dose-response curves at different lateral positions for red color channel for EBT3 film (lot 02181401) scanned with Ashland 10000XL #1 scanner.

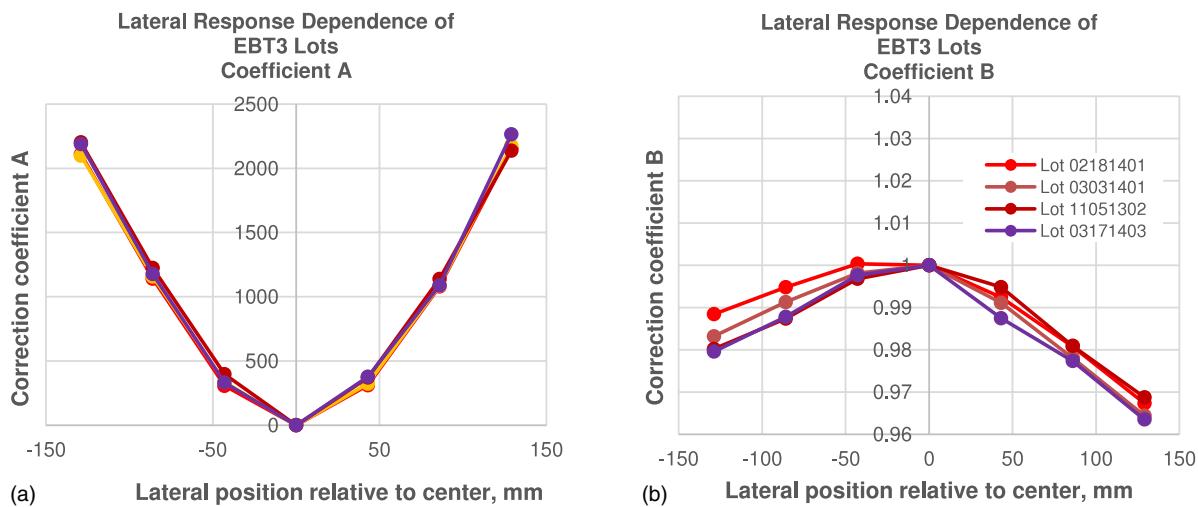


FIG. 5. (a) and (b) Values of coefficients A and B for the red color channel on four different film lots using Ashland 10000XL #1 scanner.

the header above the plots in Figs. 8(a)–8(g) refers to location in uncorrected/corrected images having different sizes. The differences should not be read as the profiles being at different locations across the $15 \times 15 \text{ cm}^2$ exposed field. Note also that the X, Y axes of the profile path in the header do not correspond to the x, y axes used to describe image acquisition (see Fig. 1) and LRA correction. The X and Y axes are correlated to the y and x axes, respectively.

The scan orientation, we chose for this report, corresponds to the “portrait” orientation—long dimension of the original $20.3 \times 25.4 \text{ cm}^2$ film parallel to the scan direction. For brevity, we chose not to report in detail here on the LRA for “landscape” orientation. While the effects are qualitatively similar, the LRA differs quantitatively for portrait and landscape orientations. The determined coefficients for film in one orientation should not be applied to correct an image from film scanned in a different orientation.

3.E. Clinical head and neck IMRT case

3.E.1. Comparing four scanners

Results summarized in Table I show the gamma passing rates for the red color channel and the dose consistencies before and after correcting the response values for LRA while

using triple-channel dosimetry. Dose consistency is a measure of the dose agreement between the color channels and is calculated by the FilmQAPro application at the same time as the dose map. Ideal consistency is zero indicating that the dose measurements are exactly the same in all color channels. Poorer consistency is associated with greater dose differences. Table I shows the range of consistency values in the exposed film area as well as the average value. One might be tempted to base an evaluation solely on the percentage of pixels passing a gamma test, but this ignores a major advantage of triple-channel dosimetry in providing a result for each color channel. Dose values close together yield confidence, while poor consistency is a marker of uncertainty in the result. A case in point is the result for the 11000XL scanner before correcting the lateral responses. It may be tempting to go no further than the 96% gamma passing rate at 3%/3 mm/10% TH. However, with average dose consistency of 4.6 cGy and values ranging from 1 to 10 cGy for a case in which the maximum dose is 172 cGy, the high dose consistency values indicate an issue with the measurements.

Further indication of a problem before corrections are applied can be seen in the dose profiles across the full width of the film as presented in Secs. 3.E.2.a and 3.E.2.b. The behavior highlights disagreements between measurements (thin lines)

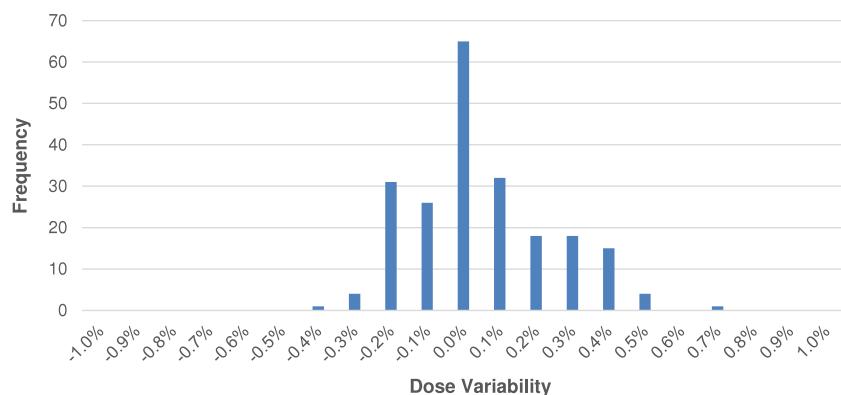


FIG. 6. Histogram of dose variability for four EBT3 film lots.

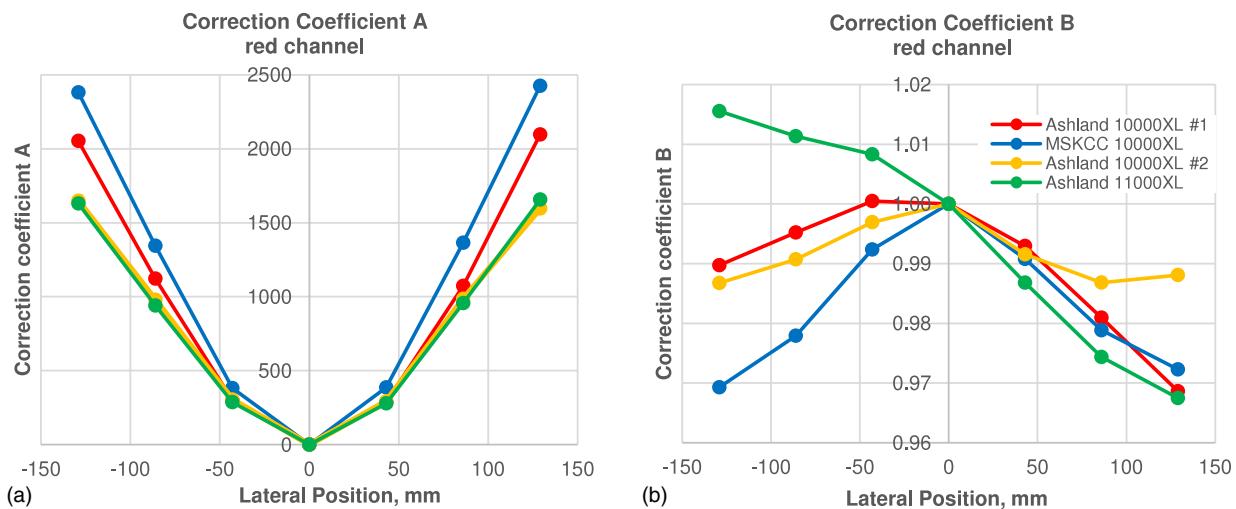


FIG. 7. (a) and (b) Values of coefficients A and B for EBT3 film lot 02181401 for the red color channel on four different scanners.

and plan (thick line) toward the sides of the scan area as well as sharp dose discrepancies between the values in different color channels. The proximate cause is an acute and asymmetric LRA for this scanner (Ashland 11000XL) further indicated by the large and unequal spread of the values of correction coefficient B as shown in Fig. 7(b). The root cause is speculative at present, but could be related to the light source in the scanner, the CCD detector, or the optical components. Further study would be required to identify the source.

3.E.2. Comparing single-channel and triple-channel dosimetries before and after correction

In this work, the film was scanned in portrait orientation at the center of the Epson 11000XL scanner with one unexposed reference film and a second exposed at 200 cGy. We chose this scanner because it exhibited the strongest LRA [see Fig. 7(b)], providing the most striking challenge to the correction protocol. Figures 9(a), 10(a), 11(a), and 12(a) in Subsections 3.E.2.a and 3.E.2.b plot selected profiles across dose map images overlaid over plan images. Information in the headers relates to the total length and position of the profile path in the overlay. Because the dose map images are smaller than the plan image, only that portion of the profile just less than 200 mm long and lying within the edges of the film (width 203 mm) is plotted in each figure.

3.E.2.a. Single (red) channel dosimetry before and after correction. The purpose of calculation and comparison to plan using single channel dosimetry is twofold. First to demonstrate the compensation for the lateral position response artifact, but more importantly to highlight that significant miscalculation of a treatment plan may occur when using single, red channel dosimetry (as opposed to triple-channel dosimetry) without consideration of LRA. This test case might frequently pass evaluation because nearly 92% of pixels meet a 3%/3 mm global gamma criteria with a dose threshold of >10% (10% TH) of the maximum. But this evaluation hides the significant discrepancies in measurement vs plan near the edges of the film as shown by the profile in Fig. 9(a). The thick red line

represents plan and the thin line represents the measurements. Measured doses are 5%–10% greater than plan near the left edge. The red areas near the left edge of the dose-difference map [Fig. 9(b)] highlight the problem. Making an evaluation based only on the gamma passing rate is inadequate. Using 2%/2 mm test criteria make the discrepancy more obvious in that the passing rate falls to around 76%, but it has not solved the problem.

With compensation for LRA applied to the raw red channel response values and the dose map recalculated a dramatic improvement result and >99% of pixels meets the 3%/3 mm global gamma criteria. The dose profile and dose-difference map [Figs. 10(a) and 10(b)] show obvious improvement on the left side, but there are small discrepancies on the right hand side. Using red channel dosimetry 2%/2 mm, 10% TH criteria >92% of pixels match to the plan, but unless triple-channel dosimetry is applied, the effects of nonuniformities seen on the right side of the dose map are not accounted for and the dosimetry is not optimized.

3.E.2.b. Triple-channel dosimetry before and after correction. Use of triple-channel dosimetry compensates the measured response for thickness differences in EBT3 radiochromic film and as shown previously it also mitigates, but does not eliminate, the LRA. In this example, the triple-channel protocol increases the passing rate at 3%/3 mm, 10% TH from 92% for single channel dosimetry to >97%. Although this is an improvement, the results in Figs. 11(a) and 11(b) illustrate that only partial relief has been provided, not a complete refinement. Close to the left edge, the measured doses (thin lines) are still 5% greater than plan (thick line). In addition, there is a considerable difference between the red, green, and blue dose values away from the center of the scanner. With stricter evaluation criteria of 2%/2 mm, 10% TH the effect of the discrepancies due to LRA becomes more obvious as the passing rate decreases to about 86%.

However, when the raw responses are corrected for LRA and then triple-channel dosimetry is applied, there is a very positive improvement in passing rates. Not only is this seen in the profiles where the red channel measurement (thin red line)

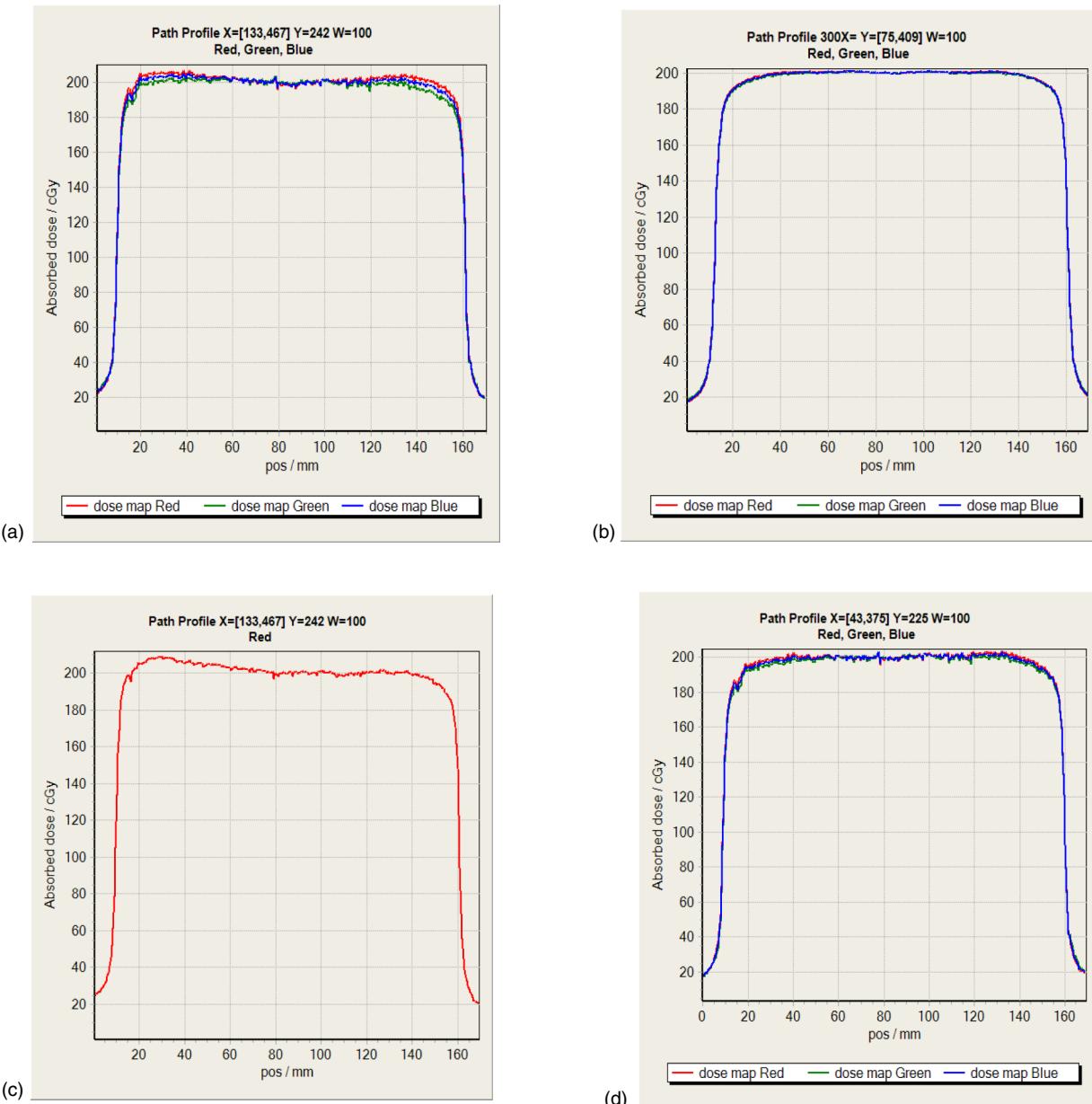


Fig. 8. (a) Dose profiles perpendicular to scan direction using triple-channel dosimetry before LRA correction. (b) Dose profiles parallel to scan direction using triple-channel dosimetry. (c) Dose profile perpendicular to scan direction using red-channel dosimetry before LRA correction. (d) Dose profiles perpendicular to scan direction using triple-channel dosimetry after LRA correction. (e) Dose profile perpendicular to scan direction using red-channel dosimetry after LRA correction. (f) Dose profiles perpendicular to scan direction at extreme lateral position using triple-channel dosimetry before LRA correction. (g) Dose profiles perpendicular to scan direction at extreme lateral position using triple-channel dosimetry after LRA correction.

closely matches the plan (thick line) and in the dose-difference map [Figs. 12(a) and 12(b)], but gamma analysis shows 99.6% of pixels passing at 3%/3 mm, 10% TH and 96% passing with 2%/2 mm, 10% TH criteria.

More striking examples may be had by displacing the IMRT film to the edges of the scan window and obtaining images in those locations. While the correct protocol would be to scan film in the central location, scanning film at an extreme lateral position provides the severest test of the correction protocol. Before applying corrections to compensate for LRA, we observed dose disagreements up to 18% high within about 4 cm of the edge of the scan window and the gamma passing rates were <70% at 3%/3 mm and <60% at 2%/2 mm. After

applying corrections to compensate LRA, the dose differences at the lateral edges fell to less than 2% and gamma passing rates were >99.5% for 3%/3 mm, 10% TH and >93% for 2%/2 mm, 10% TH.

3.F. Clinical lung SBRT VMAT SBRT case

3.F.1. VMAT film scanned at extreme lateral position

This film, described in Sec. 2.E.3, was scanned at an extreme lateral position on the Ashland Epson 10000XL #1 scanner. While the correct protocol is to place films centrally, the high dose applied to this film (>800 cGy) coupled with the side

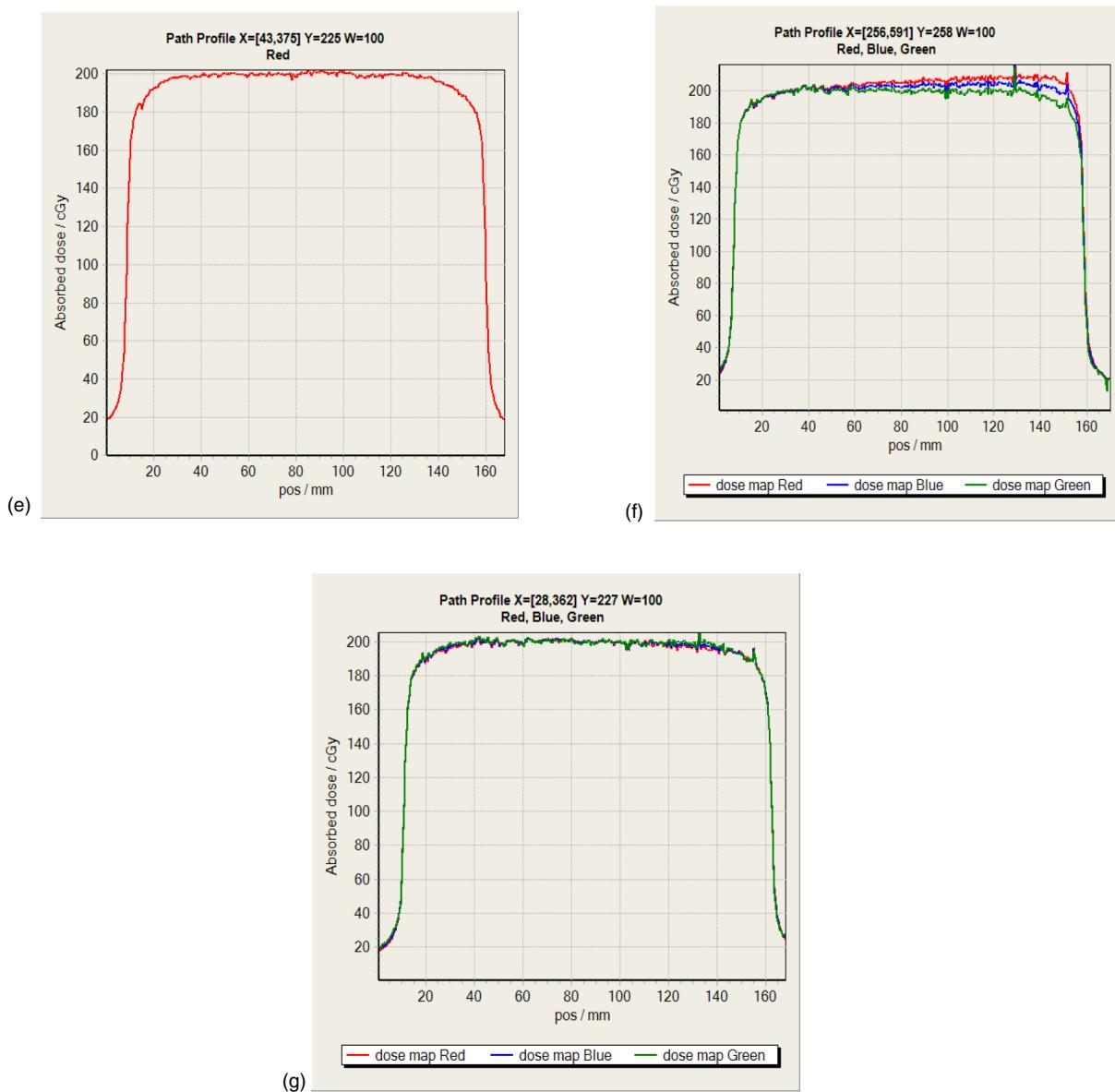


FIG. 8. (continued.)

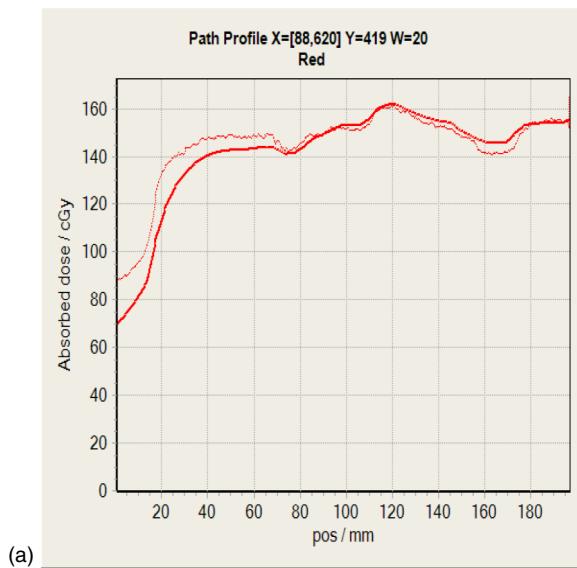
placement provided the opportunity for clearly demonstrating the value of LRA correction. With the film scanned in this position where the center of the exposed area was about 6 cm from the edge of the scanner, the lateral response artifact was very evident [Fig. 13(a)] as the measured dose in the red color channel was 4% higher than in the green or blue channels. Note that these figures plot a selected profile across a dose map

image overlaid on a plan image. Information in the headers relates to the total length and position of the profile path in the overlay. Only the 9.5 cm portion of the total profile covering the exposed area on the film is plotted in each figure.

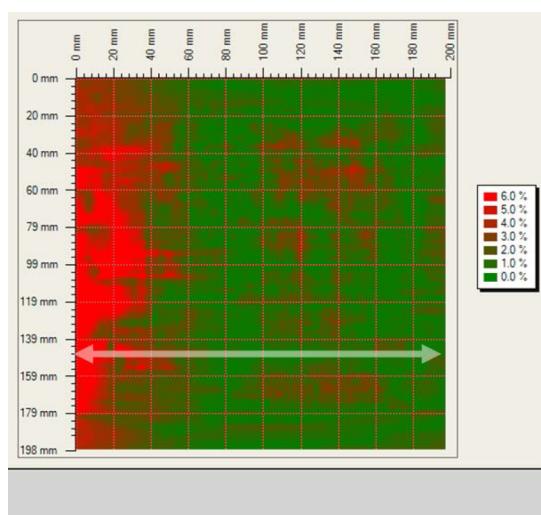
The average inconsistency in dose measurement over the area exposed to doses >100 cGy was about 11.8 cGy and in areas closest to the edge of the scan window—the location

TABLE I. Dose consistency within the exposed film area before and after LRA correction.

Scanner	No correction for lateral response		With correction for lateral response	
	Γ test, % passing, 2%/2 mm, 10% TH	Dose consistency range (cGy) [mean (cGy)]	Γ test, % passing, 2%/2 mm, 10% TH	Dose consistency range (cGy) [mean (cGy)]
Ashland 10000XL #1	77.0	1–6 (3.4)	94.2	1–3 (1.8)
MSKCC 10000XL	74.3	1–8 (5.3)	94.8	1–3 (2.1)
Ashland 10000XL #2	75.6	1–4 (2.9)	93.9	1–3 (1.5)
Ashland 11000XL	80.1	1–10 (4.6)	94.5	1–5 (2.9)



(a)



(b)

FIG. 9. (a) Red-channel dose profile vs plan (pre-LRA correction). (b) Red-channel dose-difference map (pre-LRA correction)—white line shows profile location.

from the edge is at about 10 mm—the differences exceeded 30 cGy.

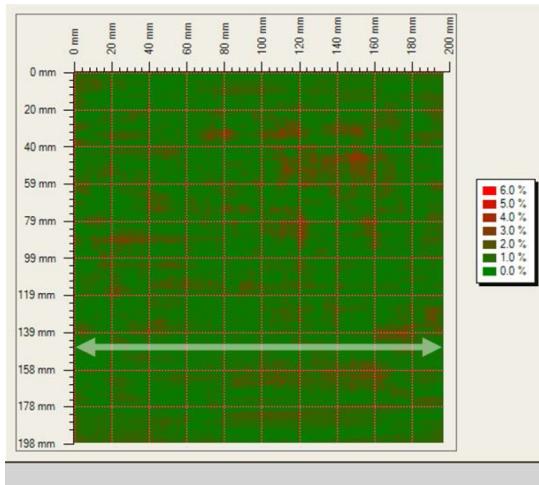
Using the correction factors for the same production lot (02181401), a refinement was made to the VMAT film image to compensate for the lateral response artifact. The dose map was recalculated and the dose profile was measured at the same area as before [Fig. 13(b)]. This time, the doses in the three channels were in close agreement and the average consistency in the exposed area was about 4.1 cGy. The largest interchannel dose differences were about 6 cGy. This result demonstrates the improvement provided by correcting for the lateral response artifact.

3.F.2. Comparing the use of correction coefficients for four different film lots

Results for all four production lots are presented in Table II in the form of gamma function passing rates with 2%/3 mm, 10% TH test criteria. In each case, there is a similar improve-



(a)



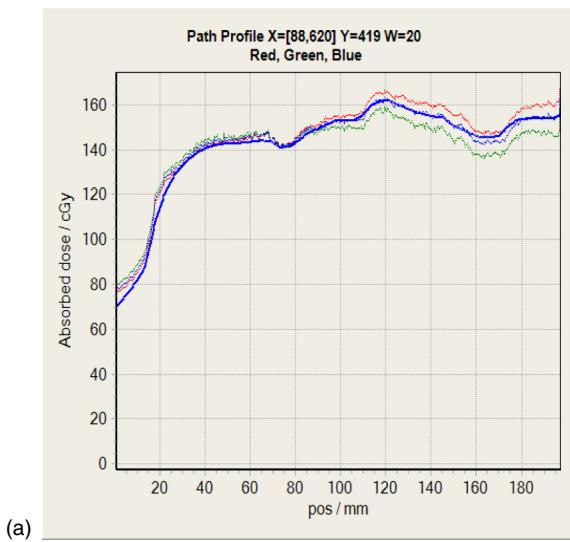
(b)

FIG. 10. (a) Red-channel dose profile (post-LRA correction). (b) Red-channel dose-difference map (post-LRA correction)—white line shows profile location.

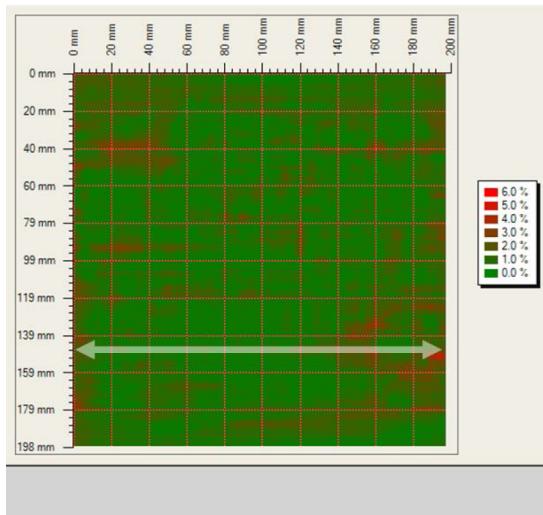
ment in the over-response in the red color channel leading to consistent gain in the passing rates. Moreover, the dose consistency between the color channels has been enhanced reproducibly as evidenced by similar percentages of pixels in all color channels that meet the test criteria. These findings confirm that corrections for the lateral response artifact are independent of film production lot. We propose the possibility of characterizing correction coefficients for a given scanner using any lot of EBT3 film, and speculate that the corrections are unique for each scanner dependent on the characteristic of the light source, detector, and other optical elements in the equipment.

4. DISCUSSION

Precautions and strategies dealing with nonuniform response of flatbed scanners in radiochromic film dosimetry have been reported extensively. Chung *et al.*²² presented a



(a)

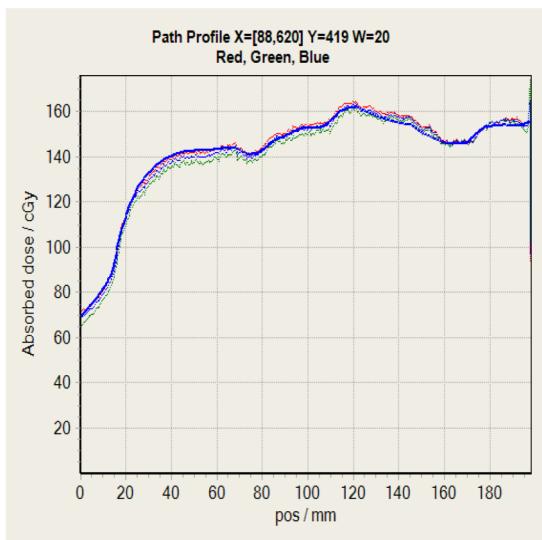


(b)

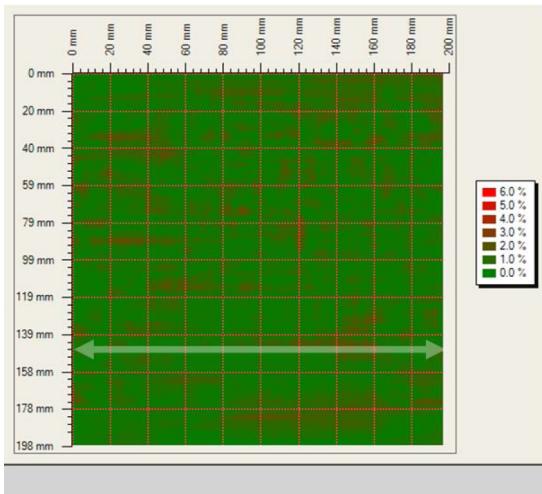
FIG. 11. (a) Triple-channel dose profiles (pre-LRA correction). (b) Triple-channel dose-difference map (pre-LRA correction)—white line shows profile location.

study of the use of EBT film digitized with Epson 1680 and 10000XL scanners retrofitted with light-diffusing glass to minimize the effects of Newton rings. Without particular scanner nonuniformity effect corrections or significant postscan image processing, they could achieve reasonably high pass rates with 3%/3 mm gamma criteria. Therefore, they suggested that no significant scanner nonuniformity correction was necessary for accurate absolute dosimetry using EBT films for field sizes smaller than or equal to $15 \times 15 \text{ cm}^2$.

Paelinck *et al.* studied the possible drift, warm-up effects, direct physical influence of the scanner light, and scan field uniformity using an Epson Pro 1680 scanner using EBT film.⁷ They found that the use of a correction matrix was necessary to correct for the nonuniform scanner response over the scan field. Subtracting the optical density of the unirradiated blank film from the irradiated film improves the precision of the Gafchromic EBT film. The scanner was examined as a densitometer using red color channel 2D film dosimetry. The



(a)



(b)

FIG. 12. (a) Triple-channel dose profile (post-LRA correction). (b) Triple-channel dose-difference map (post-LRA correction)—white line shows profile location.

validation was done using percent depth dose (PDD) and beam profiles measured by film against the diamond detector (PTW, Freiburg, Germany).^{23,24}

Chang *et al.*⁹ also presented a PDD method that can accurately calibrate EBT2 film together with the scanner nonuniformity correction on an Epson 10000XL scanner at doses up to 320 cGy. After the postirradiated scan, the net optical densities on the beam central axis on the films were autoextracted and compared with the corresponding depth doses that were calculated through the measurement of a 0.65 cm^3 farmer chamber and the related PDD table to perform the curve fitting. For scanner nonuniformity calibration, the cross-beam profiles of the film were analyzed by referencing the measured profiles from a Profiler™ (Sun Nuclear Corp., Melbourne, FL). The fitting uncertainty was less than 0.5% due to the many calibration points, and the overall calibration uncertainty was within 3% for doses above 50 cGy, when the average of four films was used for calibration purpose.

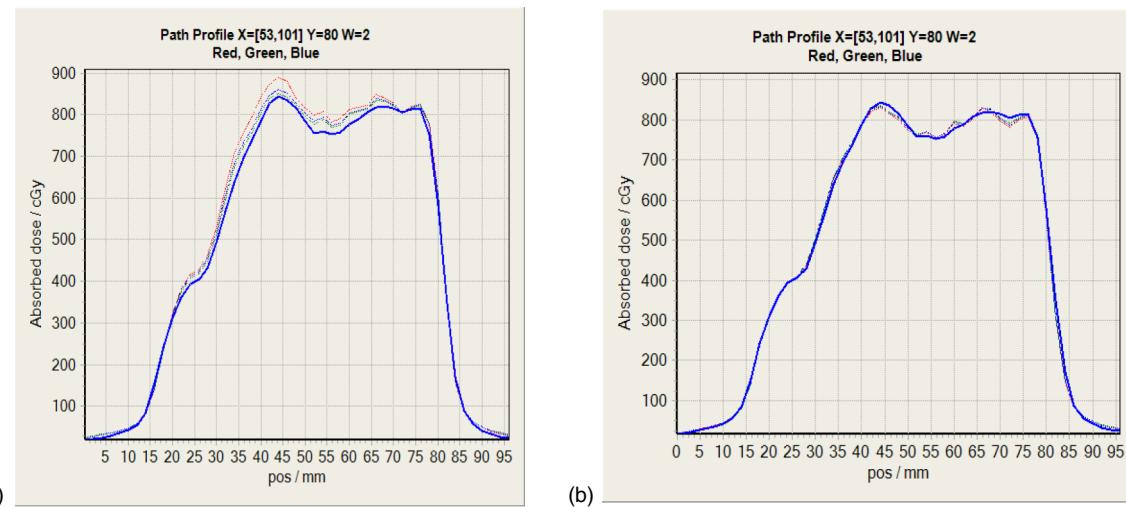


FIG. 13. (a) and (b) Triple-channel dose profiles at extreme lateral position before and after correction for LRA. The thick blue line represents plan.

In addition, their study found that the nonuniformity calibration was independent of the given dose for the EBT2 film and the relative dose differences between the profiles measured by the film and the Profiler were within 1.5% after applying the nonuniformity correction. Their conclusion of the lateral correction being dose-independent is in contrast to our observations.

Butson *et al.*⁸ reported a method for increasing the uniformity for the analysis of radiochromic films on an Epson V700 using reflectance scanning in combination with a matt, white backing material instead of the conventional gloss scanner finish. The authors raised the possibility of eliminating the need to perform scanner corrections for position on the flatbed scanners for radiochromic film dosimetry.

Poppinga *et al.* recently developed an algorithm to correct the lateral scanner artifact (parabola effect) using EBT3 films on an Epson 10000XL scanner.⁶ Any optical density measured at given position x is transformed into the equivalent optical density c at the apex of the parabola and then converted into the corresponding dose via the calibration of c vs dose. This correction method has been validated up to doses of 520 cGy within the entire region of the scanner bed with 2D dose distributions of an open square photon field and an IMRT distribution. However, their study used only one single lot of EBT3 film on a single flatbed scanner with single channel (red color) dosimetry.

In our study, we have used four different film lots and four different flatbed scanners to validate the correction method in

all three-color channels for various doses up to 1600 cGy. Our method is especially designed for use with triple-channel film dosimetry to compensate for the LRA by measuring a single set of calibration films at known locations on the scanner. This approach gets around the problem of providing large, uniform, and uniformly exposed pieces of film to characterize the LRA at all locations in parallel. Our experience has been that providing such films is an overwhelming task. Taking care to compensate for the scan-to-scan variability of the scanner as well as ensuring films were flat on the scanner to neutralize possible measurement uncertainties caused by the Callier effect, we used the measurement data to determine correction coefficients specific to each lateral location. While the correction coefficients are applied to raw response data, the image is corrected as though the entire film was located at the reference position at the center of the scan window. In principle, films with just two different doses are required and one of those could be an unexposed film, e.g., zero dose. If the second film was exposed to a dose D , the correction coefficients could be applied to image data for any film exposed to a dose between zero and D as a linear scaling. In our testing, we have observed that compensation for the lateral response artifact is independent of the production lot of the EBT3 film. As a result, correction of the LRA for a particular scanner should be possible from measurements of a single lot of EBT3 film on that specific scanner. This concept has been demonstrated using measurements obtained from four lots of EBT3 film; however, further confirmation is advisable.

TABLE II. Passing rates on the same VMAT image with LRA correction for four film lots.

Production lot of dose map film	Production lot used to determine lateral response correction	Red channel Gamma pass rate, 2%/3 mm, 10% TH	Green channel Gamma pass rate, 2%/3 mm, 10% TH	Blue channel Gamma pass rate, 2%/3 mm, 10% TH
EBT3 02181401	No correction	89.7%	94.2%	92.4%
EBT3 02181401	EBT3 02181401	97.2%	96.9%	97.3%
EBT3 02181401	EBT3 03031401	97.3%	96.9%	97.3%
EBT3 02181401	EBT3 11051302	96.2%	97.4%	96.9%
EBT3 02181401	EBT3 03171403	97.3%	97.1%	97.4%

5. CONCLUSION

The methodology developed in this work provides a technique to solve the lateral response issues in radiochromic film dosimetry. While the correction coefficients needed to correct the lateral response artifact are independent of the film production lot and independent of dose, they are dependent on the scanner used for the radiochromic film dosimetry. Since users need only one-time measurement to establish the necessary correction coefficients for a specific scanner, this process could be considered as part of the commissioning process of the flatbed scanner for film dosimetry validation. Thereby, implementation of LRA correction improves the accuracy of radiochromic film dosimetry in patient-specific IMRT and VMAT dose QA in radiotherapy.

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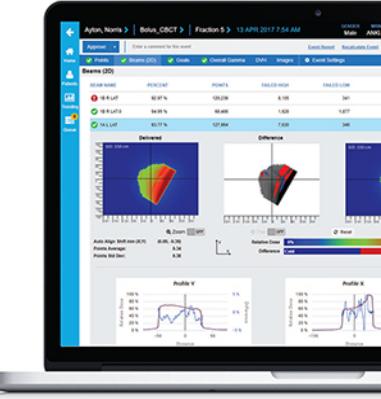


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