Multichannel film dosimetry with nonuniformity correction

Andre Micke,[a] David F. Lewis, and Xiang Yu
International Specialty Products, 1361 Alps Road, Wayne, New Jersey 07470

(Received 13 August 2010; revised 24 February 2011; accepted for publication 22 March 2011; published 2 May 2011)

Purpose: A new method to evaluate radiochromic film dosimetry data scanned in multiple color channels is presented. This work was undertaken to demonstrate that the multichannel method is fundamentally superior to the traditional single channel method. The multichannel method allows for the separation and removal of the nondose-dependent portions of a film image leaving a residual image that is dependent only on absorbed dose.
Methods: Radiochromic films were exposed to 10×10 cm radiation fields (Co-60 and 6 MV) at doses up to about 300 cGy. The films were scanned in red–blue–green (RGB) format on a flatbed color scanner and measured to build calibration tables relating the absorbed dose to the response of the film in each of the color channels. Film images were converted to dose maps using two methods. The first method used the response from a single color channel and the second method used the response from all three color channels. The multichannel method allows for the separation of the scanned signal into one part that is dose-dependent and another part that is dose-independent and enables the correction of a variety of disturbances in the digitized image including nonuniformities in the active coating on the radiochromic film as well as scanner related artifacts. The fundamental mathematics of the two methods is described and the dose maps calculated from film images using the two methods are compared and analyzed.
Results: The multichannel dosimetry method was shown to be an effective way to separate out nondose-dependent abnormalities from radiochromic dosimetry film images. The process was shown to remove disturbances in the scanned images caused by nonhomogeneity of the radiochromic film and artifacts caused by the scanner and to improve the integrity of the dose information. Multichannel dosimetry also reduces random noise in the dose images and mitigates scanner-related artifacts such as lateral position dependence. In providing an ability to calculate dose maps from data in all the color channels the multichannel method provides the ability to examine the agreement between the color channels. Furthermore, when using calibration data to convert RGB film images to dose using the new method, poor correspondence between the dose calculations for the three color channels provides an important indication that the this new technique enables easy indication in case the dose and calibration films are curve mismatched. The method permit compensation for thickness nonuniformities in the film, increases the signal to noise level, mitigates the lateral dose-dependency of flatbed scanners effect of the calculated dose map and extends the evaluable dose range to 10 cGy-100 Gy.
Conclusions: Multichannel dosimetry with radiochromic film like Gafchromic® EBT2 is shown to have significant advantages over single channel dosimetry. It is recommended that the dosimetry protocols described be implemented when using this radiochromic film to ensure the best data integrity and dosimetric accuracy.
[DOI: 10.1118/1.3576105]

Key words: multichannel, dosimetry, Gafchromic® EBT2, thickness compensation

I. INTRODUCTION

Advanced techniques in radiotherapy, like intensity modulated radiotherapy (IMRT) offer dose delivery targeted for specific lesions. While such advances have provided great success in reducing dose to healthy tissue and shortened treatment time, they have constantly increased the complexity of treatment planning and delivery and increased the demand for quality assurance. Film dosimetry using radiochromic film like Gafchromic® EBT is a common tool to verify the dose distribution of intensity-modulated radiation treatment plans and for general quality assurance of treatment planning systems and linear accelerators. Due to its high spatial resolution, weak energy dependence[1–3] and near-tissue equivalence[4] radiochromic film has a suitable characteristics for complex treatment dose verification.[5,10] Since Gafchromic® radiochromic films produce colored images when exposed to radiation, it has long been known that multichannel flatbed scanners offer better usability than white-light scanners. A multichannel scanner provides a choice of colors for scanning and this has been useful in offering the selection of the red color channel for greater sensitivity at lower doses, yet being able to extend the dynamic range of the film to much higher doses using the green of blue channels.[6–9,13]

However, a number of investigators[11,12,14,15,21] have pointed to challenges in radiochromic film dosimetry, particularly those related to the scanning of the radiochromic film. To date, radiochromic film dosimetry has relied on the use of information from a single color channel of an red–blue–green (RGB) scanner. The signal thus provided is relatively weaker at equal dose to that obtained when using a conventional silver film. Also, when RGB color scanners are used to digitize radiochromic film, the images may suffer from an artifact that causes film density values to increase as the lateral distance from the scan axis increases.[16,19] While the effect is relatively minor at low doses (<100 cGy) and positions within about 5–7 cm of the scan axis, it can create significant overestimate of higher doses, particularly as film position approaches the lateral edges of the scan area. Other investigators have questioned the suitability of EBT2 film for dosimetry application owing to errors from multiple sources including thickness artifacts in the radiochromic film coating,[17] but their dosimetry method utilizes only the data from a single color channel. The work presented in this paper describes a superior approach using data from all the color channels to separate the nondose-dependent artifacts due to film and scanner from the dosimetric result.

This paper describes a novel approach to film dosimetry using a colored radiochromic film and an RGB flatbed color scanner. Since the radiochromic film provides a different response in each of the three color channels, and particularly because the slopes of the color response vs dose response curves are different in each color channel, this new multichannel approach to dosimetry enables scanned film images to be separated into two parts—one part that is dose-dependent and one part that is independent of dose. The dose-independent part of the image contains information related to thickness, or other response differences in the film coating as well as to scanner artifacts, including noise, and to some effects caused by dust particles on the scanner. Having separated the dose-independent part of the scan information, the remaining dose-dependent information constituting the dose map has higher fidelity and becomes more useful to the user for the purposes of the dosimetry.

II. MATERIALS AND METHODS

II.A. Radiochromic film and irradiation procedure

The film used in this study was Gafchromic® EBT2 with sheet dimensions of 20.3×25.4 cm^2. The film was handled according to the procedures described in the (AAPM) task group 55 report. Exposure to light was minimized by keeping the films in black envelopes when they were not being handled for exposure or scanning. Several different sources were employed to irradiate the sets of films used for this work. This included irradiation with a Co-60 source in an AECL Theratron T-780 as well as irradiation with 6 MV photons on Varian linear accelerators. For exposures the film was placed in a phantom composed of 30×30 cm sheets of solid water or polystyrene with 5 cm of the build-up material above and below the film. The source-to-surface distance was 100 cm. Exposure of film for dose calibration was performed with 10×10 cm fields, and the film perpendicular to the axis of the beam. Depending on the source, sets of calibration films were generated using between eight and ten discrete exposures to doses ranging from about 20 cGy to about 250 or 300 cGy. One film was used for each dose level. Measurement and analysis of film sets exposed with the two radiation sources were kept separate.

Similar solid water or polystyrene phantoms were used for the exposure of films to IMRT treatment fields. Patient IMRT films were placed at a depth of 5 cm in the phantom and exposed in clinical mode to the full dose by all fields of the treatment plans. Films were scribed with pen-marks prior to irradiation to indicate the positions of the cross-hairs of the Linac at 0° gantry angle. Depending on the treatment plan the maximum doses delivered to the film were in the range from about 200 cGy to about 250 cGy.

II.B. Scanners and scanning

The films were scanned and digitized with an Epson expression 10000XL or an Epson V700 flatbed color scanner. It is well known that radiochromic films like the EBT2 film undergo postexposure changes. Data sets obtained with the two scanners were kept separate for the subsequent analysis. That is to say the films continue to darken after exposure, although the rate diminishes rapidly with time. To account for the postexposure changes all films within a set of calibration films were scanned within a time window of less than 10 min and at least 24 h after exposure. Under these circumstances errors due to time-after-exposure differences can be neglected. When IMRT images were obtained for analysis the images were obtained within 10 min of the calibration film images and at least 24 h after exposure data was collected from change in the films. The scanners were fitted with transparency adapters and the images were acquired in transmission mode. RGB positive images were collected at a depth of 16 bits per color channel and a spatial resolution of 72 dpi. Scanning was conducted through the Epson scan driver for each model of scanner. Software settings were chosen to disable all color correction options and thereby deliver the raw scanner data without any photographic enhancements. This choice is critical because it prevents the scan data from being altered to present an image optimized for display by adjusting the color balance and exposure.

It is well known that the scan response of EBT2 radiochromic is sensitive to the orientation of the film on the scanner.[19] Therefore the orientation of the film in each image was recorded. In the subsequent measurement and analysis of the calibration film and IMRT film images care was taken not to mix film images acquired in different orientations. It has also been established that the scanner response of radiochromic films like the EBT2 film is sensitive to the position of the film on the scanner relative to the scan axis. That is the lateral position on the scanner in the direction perpendicular to the scan direction and relative to the center of the scanner. This so called lateral artifact is position dependent and dose-dependent. At doses less than about 200 cGy and positions within about 5 cm of the scan axis the lateral artifact is less

than about 2%, but is increasingly important at higher doses and further away from the central axis of the scanner parallel to the scan direction. To minimize the effect of the lateral artifact films were positioned along the central axis for scanning.

One advantage of the triple-channel dosimetry method described in Subsections II C–II F is that it substantially corrects the lateral artifact. To provide data illustrating this behavior some scans were made by deliberately positioning the film to one side of the scan window away from the scan axis and close to the edge of the window.

II.C. Image measurement and analysis

Scanned images were measured using Film QA Pro software. Calibration films exposed with 10×10 cm fields were measured by defining an area of interest approximately 6×6 cm in size at the center of the field. Data was obtained for the red, green, and blue color channels at a resolution of 16 bits per channel. The images are defined as positive images where black (no observed signal)—white (maximum signal) range is mapped to [0, 65 535].

Data and image analysis such as conversion of images from scanner space to dose space and measurement of film profiles and was also performed with the Film QA Pro software. This application has a utility for calculating dose images using single, dual, or triple-channel dosimetry as described in the following Subsections II D–II F. It also provides the ability to separate film images into portions that are either dose-dependent or dose-independent. This is also described in the following Subsections II E–II F.

Calibration data correlating film response to dose for each of the three color channels was fit to analytical functions described as rational functions. In terms of optical density d_X at dose D and wavelength X, these functions take the form $d_x = -\log((a_X + b_X D)/(c_X + D))$ therein a_X, b_X, and c_X are the constants to be fitted. Rational functions have already the correct steady state limit case behavior for very high dose values D.

II.D. Single channel film dosimetry method

Radiochromic films, such as Gafchromic® EBT2 develop a colored image upon exposure to radiation. The inherent color of the image indicates that the optical absorption of the exposed film varies by wavelength.[18] The process of dosimetry with such a film involves a number of steps including: exposing the film to radiation; scanning the film to determine the optical density d_X over one or more spectral color bands of different wavelength X and using the dose-optical density response information for each color channel to convert the scanned image into its dose equivalent (dose mapping).

One of the ways to determine the optical density d_X is through the use of a color flatbed scanner. This is an image digitization device that measures film response over wavelength bands corresponding to the red (R), green (G), and blue (B) bands of the visible spectrum. The scanned optical density is defined as

$$d_X = -\log(X), \tag{1}$$

therein $X\varepsilon$ [0,1] stands for the normalized color channel stipulated by the output of the scanner. The color channel value X depends on scanner coordinates (i,j), i.e., $X = X_{ij}$ reflects the optical density of the film at coordinates (x_i, y_j).

The dose mapping process is recognized as a nonlinear process and its conversion parameters are determined in a calibration process using areas of film (calibration patches) exposed to known doses of radiation. A sufficient number of homogeneously exposed calibration patches are scanned to generate a calibration table $\{D_i, d_X(D_i)\}$, $1 = 1(1)L$, where L is the number of scanned calibration patches.

In accordance with the Beer–Lambert Law, the scanned optical density value $d_X(D)$ at any point is inversely proportional to some dimensionless measure τ of the thickness of the active layer coated on the film

$$d_X(D) = d_X^D(D)\tau \tag{2}$$

where the quantity $d_X^D(D)$ is independent of relative thickness τ and varies only with the exposure D. It is easy to directly verify that the model Eq. (2) fulfills the limit cases

$$\lim_{\tau \to 0} X(D) = 1 \tag{3}$$

i.e., film is fully transparent for zero thickness and

$$\lim_{\tau \to \infty} X(D) = 0 \tag{4}$$

i.e., film is fully opaque for infinite thickness.

When averaging density values $d_X(D)$ across the homogeneously exposed film region one finds that

$$d_X(D) = \frac{1}{N}\sum_{i,j} d_X^D(D)\tau = d_X^D(D)\bar{\tau}, \tag{5}$$

where $\bar{\tau}$ stands for the average film thickness with

$$\bar{\tau} = \frac{1}{N}\sum_{i,j} \tau. \tag{6}$$

and N is the number of pixels used in the averaging process.

The commonly used method to determine a dose value D from a density value scanned on a film utilizes a single color channel X only. The dose is determined as

$$D = \bar{d}_X^{-1}\left(d_X \frac{\tau}{\bar{\tau}}\right). \tag{7}$$

Assuming that $\tau/\tau \equiv 1$, i.e., active layer is perfectly uniform, Eq. (7) becomes

$$D = \bar{d}_X^{-1}(d_X). \tag{8}$$

The calibration function $\bar{d}_X$ is determined by correlating a calibration table $\{D_i, \bar{d}_X(D)_i\}$, $1 = 1(1)L$. Members of one class of functions used to correlate values in the calibration table are known as rational functions. In terms of optical density such functions take the form

$$\bar{d}_X(D) = -\log\left(\frac{a + bD}{c + D}\right), \tag{9}$$

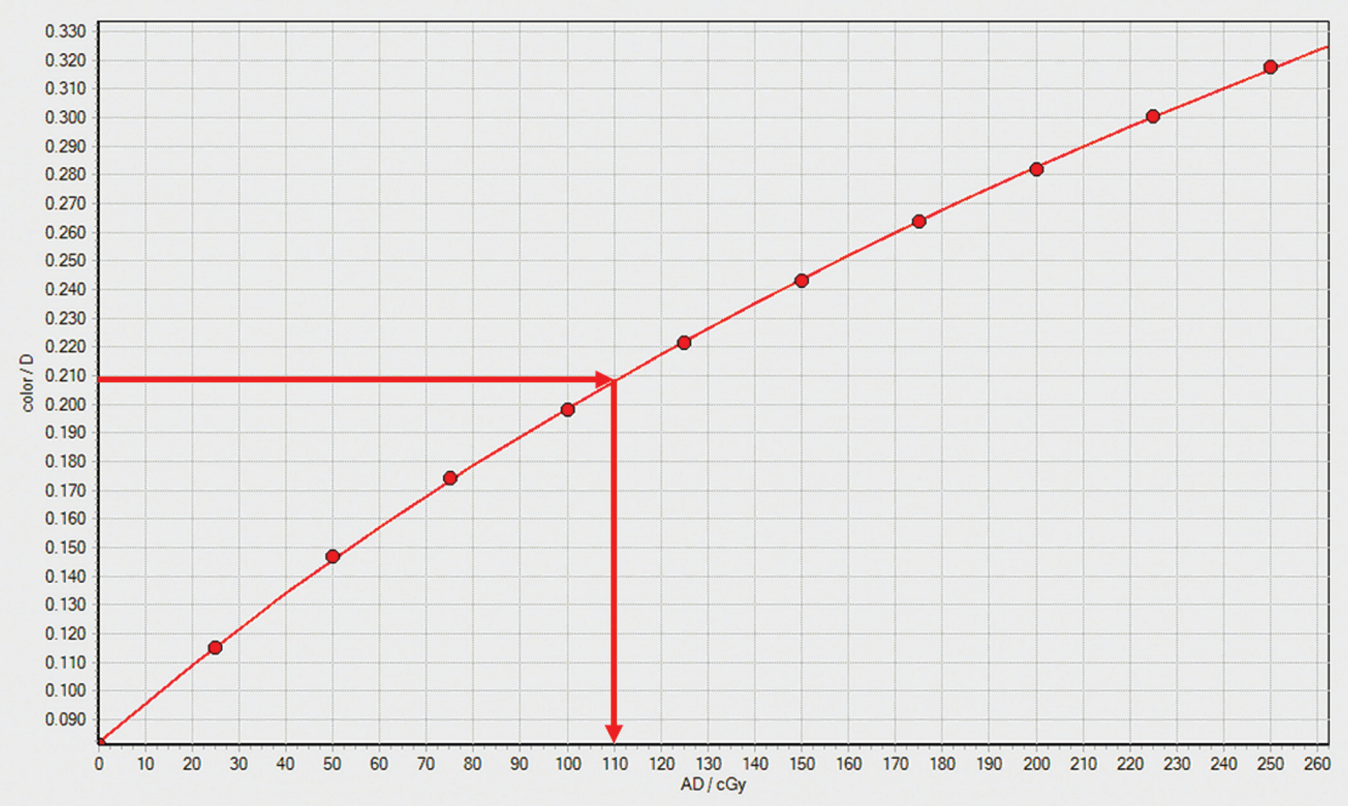

FIG. 1. Single channel calibration curve and data flow of dose mapping using Eq. (8).

where a, b, and c are the equation parameters to be fitted. Figure 1 shows an example of a calibration curve for Gafchromic® EBT2 film as determined from the red color channel image from an Epson 10000XL scanner. The calibration table and correlated function parameters are given in Table I. In this example the density values are derived from the 16-bit scanner response values, the pixel values $PV_x(D)$, with $x = \mathrm{R}, \mathrm{G}, \mathrm{B}$, and the channel values X in Eq. (1) become

$$X(D) = \left(\frac{PV_x(D)}{65535}\right). \tag{10}$$

TABLE I. EBT2 @ Epson 10000XL calibration table and correlated function parameters for R, G, and B.

D/cGy	d_R	d_G	d_B
250	0.31776	0.26153	0.56340
225	0.30324	0.25026	0.55564
200	0.28148	0.23533	0.54572
175	0.26510	0.22176	0.53753
150	0.24328	0.20905	0.53208
125	0.22144	0.19456	0.52267
100	0.19799	0.17914	0.51279
75	0.17431	0.16398	0.50556
50	0.14685	0.14811	0.49630
25	0.11521	0.13128	0.48812
0	0.08137	0.11710	0.47790
a_X	2.22726	5.22144	3.01197
b_X	0.10730	−0.05009	0.06079
c_X	2.68937	6.81595	9.04245

The single channel approach is robust in the sense that for any scanned optical density d_X a corresponding dose value D can be calculated. However, if the density value is disturbed by the dimensionless amount Δd_X (e.g., because of variation of the thickness τ of the film coating or because of a scanner nonlinearity like the lateral distortion) one obtains a corresponding disturbance ΔD of the dose value with

$$D(1+\Delta D) = \bar{d}_X^{-1}(d_X(1+\Delta d_X)), \tag{11}$$

This appears directly as error of the dose value D and provides no indication of the discrepancy.

II.E. Dual channel film dosimetry method

From Eq. (7) it is clear-cut that picking two scanning wave lengths, i.e., two color channels X_1 and X_2, results in a system of two equations and two variables: dose D and relative thickness $\tau/\tau_{\frac{\tau}{\tau}}$.

$$\begin{aligned} D &= \bar{d}_{X_1}^{-1}\left(d_{X_1}\frac{\tau}{\bar{\tau}}\right) \\ D &= \bar{d}_{X_2}^{-1}\left(d_{X_2}\frac{\tau}{\bar{\tau}}\right) \end{aligned} \tag{12}$$

and requires the calibration functions $\bar{d}_{X_1}$ and $\bar{d}_{X_2}$ of the selected color channels. This equation system can be separated to obtain

$$D = \bar{d}_{X_1}^{-1}\left(\frac{d_{X_1}}{d_{X-1}}\bar{d}_{X_2}(D)\right) \tag{13}$$

and

$$\frac{\tau}{\bar{\tau}} = \frac{\bar{d}^{(D)}_{X_{1/2}}}{d_{X_{1/2}}} \tag{14}$$

which requires only the solution of a single nonlinear equation and evaluation of the explicit Eq. (14) for one of the color channels employed.

This method works optimally for low exposures of EBT2 film by selecting $X_1 = R$ and $X_2 = B$ and using the blue channel to evaluate Eq. (14). If the exposure is low enough the density recorded in the blue channel becomes insensitive to dose, i.e., $\bar{d}_B(D) \approx \bar{d}^0_B = \bar{d}_B(0)$, and Eq. (13) becomes

$$D = \bar{d}^{-1}_R\left(\bar{d}^0_B \frac{d_R}{d_B}\right) = \bar{d}^{-1}_{R/B}\left(\frac{d_R}{d_B}\right) \tag{15}$$

which calculates the dose D as a function of the ratio of the responses in the red and blue color channels. The foregoing is equivalent to calibrating dose D vs color channel ratio $d_R/d_B = 1$ d_R/d_B as proposed in Ref. 8 p.10, as reference channel method.

Note that if the dose value D is known (using any procedure), it is still possible to use Eq. (14) to calculate the relative layer thickness τ/τ using the calibration function of an additional channel. However, the limiting single channel dosimetry case results in $\tau/\tau = 1$, and it is not possible to separate the dose map into its dose-dependent and dose-independent parts.

The dual channel dose mapping can account for signal disturbances caused by thickness variations and the like, but the results may depend on the exposure range used. Equation (13) is not symmetric with respect to the chosen color channels. The method will work best for low exposures of EBT2 film less than about 10 Gy when $X_1 = R$ and $X_2 = B$, and for high exposures greater than about 30 Gy when $X_1 = B$ and $X_2 = R$. In the latter case the film response in the red channel approaches saturation and the term $\bar{d}_R$ is dominated by the value of the relative layer thickness τ/τ in the same way as the blue channel response is dominated at low exposures due to the presence of the yellow marker dye. The dual channel method uses explicitly the Beer–Lambert Law in form of Eq. (2) to describe the disturbance Δd, i.e., this method is not able to remove disturbances that are caused by effects other than thickness variation of the active film layer. However, the use of Eq. (2) allows to separate the equation system and reduces the calculation of the dose D to a simple inversion of the single nonlinear Eq. (13).

Since the dual channel method is a special case of the multichannel method described in the following Subsections II F, specific examples are not presented.

II.F. Triple-channel film dosimetry method

The dual channel method addresses only disturbances caused by thickness variations of the active film layer. The more general target is to separate numerically the dose-dependent part of a scanned optical density signal from any disturbance Δd that might be present in the system consisting of radiation source, radiochromic film, and film scanner unit. To model this case, Eq. (2) is modified to

$$d_X(D) = d^D_X(D)\Delta d \tag{16}$$

which includes the previous case for $\Delta \mathrm{d} = \tau/\tau$. Note that when calibration films are used to determine $\bar{d}_X$, it is important that the averaging regions, i.e., the exposed measurement areas, must be sufficiently large to ensure that the calibration condition for the average disturbance

$$\Delta \bar{d} = 1 \tag{17}$$

is fulfilled. This is equivalent to requesting that the measurement area should be large enough to reflect average response of the system, otherwise $\bar{d}_X$ will develop a systematic bias. The disturbance Δd is dose-independent since all dose-dependent parts are presented by the calibration function $\bar{d}_X$.

A dose value can be calculated for each color channel X using (Fig. 2)

$$D_X = \bar{d}^{-1}_X(d_X \Delta d). \tag{18}$$

Since the dose cannot depend on the color channel X selected for evaluation of Eq. (18). one can consider a sequence of multiple channels $\{X_k\}^K_{k-1}$ and minimize the differences in the dose results from the individual color channels, i.e.,

$$\Omega(\Delta d) = \sum_{i \neq j}(D_{X_i} - D_{x_j})^2 \rightarrow \min_{\Delta d}. \tag{19}$$

The solution to this least square equation can be found by solving the single nonlinear equation

$$\frac{d}{d\Delta d}\Omega = 0. \tag{20}$$

This minimization is equivalent to finding the "nearest" color to the color path $\{\bar{d}_R(D), \bar{d}_G, \bar{d}_{B](D)}\}$. The distance of a point from this color path represents the disturbance value, Δd, and the value of the path parameter is the "best" dose value. This method works as long as the slopes of the calibration functions $\bar{d}_x$ for the individual color channels are sufficiently different. The more color channels involved, the more deterministic the system becomes, and the better will this method separate the dose-dependent part of the signal from the dose-independent part.

In case of two color channels ($K = 2$) Eq. (20) becomes $D_{X_1} = D_{X_2} = 0$ and with $D = D_{X_1} = D_{X_2}$ and $\tau/\tau = \Delta \mathrm{d}$ one recovers Eq. (12) of the dual channel method.

III. RESULTS

III.A. Single channel film dosimetry

Figure 3 shows the scanned image of an EBT2 film exposed to a dose of 225 cGy using a 10×10 cm^2 flat field exposure and the corresponding dose map based on Eq. (8) for X = R, G, B.

Nonuniformities in the form of vertical stripes are obvious by visual inspection of both the film image and the dose map. A horizontal profile across the dose map in Fig. 4 reveals the oscillations especially in the flat part of the

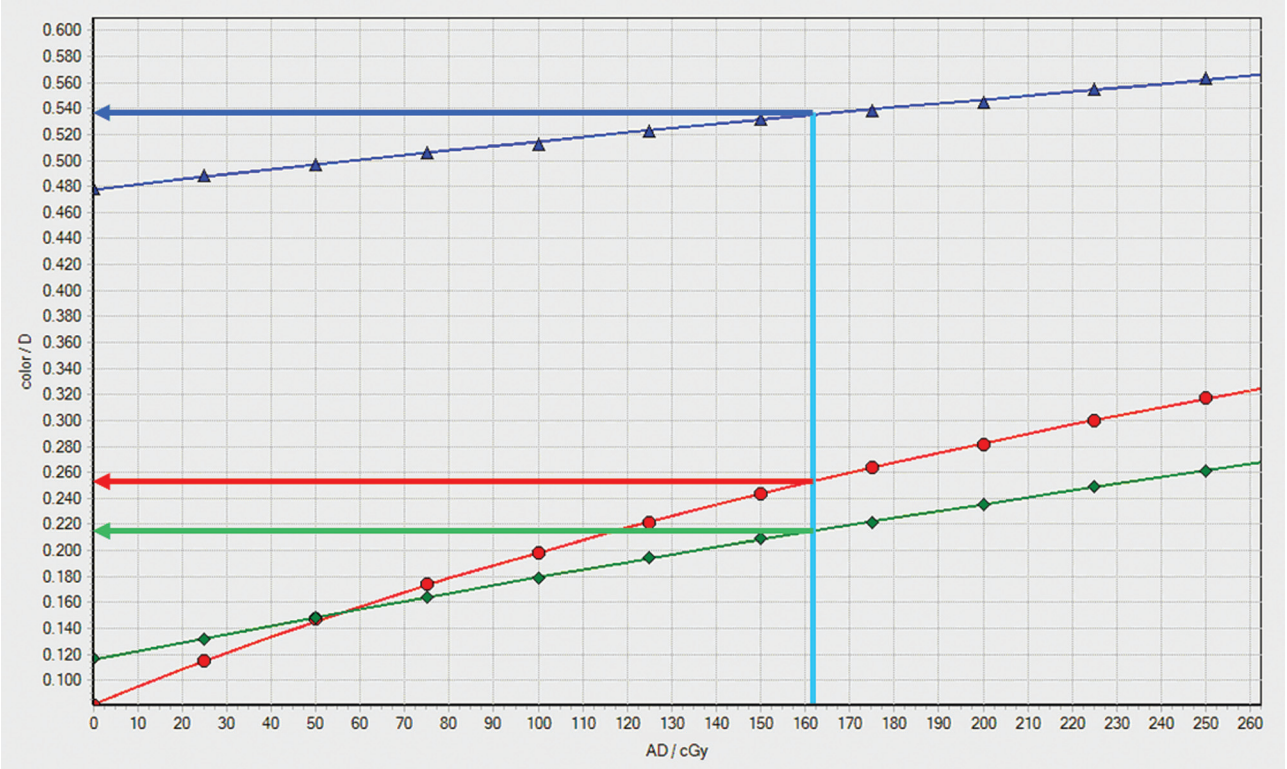

FIG. 2. Multichannel calibration curves and data flow of dose mapping using Eq. (8).

exposure field, which must stem from dose disturbances ΔD described in Eq. (11).

Figure 4 shows the dose profiles across the flat field as calculated separately for the R, G, and B color channels. The EBT2 film includes a yellow marker dye in the active coating[8] that significantly increases the dependence of the signal in the blue color channel with respect to disturbances in the thickness of the active layer. The profile of the blue channel in Fig. 4 suggests that the disturbances ΔD are dominated by the variations of the term τ/τ, i.e., the nonuniformity of the active layer in the film causes this type of oscillation and when using a single channel based dose mapping method, results in dose error.

In the following Subsections III B–III D dose mapping methods are presented that account for thickness variations of the active film layer, separate these variations from the dose-dependent portion of the image and remove their effect from calculated dose maps.

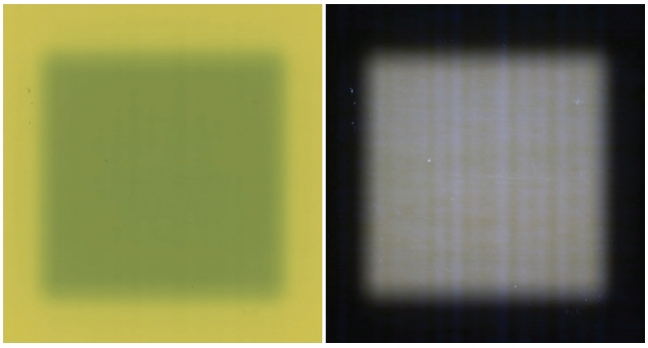

FIG. 3. EBT2 film with 225 cGy exposed and corresponding dose map image showing nonuniformities stemming from thickness variations of the active film layer [Calculations were carried out using ISP software package Film QA Pro 2010 (Ref. 20)].

III.B. Triple-channel film dosimetry

Figure 2 shows results for the same EBT2 films as given in Fig. 1 and Table I except that calculations have been made using the multichannel method. Compared to the single channel data approach, the multiple channel method varies the dose values until the corresponding scanned optical density values for the various color channels are best matched.

After extracting the disturbance value Δd from Eq. (20), one can calculate the corresponding dose values D_X for each color channel. Figure 5 shows the dose map $\{D_R, D_G, D_B\}$, and the disturbance map using Eq. (14) with D_Z, $X = $ R, G, and B for the scan depicted in Fig. 3. The separation of the dose-dependent part and dose-independent parts are recognizable. Whereas the dose map represents the intrinsic result of the dosimetric measurement, the disturbance map gives information about the error sources of measurement process.

The horizontal profile of the dose map in Fig. 6 shows the improved flatness across the exposed area for all involved color channels. The corresponding profile across the disturbance map consists of a low frequency pattern dominated by thickness variations of the active layer (see also τ/τ). The pattern becomes more visible by applying a simple average filter to the disturbance map (see right part of Fig. 7). The disturbance signal in the example varies by a little more than $\pm 1\%$ around the average value of 100% as defined by the calibration patches. The latter figure is consistent with the

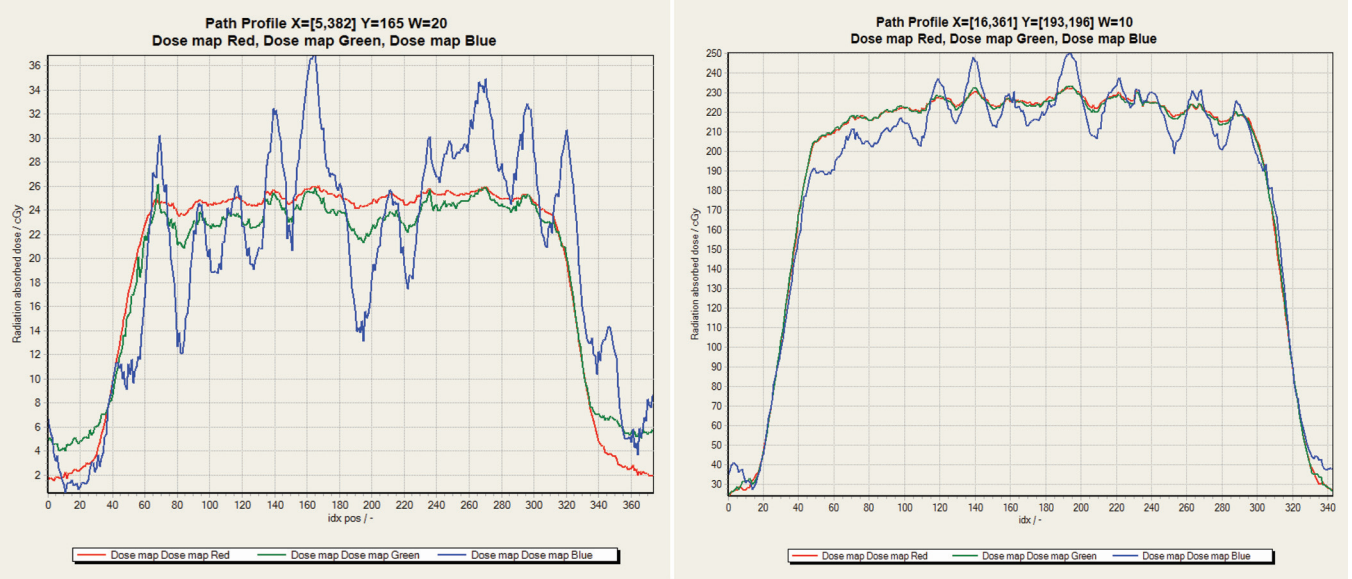

FIG. 4. Horizontal profile across the dose map for 25 and 225 cGy (see Fig. 3) exposure showing red, green, and blue channel results.

aim of having the size of the calibration patches large enough to represent the average system response including the film and the average thickness of the active layer.

Since nonuniformities are broadly distributed in the active layer of the film, it is good practice to expose and measure large calibration patches. This makes it more probable that each of the measurements will capture the average response of the film. If small pieces of film are used for the calibration, it is more likely that they will have a response significantly above or below the average. As a practical matter, it is preferred to use the calibration patches sized at least 5×5 cm^2 and even more desirably, 10×10 cm^2. Because larger calibration patches better represent average film behavior, a smaller number are necessary to construct the response curve. Experience shows that a calibration for a dose range from 0 to 300 cGy is better served by using six to eight 10×10 cm patches rather than two to three times that number of smaller patches. Whereas the single channel dosimetry method is indiscriminate and converts any thickness variations directly into erroneous dose values (see Ref. 8), the multichannel method described accounts for such disturbances, resolves them from the dose information and places them into a separate map displaying the relative thickness deviations.

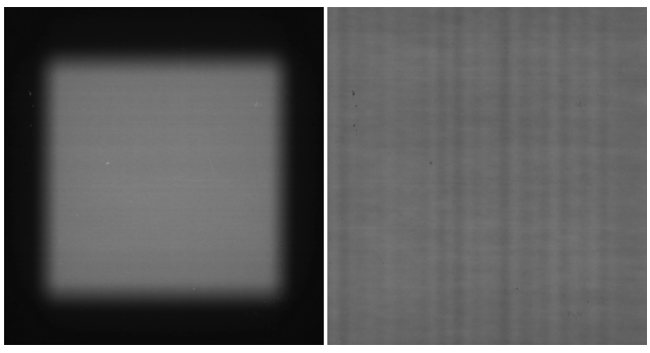

FIG. 5. Dose map and disturbance map for EBT2 film with 225 cGy exposure shown in Fig 3.

III.C. Comparing dosimetry methods using IMRT dose distributions

Figure 8 displays the dose plan image in the coronal plane of an IMRT treatment composed of seven beams and the corresponding dose image recorded on EBT2 radiochromic film. The radiochromic IMRT film and eight calibration films exposed to 6MV x-ray doses between zero and 281 cGy were digitized in transmission mode on an Epson 10000XL scanner. The dose response is shown in Fig. 9 where the calibration data for each color channel have been fit to a function of the type $X(D) = (a + b \quad D)/(c + D)$, where the scanner response at dose D is $X(D)$ and a, b, and c are constants.

Using this calibration data dose images were calculated from the IMRT measurement film image using the single, red channel dosimetry method, and the triple-channel method using the red, green, and blue response data. Isodose maps are presented in Fig. 10 showing the agreement between dose contours in the treatment plan and the measured dose contours in the single-channel triple-channel dose maps. Contour lines are shown for doses at 90, 70, 50, and 30% of the maximum value in the plan map. Inspection of the iso-contour maps shows that the contours in the triple-channel map have a closer conformance to the plan than those in the single channel map. Quantitative assessment of the accordance between measurements and plan was made using the gamma function distribution using factors of 3% dose agreement within 2 mm. The results are shown in Fig. 11 in the form of a gamma function histogram. While there is measured agreement of 91% between the single channel dose map and the plan the triple-channel dose map has a 99% agreement, a much closer concordance with the plan. The measurements and comparisons were repeated for exposures of four other EBT2 films to the same IMRT treatment plan. Dose maps were calculated using

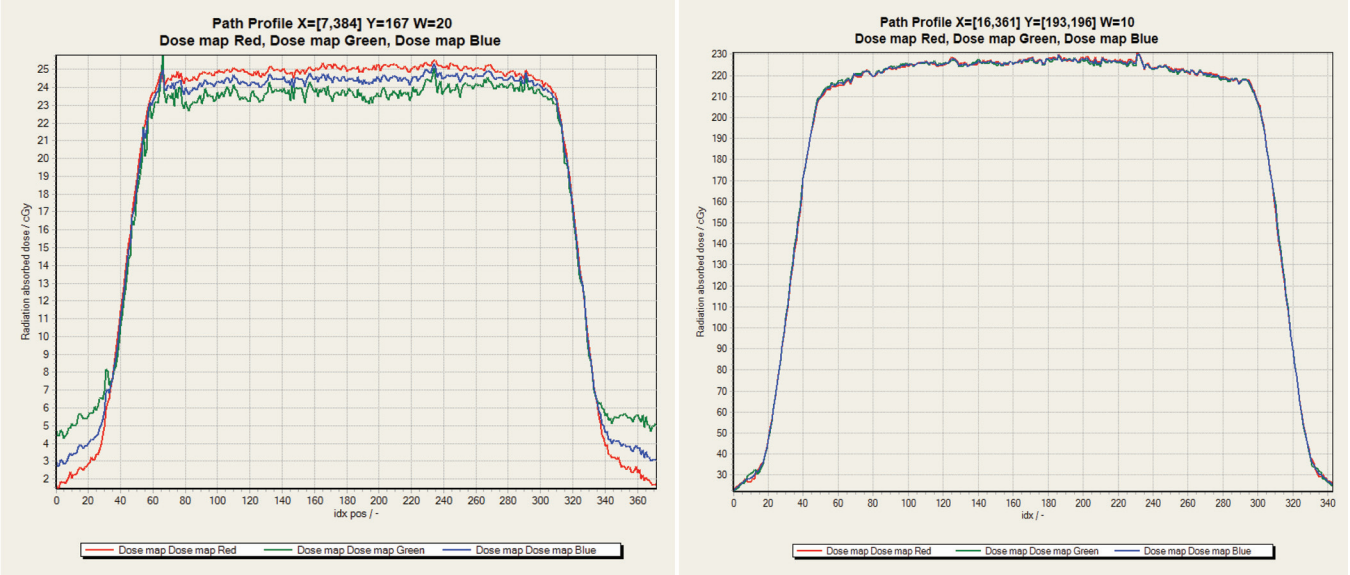

FIG. 6. Horizontal profile across the dose map for 25 and 225 cGy exposure (see Fig. 5) showing the red, green, and blue channel results.

the single (red) channel and triple-channel methods. The agreements with plan using the single channel dosimetry protocol were 90.4, 86.0, 98.1, and 83.3 (average 89.5) for the four measurement films. For maps calculated using the triple-channel method the agreements were 99.6, 99.2, 99.8, and 98.4 (average 99.2). Radiochromic film dosimetry with EBT2 film consistently provided better concordance with the treatment plan when the triple-channel protocol dosimetry was used rather than the single channel method.

III.D. Mitigation of lateral displacement effect

Because EBT2 film partially polarizes transmitted light,[22] the doses calculated using images from a CCD scanner may show substantial lateral distortions.[16,20,21,23] The multichannel technique is able to mitigate this lateral dependence. To demonstrate this, one of the EBT2 films exposed to a 10 m × 10 cm field and used to generate the calibration curve shown in Table I was scanned in the center of an Epson 10000XL scanner and then moved to a new position displaced "4" laterally from the center of the scanner and rescanned a position close to the left edge of the scan window. The calibration fitting functions were used to convert the images to dose maps using the single channel and triple-channel mapping. Profiles in the lateral direction across the exposed areas of the film scanned close to the edge of the scan window are shown in Fig. 12. The left side of each profile is furthest from the scan axis. The single channel profile shows a large increase in the dose on the left side of the field, i.e., the side of the field farthest from the center of the scanner. Qualitatively this behavior is characteristic of the response of CCD scanners[16,18] including those made by

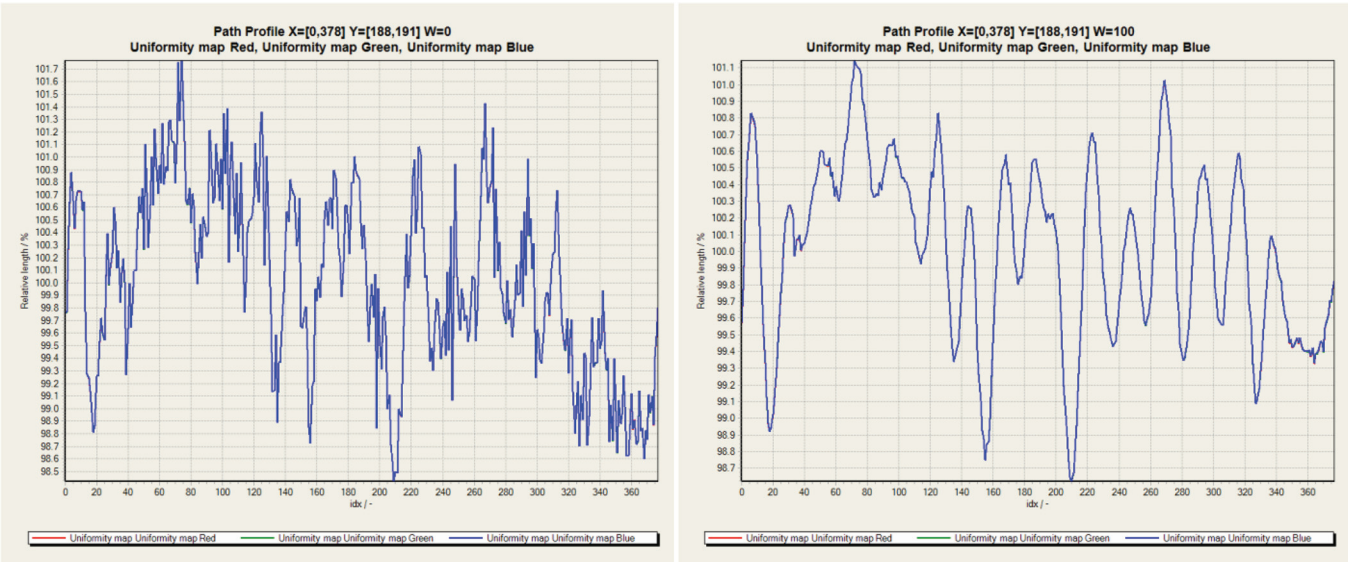

FIG. 7. Horizontal profile across the dose map from Fig. 5 for red, green, and blue channel.

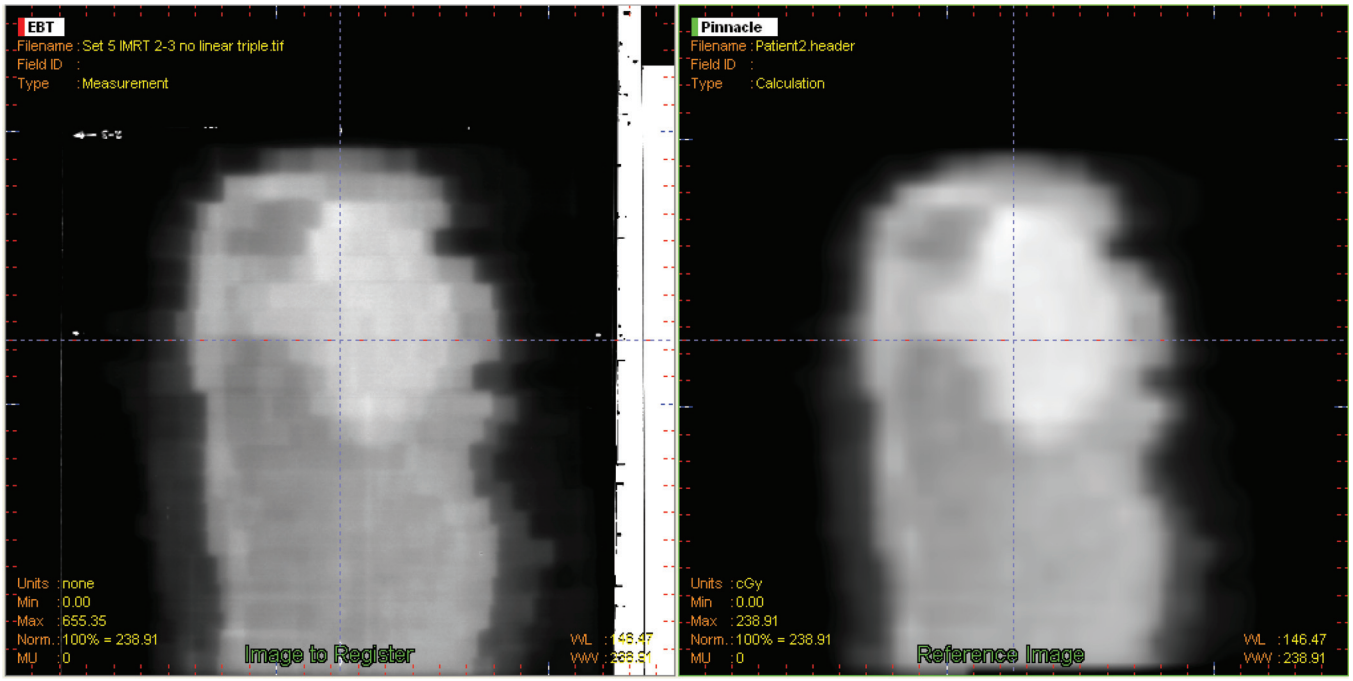

FIG. 8. Dose images calculated for IMRT plan (right) and measured with EBT2 film.

Epson, Microtek, and Vidar. The indicated optical density tends to be greater approaching the lateral edges of the scanner's field of view. Not only is this effect sensitive to position on the scanner, but it is also dose-dependent, being smaller at low doses, but becoming more substantial at higher doses. The triple-channel method will compensate for the dose-independent part of the lateral effect (e.g., at zero exposure). However, the dose-dependent part will remain.

By comparison, the profile of the same area of the triple-channel map shows that the apparent increase in dose closer to the edge of the scanner can be mitigated by using all three color channels to perform the dosimetry as depicted in Fig. 12. This is further demonstrated by showing the profile across the triple-channel map of the laterally displaced film together with the profile across the same area of the same film scanned at the center of the scanner. These profiles are demonstrating how the triple-channel dosimetry method is

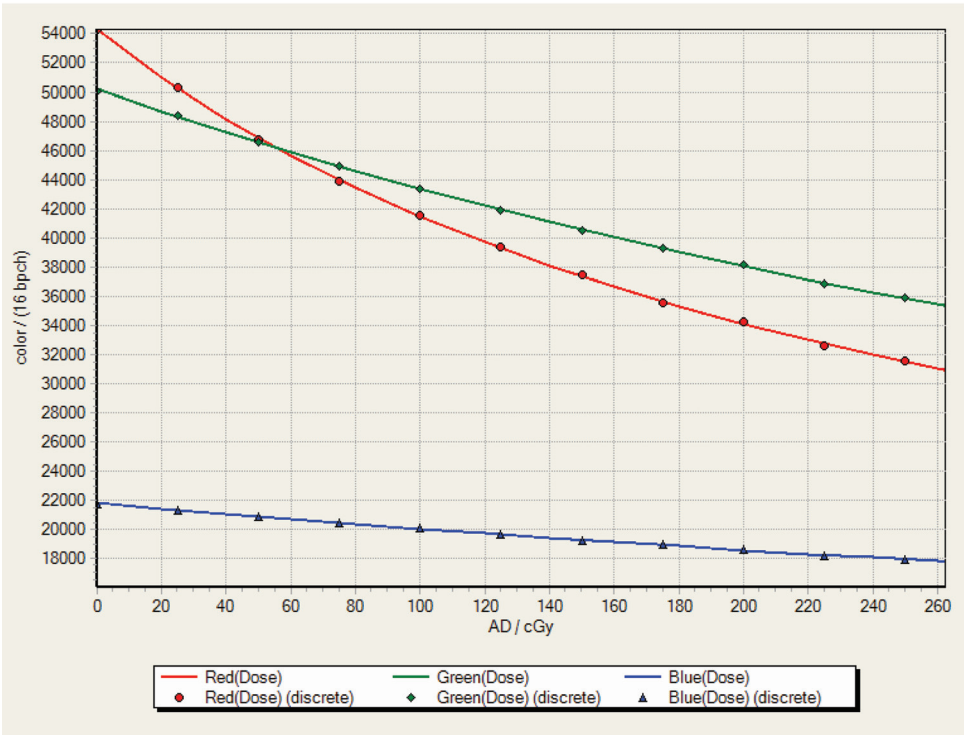

FIG. 9. Dose calibration curves for EBT2 film in three color channels.

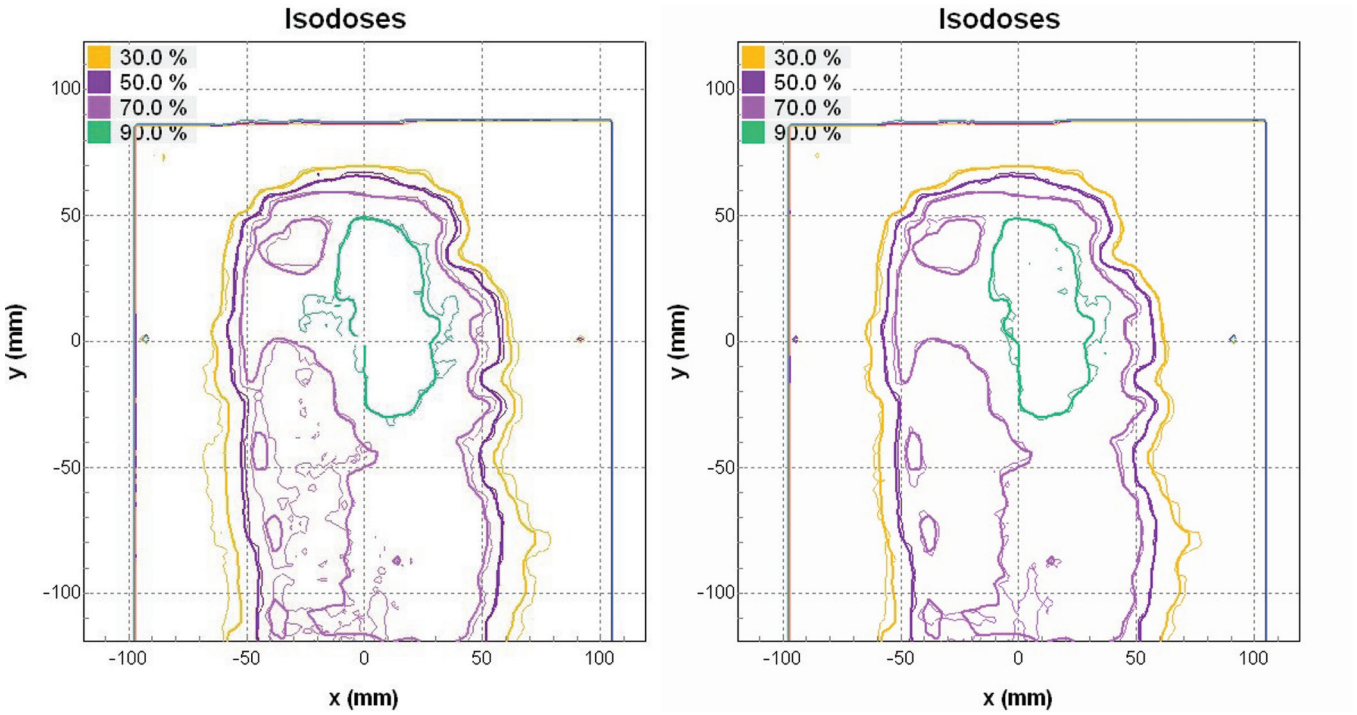

FIG. 10. Iso-dose maps– measurement (thin lines) vs IMRT plan (thick lines): Red channel dosimetry to left; triple-channel dosimetry to right.

mitigating the lateral scanner effect and delivers results superior to the single channel method.

The dose values calculated for the different color channels with the multichannel method should be in close agreement. Offsets indicate that the dose-dependent properties of the scanned film do not match sufficiently with those of the calibration films or the calibration condition (17) is not fulfilled. Comparison of the dose values from the color channels makes it possible to pinpoint local defects and errors of the scanned radiochromic film and the scanning protocol.

The example given in Fig. 13 is based on the scan of the 200 cGy calibration patch used in Table I, but in this case the film was rotated by 90° before scanning. It is well known that the response of EBT2 film is dependent on its orientation on

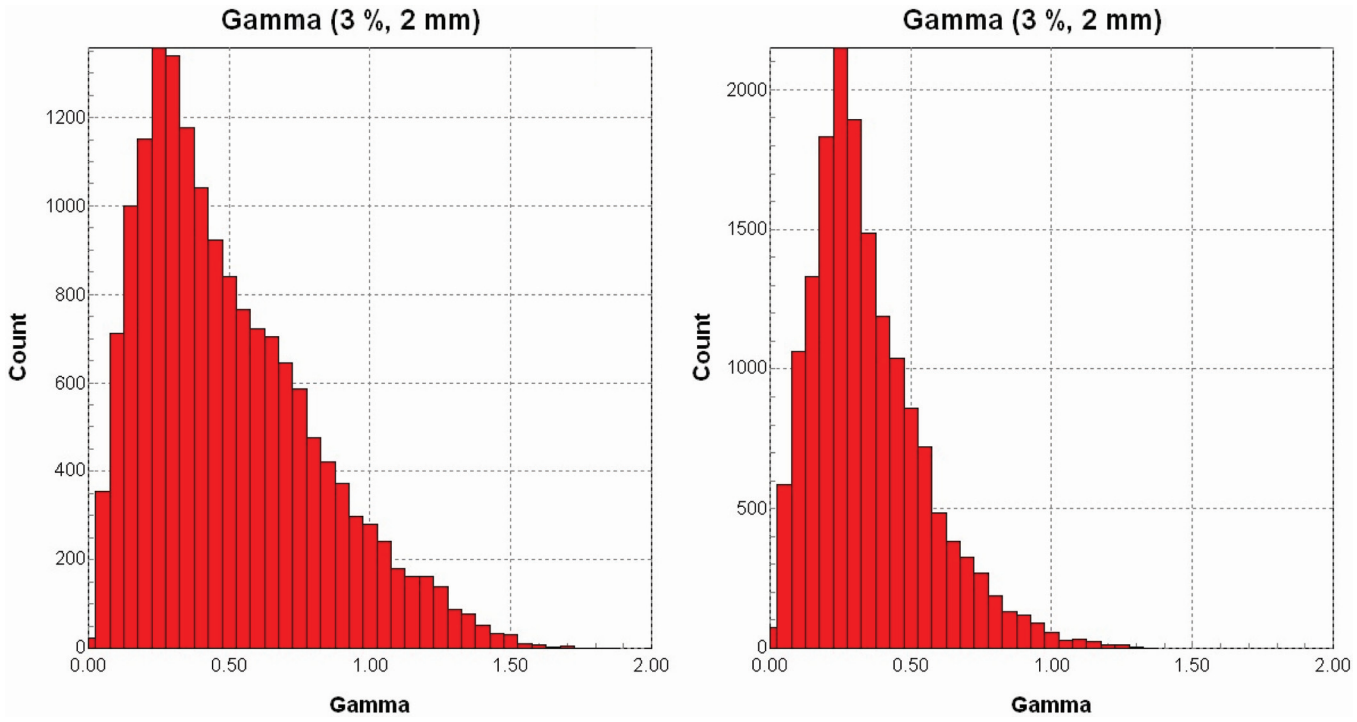

FIG. 11. Gamma distribution and histogram maps: Red channel dosimetry, 91.0% agreement, to left; triple-channel dosimetry, 99.0% agreement, to right.

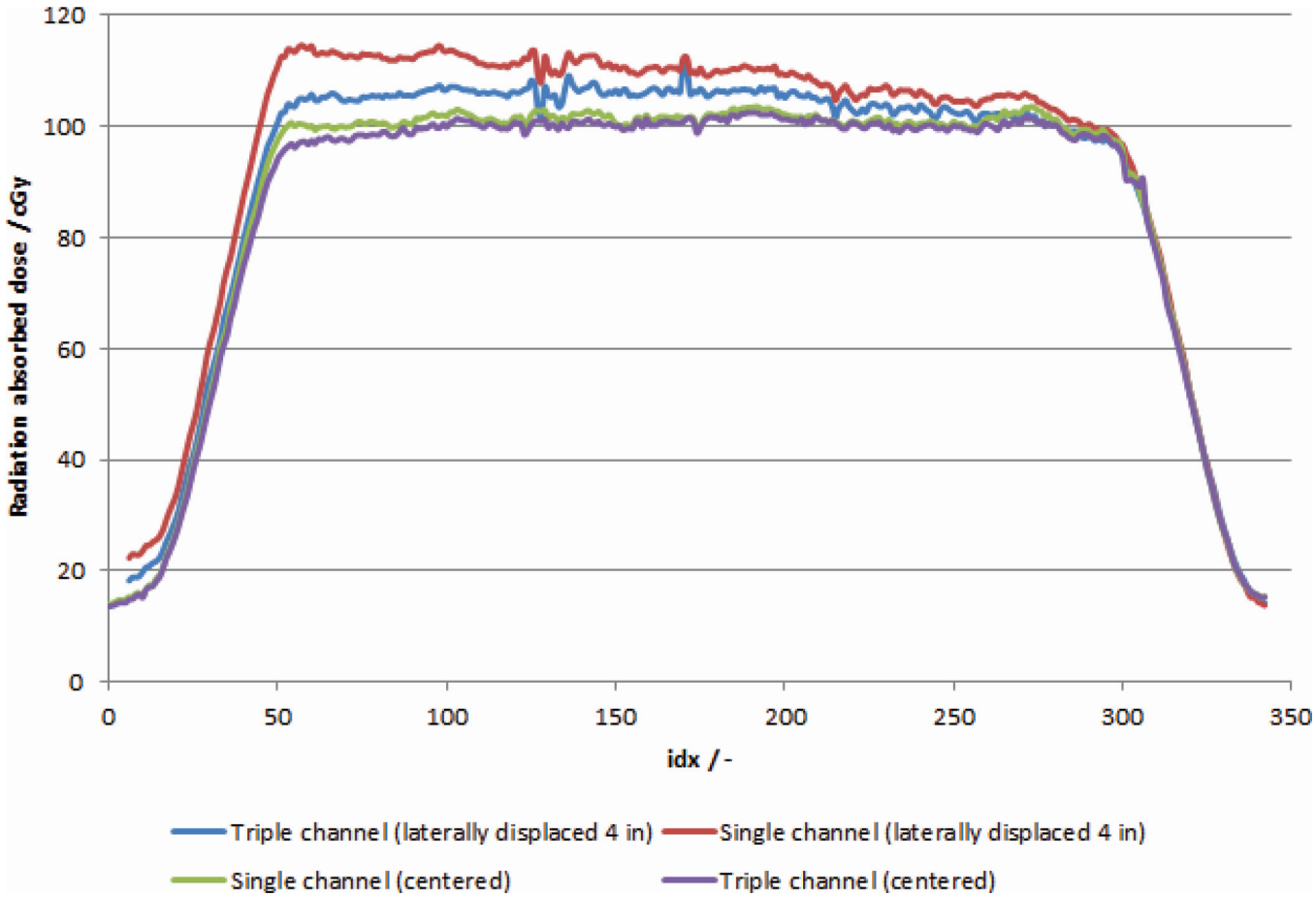

FIG. 12. Comparison single and triple channel method using dose map from film positioned at left side of the scanner where lateral effect reaches maximum and single and triple channel dose map of film at the center of the scanner.

the scanner and the calibration Table I obtained for one orientation will not match the film behavior in another orientation. When dosimetry is performed using the single channel method, there is no indication in the dose result to signify that a film was misaligned when scanned. However, such an indication is inherent when using multichannel dosimetry because the doses from the color channels should be in close agreement. In the example, there is an offset of about 10 cGy

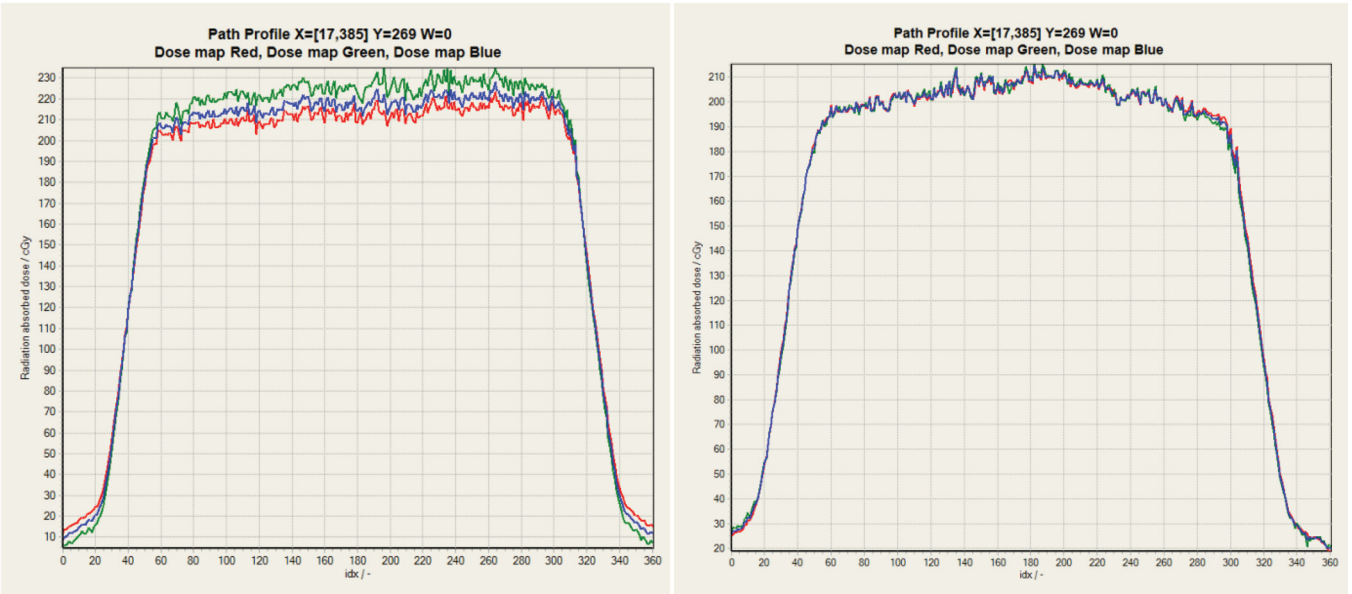

FIG. 13. Horizontal profile across the dose maps of 200 cGy film patch scanned rotated by 90° compared to calibration scans (left) and the scan with original orientation (right) for R, G, B channels.

(approximately 5%) between the color channels, providing a clear indication of a mismatch between the scanned film and calibration data used to calculate the dose map.

The multichannel method is symmetric with respect to all color channels used in the measurement. It characteristically balances the color channel with the highest sensitivity because the component with the highest derivative value is the dominant factor in Eq. (18). The use of multiple wavelengths to scan the absorption spectrum of the film makes it possible to use the entire sensitivity range of the film covered by the spectral response of the scanner. This range could even be extended by using additional wave lengths or a larger number of color bands, although this would require the utilization of a specialized scanner. In the case of using EBT2 film and Epson flatbed color scanners (e.g., models 10000XL, V700, V750, 1680, and 4900) the RGB channels cover a dose measurement range from below 10 cGy to above 100 Gy, i.e., more than 3 orders of magnitude (see Ref. 8).

IV. CONCLUSIONS

The fundamentals of a new method using multiple color channels to convert scanned images of radiochromic film into dose maps have been presented. This method allows the separation of the dose-dependent and dose-independent parts of a scanned signal and compensates for a variety of anomalies, artifacts, and other disturbances, such as variations of the thickness of the active layer, scanner nonlinearity and process noise and enables the use of the entire available sensitivity range of the film in the same procedure. The substantial gain in accuracy is illustrated by improved flatness and symmetry of the tested flat field exposures.

NOMENCLATURE

Symbol(SI unit)	Explanation
D (Gy)	absorbed dose
X	normalized color channel value, $X\varepsilon$ [0, 1], typical color channels are R, G, B
R, G, B	normalized of red, green, blue color channel, $X\varepsilon$ [0, 1]
d_X	optical density of color channel X, $d_X = -\log(X)$
d_X^D	dose-dependent part of the optical density d_X
$\bar{dot}$	script to mark average value of a quantity
τ	relative thickness of the active film layer
Δd	disturbance factor of optical density value
x, y (m)	absolute locations x and y coordinates
i, j	discretized locations in x (i) and y (j) direction of pixelated coordinate system

ACKNOWLEDGMENTS

The authors are employees of International Specialty Products the manufacturer of Gafchromic® dosimetry film and owner of the FilmQA Pro software (www.FilmQA Pro.com).

[a]Author to whom correspondence should be addressed. Electronic mail: amicke@ispcorp.com

[1]M. J. Butson, T. Cheung, and P. K. Yu, "Weak energy dependence of EBT Gafchromic film dose response in the 50 kVp–10 MVp x-ray range," Appl. Radiat. Isot. **64**, 60–62 (2006).
[2]S. T. Chiu-Tsao, Y. Ho, R. Schankar, L. Wang, and L. B. Harrison, "Energy dependence of response of new high sensitivity radiochromic films for megavoltage and kilovoltage radiation energies," Med. Phys. **32**, 3350–3354 (2005).
[3]P. Lindsay, A. Rink, M. Ruschin, and D. Jaffray, "Investigation of energy dependence of EBT and EBT-2 Gafchromic film," Med. Phys. **37**(2), 571–576 (2010).
[4]A. Niroomand-Rad, C. R. Blackwell, B. M. Coursey, K. P. Gall, J. M. Galvin, W. L. McLaughlin, A. S Meigooni, R. Nath, J. E. Rodger, and C. G. Soares, "Radiochromic film dosimetry: Recommendations of AAPM radiation therapy committee task group 55, Med. Phys. **25**, 2093–2115 (1998).
[5]AAPM Report No. 63, Radiochromic film dosimetry, 1998.
[6]S. Devic, J. Seuntjens, G. Hegyi, E. Podgorsak, C. Soares, A. Kirov, I. Ali, J. Williamson, and A. Elizondo, "Dosimetric properties of improved Gafchromic films for seven different digitizers," Med. Phys. **31**(9), 2391–2398 (2004).
[7]S. Devic, N. Tomic, C. Soares, and E. Podgorsak, "Optimizing the dynamic range extension of a radiochromic film dosimetry system," Med. Phys. **36**(2), 429–437(2009).
[8]Gafchromic® EBT2 Self-Developing Film for Radiotherapy Dosimetry, ISP White Paper, October, 2010.
[9]E. Willcox, G. Daskalov, and L. Nedialkova, "Comparison of the Epson expression 1680 flatbed and the VXR-16 dosimetry PRO film scanners for use in IMRT dosimetry using Gafchromic and radiographic film," Med. Phys. **34**(1), 41–48 (2007).
[10]M. Fuss, E. Sturtewagen, C. De Wagter, and D. Georg, "Dosimetric characterization of GafChromic EBT film and its implication on film dosimetry quality assurance", Phys. Med. Biol. **52**(14), 4211–4225 (2007).
[11]S. Devic, J. Seuntjens, and E. Sham, "Precise radiochromic film dosimetry using a flat-bed document scanner," Med. Phys. 32(7), 2245–2253 (2005).
[12]B. D. Lynch, J. Kozelka, and M. K. Ranade, "Important considerations for radiochromic film dosimetry with flatbed CCD scanners and EBT Gafchromic Film," Med. Phys. **27**(10), 2462–2475 (2006).
[13]ISP presentation: www.FilmQA Pro.com/Micke_Lewis_Yu_Triple_Channel_Technique_201001.pdf.
[14]L. Paelinck, W. de Neve, and C. De Wagter, "Precautions and strategies in using a commercial flatbed scanner for radiochromic film dosimetry," Phys. Med. Biol. **52**(1), 231–242 (2007).
[15]L. J. Van Battum, D. Hoffmans, D. Piersma, and S. Heukelom, "Accurate dosimetry with Gafchromic EBT film of a 6 MV photon beam in water: What level is achievable?," Med. Phys. **35**(2), 704–716 (2008).
[16]J. Menegotti, A. Delana, and A. Martignano, "Radiochromic film dosimetry with flatbed scanners: A fast and accurate method for dose calibration and uniformity correction with single film exposure," Med. Phys. **35**(7), 3078–3085 (2008).
[17]B. Hartmann, M. Martisiková, and O. Jäkel, "Homogeneity of Gafchromic EBT2 Film," Med. Phys. **37**(4), 1753–1756 (2010).
[18]S. Devic, S. Aldelaijan, H. Mohammed, N. Tomic, L. H. Laing, F. DeBlois, and J. Seuntjens, "Absorption spectra time evolution of EBT-2 model Gafchromic film," Med. Phys. **37**(5), 2207–2214 (2010).
[19]L. Paelinck, A. Ebongue, W. De Neve, and C. De Wagter, "Radiochromic EBT film dosimetry: Effect of film orientation and batch on the lateral correction of the scanner," Radiother. Oncol. 84, 194–195 (2007).
[20]FilmQA Pro 2010 software: www. FilmQA Pro.com.
[21]L. J. Van Battum, D. Hoffmans, S. Kwa, and S. Heukelom, Accuracy of GafChromic EBT Film as dose meter in radiotherapy QA, Proc. IFMBE, **25**, 105–108 (2009).
[22]M. J. Butson, T. Chueng, and P. K. Yu, "Evaluation of the magnitude of EBT Gafchromic film polarization effects," Australas. Phys. Eng. Sci. Med. **32**(1), 21–25 (2009).
[23]S. Saur and J. Frengen, "GafChromic EBT film dosimetry with flatbed CCD scanner: A novel background correction method and full dose uncertainty analysis," Med. Phys. **35**(7), 3094–3101 (2008).