An efficient protocol for radiochromic film dosimetry combining calibration and measurement in a single scan

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Purpose: Radiochromic film provides dose measurement at high spatial resolution, but often is not preferred for routine evaluation of patient-specific intensity modulated radiation therapy (IMRT) plans owing to ease-of-use factors. The authors have established an efficient protocol that combines calibration and measurement in a single scan and enables measurement results to be obtained in less than 30 min. This avoids complications due to postexposure changes in radiochromic film that delay the completion of a measurement, often for up to 24 h, in commonly used methods. In addition, the protocol addresses the accuracy and integrity of the measurement by eliminating environmental and interscan variability issues.

Methods: The authors collected dose–response data from six production lots of Gafchromic EBT3 film and three production lots of EBT2 film at doses up to 480 cGy. In this work, the authors used seven different scanners of two different models—Epson 10000XL and V700; postexposure times before scanning from 30 min to 9 days; ambient temperatures for scanning spanning 11 °C; and two film orientations. Scanning was in 48-bit RGB format at 72 dpi resolution. Dose evaluation was conducted using a triple-channel dosimetry method. To evaluate the measurement protocol, patient specific IMRT and volumetric modulated arc therapy (VMAT) plans were exposed onto EBT3 films on a Varian Trilogy Linac. Film scanning was done following the protocol under a number of different conditions and the dose maps were analyzed to demonstrate the equivalence of results.

Results: The results indicated that the dose–response data could be fit by a set of related rational functions leading to the description of a generic calibration curve. A simplified dosimetry protocol was established where dose–response data for a specific film lot, scanner, and scanning conditions could be derived from two films exposed to known doses. In most cases only one calibrated exposure was required since the dose for one of the films could be zero. Using the Gamma test criterion of 2%/2 mm to evaluate the measurements, similar passing rates ranging between about 95% and 99% for the fields studied were obtained from application films digitized under a variety of conditions all of them different than the conditions under which the calibration films were scanned.

Conclusions: The authors have developed a simplified and efficient protocol to measure doses delivered by an IMRT or VMAT plan using only the patient film, one calibration film, one unexposed film, and applying a single scan to acquire a digital image for calculation and analysis. The simplification and timesaving offer a potential practical solution for using radiochromic film for routine treatment plan quality assurance without sacrificing spatial resolution for convenience. © *2012 American Association of Physicists in Medicine*. [http://dx.doi.org/10.1118/1.4754797]

Key words: dosimetry, quality assurance, IMRT, radiochromic film, multichannel

I. INTRODUCTION

Modern state-of-the-art techniques in radiotherapy, such as intensity modulated radiation therapy (IMRT) and volumetric modulated arc therapy (VMAT), have enabled significant reduction of side effects while improving the delivery of radiation to kill cancer cells. While such advances have provided great success in reducing dose to healthy tissues, they have constantly increased the complexity of treatment planning and delivery and increased the demand for quality assurance (QA). Dosimetry using radiochromic films such as Gafchromic EBT2 and EBT3 is a tool sometimes selected to verify the dose distribution of treatment plans and for general QA of treatment planning systems (TPS) and linear accelerators. The principal factor in making this selection is often the high spatial resolution offered by radiochromic film. Other positive factors in choosing radiochromic film are its weak energy dependence from the kV to the MV range[1–8] as well as its near-tissue equivalence.[9] In combination these characteristics make radiochromic film an excellent choice for complex treatment dose verification involving beams delivered with oblique as well as normal incidence.[9,10] GafChromic radiochromic films produce colored images when exposed to radiation with strong absorbance in the red spectrum (575–675 nm). For this

reason it has long been recognized that multichannel flatbed scanners have better usability with radiochromic film than white-light scanners because the multichannel scanners offer the selection of the red color channel for greater sensitivity at lower doses, while providing extension of the dynamic range of the film to higher doses using the signal from the green or blue channels.[11–15] Multichannel dosimetry has been shown to have significant advantages over single channel dosimetry by its better dosimetric accuracy.[16,17] The improved accuracy of the multichannel method comes from its ability to resolve the digital image of a measurement film into two parts, i.e., a dose image containing the information behaving like the dose function and a disturbance image containing the portion that is independent of dose and color.[16] In the case of single-channel dosimetry all response artifacts convert directly to dose artifacts. By comparison, multichannel dosimetry separates artifacts like thickness of the active layer, fingerprints, scratches, and dust from the dose image thereby improving its accuracy. Since the multichannel method does not require the prescanning of films before exposure or dual exposures, it is more efficient than the protocols employing those previously published techniques.[18,19]

While radiochromic film provides dose measurement at submillimeter spatial resolution, negative ease-of-use factors often interfere with its selection for routine evaluation of patient-specific treatment plans.[20] Recently, researchers from Canada have demonstrated the use of functional argument to linearize the inherently nonlinear response of a radiochromic film based reference dosimetry system.[21] In this way they showed that relative dosimetry can be conveniently performed using radiochromic film without the need of establishing a calibration curve. Now, we have developed a simplified and efficient protocol for using radiochromic film that avoids complications encountered in commonly used methods, i.e., multiple-film calibration and multiple-scan image acquisition prior to patient-specific QA in order to obtain absolute dose values. This paper describes an innovative approach to radiochromic film dosimetry using GafChromic EBT3 or EBT2 film and an RGB flatbed color scanner. The method described allows measurement of doses delivered by a treatment plan using only the patient QA film, one calibration film, one unexposed film, and the application of a single scan to acquire a digital image for calculation and analysis. Together with the triple-channel radiochromic media dosimetry method,[16] and the response curve linearization of the radiochromic film dosimetry system,[21] this new dosimetry protocol signifies another advance in radiochromic film dosimetry by streamlining of patient-specific treatment plan QA.

II. THE NEW PROTOCOL

For this work we have adopted and evaluated new protocols applied to the dose calibration of radiochromic film as well as to measurements of two-dimensional dose distributions using such films.

The new protocol for dose calibration is not radically different from customary protocols, but it provides improvement in two ways. First, it simplifies calibration by minimizing the number of dose points. Reference to recommended calibration procedures reveals requirements for at least 12 dose points and sometimes many more.[22,23] In contrast we have implemented a protocol requiring far fewer dose points and allowing all the calibration films to fit easily on the scanner together. While this particular improvement is not profound, scanning all calibration films at once eliminates effects from interscan variability and the reduction in the number of dose points reduces the overhead in labor and materials. The fewer number of dose points comes from the adoption of rational data-fitting functions having natural behavior similar to that of radiochromic film. Dose–response data is commonly fit to a polynomial function and this type of function can provide adequate fitting within the range of dose–response data up to about 4–5 Gy. However, because the response of radiochromic film is increasingly nonlinear as the dose range increases, it is common to observe that the polynomial fitting function is not smooth when applied to response data over a wide dynamic range and oscillates between the data points at higher doses. This is illustrated in Fig. 1 which shows the red channel response of EBT3 film fit to a 3rd order polynomial. The behavior shown by the fitting function does not correspond to the behavior of radiochromic film which darkens in monotonic fashion with increasing dose as the response asymptotes to an almost constant value. A common way to deal with the oscillation is to add more calibration points at the higher doses, but this can be inconvenient because it consumes more time and materials.

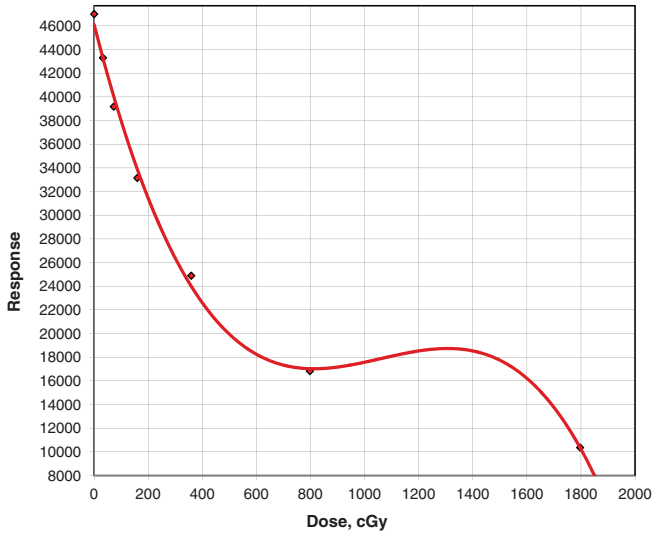

FIG. 1. Dose–response data fit to polynomial function (3rd order).

We prefer to select a fitting function with qualitative behavior similar to film, for example, the simple, rational function

$$X(D) = a + b/(D - c),$$

where X(D) represents the response at dose D, and a, b, and c are constants. At high dose, the response X(D) converges to the value of a. Figure 2 shows the fit of that function to the same data displayed for the polynomial fit illustrated in Fig. 1. For the purposes of dose measurement we do not propose extrapolation beyond the last data point, but this

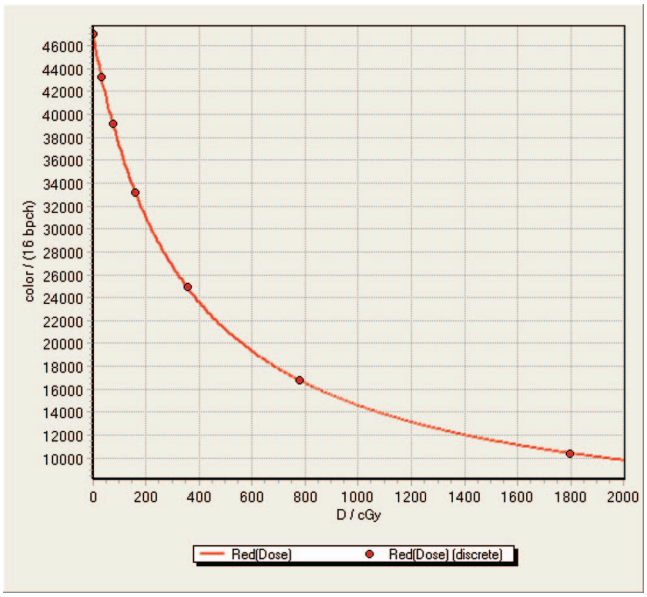

FIG. 2. Dose–response data fit to rational function $X(D) = a + b/(D - c)$.

rational function is monotonic, does not oscillate between data values, and can be fully defined from just three data points. We are not suggesting using the minimum number of values, but rather that we favor using a rational function with a shape corresponding to the dose–response characteristics of radiochromic film because it can reduce the large number of data points many investigators are using.

In practice, we have found that four or five data points arranged in a geometric progression of doses are sufficient and provide feedback of the agreement between the measurements and the fitting function to assess the goodness of the fit. To demonstrate that measurements are not impaired by using a 4-point calibration as opposed to an 8-point calibration, we assessed dose measurements of IMRT plans using dose-difference comparison. The IMRT fields had maximum doses in the range from 220–250 cGy. We found that 100% of pixels in the two maps were within 2% relative to the maximum, >99% were within 1%, and >90% were within 0.5%. If the exposed films are sized with one of the dimensions less than about 4 cm, six films (five exposed and one unexposed) will fit on an 8×10 in.^{2} (20.3×25.4 cm^2) scanner for digitization in a single scan. This is an advantage because it eliminates scan-to-scan variability and uncertainty therefrom.

The new protocol for measurement of patient or application films differs from the common practice of scanning the application film alone in that it combines the digitization of the application film with the digitization of two calibration or reference films from the same production lot as the application film. All three films are digitized concurrently in a single scan. The reference films include one film exposed to a known dose plus one unexposed film. As will be addressed in Secs. III and IV, measurement of the reference films provides data by which the dose–response function can be adapted, recalibrated, or rescaled for the conditions applying to that particular scan. The benefit is that effects of scanner variability (between calibration and measurement) and temperature differences are eliminated. In addition, when the application film and the reference film are exposed within a narrow time window the scanning, measurement, and analysis can be performed with only a small time delay. This improvement makes it possible to obtain measurement results within 30 min rather than having to wait overnight, or longer, as has been the custom with radiochromic film.

The benefits of the new calibration and measurement protocol we propose sum to faster and more efficient practice while enhancing the accuracy of the results. Specifically they are as follows:

- Fewer exposures and less film required for calibration.
- Calibration films digitized in a single scan to eliminate scan-to-scan variability.
- Employment of fitting functions that have a similar behavior to radiochromic film.
- Simultaneous digitization of application and reference films for adaptation of the dose–response function to fit the immediate conditions and eliminate scan-to-scan variability.
- The ability to obtain accurate measurement results in minutes as opposed to many hours.

III. MATERIALS AND METHODS

III.A. EBT3 radiochromic film

This work was largely done with GafChromic EBT3 film. A relatively new introduction to the field, EBT3 film is closely related to EBT2 film. Indeed, they are coated in the same fashion using the same active fluid and the nominal thickness of the active layer is the same (28 μm) for the two films. The difference between the films is in the substrates used for their construction. In EBT2 film the active layer is contained between two smooth polyester substrates of different thicknesses (175 and 50 μm). The thinner substrate is attached to the active layer with an acrylic adhesive. In EBT3 film the active layer is contained between two polyester substrates of the same thickness (125 μm) and the substrates have a special treatment to embed microscopic silica particles (less than about 10 μm diameter) in the surface. The purpose of the treatment is to relieve the formation of Newton's rings patterns that can appear when two smooth surfaces, e.g., EBT2 film and the glass on a flatbed scanner, come together with proximity of the order of the wavelength of light. Newton's rings are an artifact that can affect the accuracy of film dosimetry measurements. The silica particles in the surface of the EBT3 substrate maintain a large gap (order of magnitude greater than the wavelength of light) between the film and the scanner glass and eliminate Newton's rings' formation. The amount of silica in the substrate is much less than 1% and has no measurable effect on the dose–response of EBT3 compared to EBT2. Also, since EBT3 film has a symmetric structure, any remaining concerns that the response may be dependent upon which side faces the scanner glass are completely eliminated. While earlier reports on the response of EBT2 suggested there could be a dependence,[13] later work has shown it not to be a concern.[24]

III.B. Investigation of postexposure changes

It is well known that radiochromic film, including the EBT3 film, undergoes postexposure intensification. We evaluated the new dosimetry protocol by first collecting dose–response data from six production lots of Gafchromic EBT3 film. We investigated postexposure changes in Gafchromic EBT3 film response by exposing samples to five doses between 30 and 480 cGy within a 5-min interval. Together with an unexposed film the samples were digitized in a single scan in 48-bit RGB transmission mode on four different Epson 10000XL scanners and three different Epson V700 scanners at various elapsed times-after-exposure. Since films were scanned together, the actual time-after-exposure for individual films could vary by ±2.5 min from the average. We measured and report the error due to the timing difference.

III.C. Investigation of response equivalence

We also investigated the new protocol by utilizing the exposed film samples from one production lot, as described in Sec. III.B, in two different ways. First, we scanned the films at two ambient temperatures; second we scanned the films in two orthogonal orientations, one orientation with the 20.3 cm side of the film (25.4 × 20.3 cm^2 sheets or 3.81 × 20.3 cm^2 strips) parallel to the scan direction and the other with the 20.3 cm side aligned perpendicular to the scan direction. We measured the film responses and investigated the relationship between the results in each situation.

III.D. Radiochromic film and irradiation procedure

The films used in this study were Gafchromic EBT3 and EBT2 with dimensions of 3.81 × 20.3 cm^2 (strips for calibration) and 25.4 × 20.3 cm^2 (sheets for treatment plan QA). 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. The irradiation was performed with 6 MV photons on a Varian Trilogy Linac. For exposures, the film was placed in a polystyrene phantom with 5 cm of the buildup material above and below the film. The source-to-axis distance (SAD) was 100 cm. Exposure of film for dose calibration was performed with 10 × 10 cm^2 fields, and the film perpendicular to the axis of the beam. The same polystyrene phantom was used for the exposure of films to IMRT fields. Patient IMRT films were also placed at a depth of 5 cm in the phantom and exposed to the full dose by all fields of the treatment plans. Films were scribed with holes (marks) at the production prior to irradiation to indicate the positions of the crosshairs of the Linac at zero gantry angle. Depending on the treatment plan the maximum doses delivered to a patient film ranged from about 100 cGy to about 300 cGy.

III.E. Scanners and scanning

Datasets obtained with the seven Epson scanners were kept separate for the subsequent analysis. 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 deliver the raw scanner data without any photographic enhancements. This choice is critical because it prevents the scan data from being altered by adjusting the color balance and exposure to present an image optimized for display. It is well known that the scan response of EBT3 radiochromic film is sensitive to the orientation of the film on the scanner.[25] Therefore, the orientation of the film in each image was recorded. In the subsequent measurement and analysis of the calibration film and treatment plan film images care was taken not to mix film images acquired in different orientations. Except as mentioned, the orientation of the film was established by placing the 20.3 cm side of the film strips and sheets perpendicular to the scan direction. This is referred to as portrait orientation.

It has also been established that the scanner response of radiochromic films like the EBT3 film can be sensitive to the position of the film on the scanner relative to the scan axis and the dose exposed on the film.[15] 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 response artifact is position dependent and dose-dependent. At doses less than 200 cGy and positions within about 5 cm of the scan axis the lateral artifact measured in the red color channel is less than about 2%, but it is increasingly important at higher doses and further away from the central axis of the scanner. To minimize the effect of the lateral artifact, films were centered along the central axis for scanning. In addition, we made use of the triple-channel dosimetry method in this work because it has been shown to substantially correct the effect of the lateral artifact.[16]

III.F. Image measurement and analysis

Scanned images were measured using Film QA Pro software (Ashland Inc., Wayne, NJ and at www.filmqapro.com). Calibration filmstrips exposed with 10 × 10 cm^2 fields were measured by defining areas of interest approximately 3.5 × 6 cm^2 in size at the centers of the exposed areas. Data was obtained for the red, green, and blue color channels at a resolution of 16 bits/channel. The images were defined as positive images where black (no observed signal) and white (maximum signal) are mapped to [0, 65535]. Data and image analysis such as conversion of images from scanner space to dose space and measurement of film profiles was also performed with the Film QA Pro software.

III.G. Efficient triple-channel film dosimetry method

III.G.1. Irradiation of EBT3 films in polystyrene phantom

Except where explicitly stated, films formatted for the new dosimetry protocol were of two sizes: 3.81 × 20.3 cm^2

strips and 25.4 × 20.3 cm^2 sheets. And except where stated, the films were obtained from production EBT3 lot A101711. The film strips were cut from the film sheets. The strips were used for calibration exposures and are referred to as reference films. The sheets were used for exposure of the patient treatment plans and are referred to as application films. Irradiations for film calibration were done using the 6 MV photon beam of a Varian Trilogy Linac at the center of 10 × 10 cm^2 field. The films were irradiated at depth of 5 cm and 100 cm SAD in a polystyrene phantom (25 × 25 × 10 cm^3). Calibration film doses were calibrated against the ion chamber (Standard Imaging Exradin A-12 0.65 cc thimble chamber with ADCL calibration) measurement at the same location and depth. The output of the Trilogy Linac was calibrated per AAPM TG-51 protocol.

An application film from a known production lot of the EBT3 film was placed in the polystyrene phantom and centered at the crosshairs ready for exposure of the patient's treatment field. Small pieces of adhesive tape were used to hold the film in place. A 5-cm thickness of phantom material was placed above the film as required. The chosen radiotherapy treatment plan (i.e., IMRT field or VMAT beam) was delivered to the phantom/film and the exposure time was noted. A reference filmstrip was chosen from the same production lot as the application film and placed in the phantom with the center of the strip close to the center of the exposure area. Using a 10 × 10 cm^2 open field, the strip was exposed to a known dose about 20% greater than the highest dose expected on the application film. The reference film and application film were irradiated within a narrow time window. The width of this time window is related to the delay between the exposure and scanning of the application film and corresponding reference filmstrip and is discussed in Sec. IV and explicitly in Sec. V.B. As a matter of practice we were able to expose the application films and corresponding reference filmstrip within 3–4 min, permitting scanning to be done within 20 min of exposure.

III.G.2. Scanning of EBT3 films

The EBT3 films were scanned using the Epson Scan driver operated through the FilmQA Pro application. A previously determined calibration data file (dose–response curve as shown in Fig. 3) for the EBT3 production lot was loaded into the software. The generation of the calibration data curve is described in Subsection IV.C. The time window within which the reference strip and application film were exposed was related to the speed with which the dose measurement and comparison to plan could be completed and the time-efficiency increases by minimizing the time window. For exposures t min apart, film scanning could be done $4t$ minutes later, or any time thereafter. A rationale is given in Subsection V.B. Figure 4 depicts the arrangement of the application film, the reference strip and an unexposed reference filmstrip on the scanner. By placing the films in the center of the scanner (lateral to the scan direction) the effects of the lateral scan artifact (see Sec. III.E) are

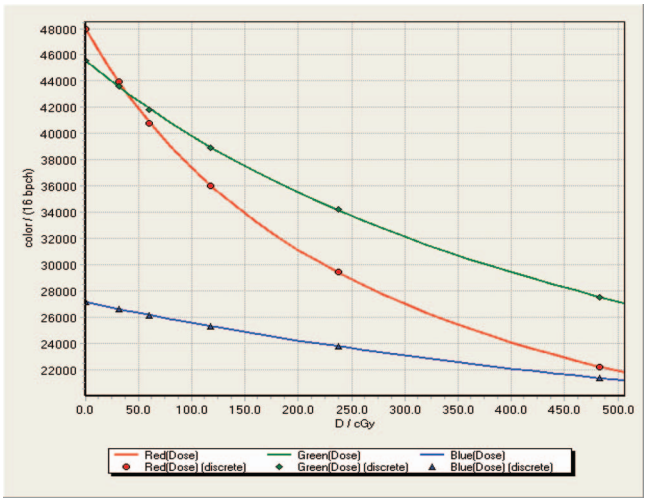

FIG. 3. Dose–response of GafChromic EBT3 film in the red, blue, and green color channels.

minimized. Areas of interest approximately 3.5 × 6 cm^2 were delineated in the centers of the reference strips. After the dose values were assigned, the dose–response function was rescaled as addressed in Sec. IV.B making the calculated doses for the unexposed and exposed reference strips equal to zero and the delivered exposure dose, respectively.

III.G.3. Data processing and analysis

The final step is to compare the measurements on the application films with the treatment plan. Using the tools available in the software the calculated dose map for the application film was moved into registration with the plan and quantitative comparison was made using gamma analysis and dose tolerance of 2% within 2 mm.

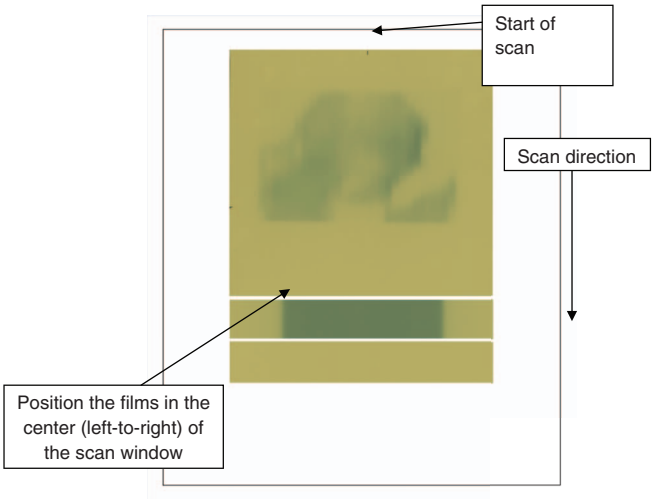

FIG. 4. Placement of films for scanning—top: application film; middle: reference film; bottom: unexposed film.

III.H. Patient-specific QA using an efficient new dosimetry protocol

III.H.1. Treatment planning calculations

Radiotherapy patients were scanned using a Phillips Big Bore CT scanner and the CT images were transferred to the Memorial Sloan-Kettering Cancer Center planning system,[26–28] which is capable of calculating IMRT, VMAT, and other complex treatment plans. The IMRT option in the planning system uses an iterative gradient algorithm to minimize an objective function which is represented as the sum of squares of the difference between the desired and the actual doses.[27] The algorithm calculates the intensity distribution of each beam so that the resultant dose distribution from all beams best matches the one specified by the planner. The dose distribution from these intensity-modulated beams is calculated with a pencil beam algorithm.[28]

III.H.2. Combined scanning of application films and reference strips

All films were scanned in transmission mode at the same central location and orientation on an Epson 10000XL flatbed scanner. Except where stated all films were oriented with the 20.3 cm dimension of the film perpendicular to the scanning direction. The settings of 48 bit color and 72 dpi (0.035 cm/pixel) were used, color correction was disabled, and files were saved in TIFF format. Each application film was scanned together with a corresponding exposed reference strip irradiated within 5 min of the application film and a strip of unexposed film. The elapsed time between exposure and scanning was at least 20 min, i.e., at least 4 times the interval between irradiation of the IMRT field and the reference film. The significance of this delay is addressed in Sec. V.B. The image processing and film analysis are done using FilmQA Pro software.

IV. RESULTS

IV.A. Postexposure changes of EBT3 films

Exposure of radiochromic film to ionizing radiation starts a solid-state polymerization in crystals of the active component, a member of the diacetylene family of compounds. The polymer grows within the crystal matrix of the monomer. The carbon–carbon interatomic distances in the polymer backbone are shorter than in the monomer and result in the gap between the end of the growing polymer chain and the next available monomer increasing as polymerization progresses. Consequently, the rate of polymerization decreases as polymerization proceeds. The behavior shown in Fig. 5 illustrates that the measured response for exposed film changes linearly in proportion to log(time-after-exposure).

Postexposure changes were measured for six production lots of EBT3 film scanned on seven different scanners of two different models (Epson 10000XL and V700). For each lot of film a set of six samples were obtained and exposed to doses between zero and 480 cGy. The example in Fig. 6 is

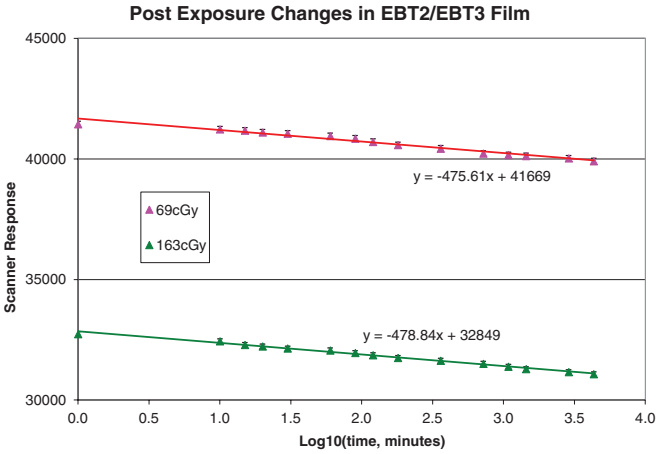

FIG. 5. The response of EBT3 film as a function of time-after-exposure.

characteristic of the way the red color channel response of each lot measured on each of the seven scanners changes with increased time-after-exposure. It is not apparent at the scale of the figure that the measured response values of the unexposed filmstrip exhibit a small degree of interscan variability. The values actually vary about ±0.3% from the average as shown in the inset. The differences are most likely due to the inherent stability of the electronic measurement circuits in the scanners as well as small temperature differences from scan-to-scan. We noted that the ambient temperature in our working environment would rise by 1–2 °C during the day. A detailed series of measurements of unexposed EBT3 film taken over 10-days time showed a small response difference that could be correlated with temperature difference, but we saw no pattern of behavior causing permanent change to the film. It is most likely that a part of the response difference of unexposed film we observed is due to temperature variation scan-to-scan.

Since the calibration strips were scanned together each time, it was reasoned that scanner and temperature effects could be eliminated by normalizing the responses measured

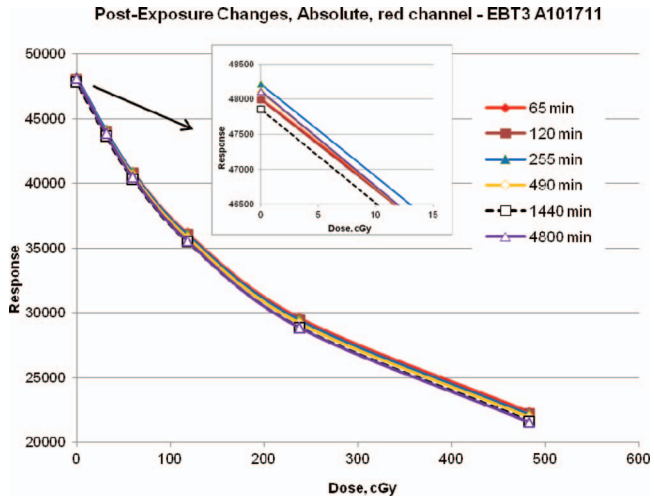

FIG. 6. Absolute response (red color channel) of EBT3 film on Epson 10000XL scanner response at various times-after-exposure.

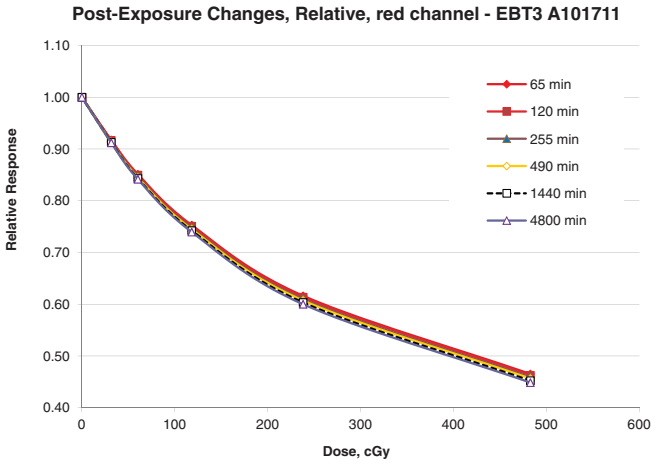

FIG. 7. Relative response of EBT3 film (red color channel) at various times-after-exposure.

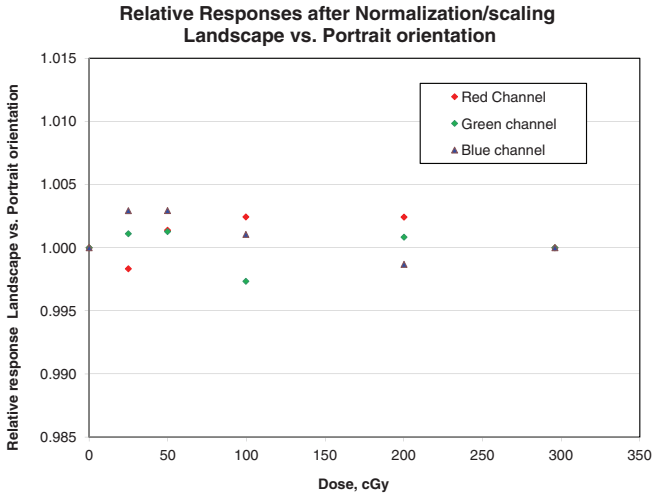

FIG. 9. Response of EBT3 scanned in different orientations—Relative values for the three color channels after normalization and scaling net responses.

for the various films in a particular scan to the response values measured for the unexposed film in that same scan. Treated in this way the observed behavior was monotonic with respect to time as illustrated in Fig. 7. Further, it was found that the calibration curves measured at the different times-after-exposure could be equalized by a linear scaling of the net response values. This is shown in Fig. 8 where the net values for all doses at time-after-exposure (T) have been scaled by the ratio of the net value at 480 cGy and 4800 min after exposure divided by the net value at 480 cGy and T minutes after exposure.

IV.B. Equivalence of response

When responses measured from images of film sets acquired in a variety of ways were treated as described in Sec. IV.A, similar behavioral equivalences were found. For instance, when the film responses measured on one scanner were normalized to the response value of the unexposed film on that same scanner, it was found that the behavior on a second scanner was equivalent and that the responses on the two

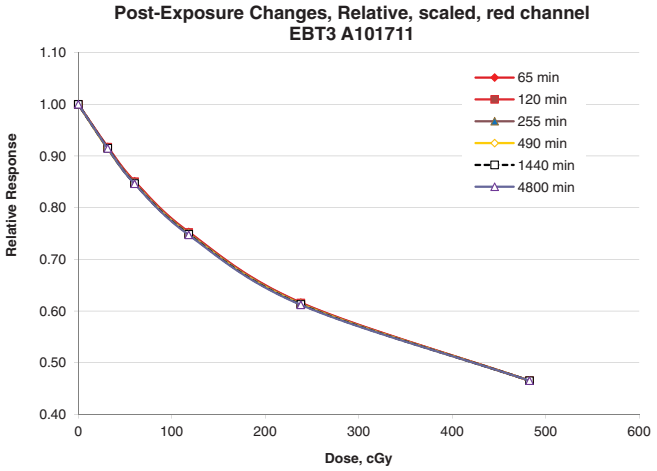

FIG. 8. Relative response curves (red color channel), postexposure, after linear scaling of the net response values.

scanners could be brought into correspondence by simple linear scaling of the net response values

$$N(D, S_{n,x}) = c.N(D, S_{m,x}),$$

where $N(D, S_{n,x})$ is the net response at any dose D for color channel x on scanner n; $N(D, S_{m,x})$ is the net response at any dose D for color channel x on scanner m; and c is a constant.

As a test we acquired data by measuring images of the same set of calibration films scanned on four different Epson 10000XL scanners. After normalization to the response of the unexposed film and scaling using values measured for two of the calibration films (0 and 482.6 cGy), we found very close agreement between the response values at each of the four intermediate doses on all four scanners. The range of response values for each intermediate dose, (maximum-minimum)/average, was <0.2%. After further measurements we found a similar pattern of equivalence in four other situations; equivalence between datasets acquired on different scanner models (Epson V700 and 10000XL); equivalence of response data acquired from films exposed at different photon energies (6 MV and 160 kVp x rays); equivalence of data acquired when films were scanned at ambient temperatures of 10 °C and 21 °C; and equivalence of data acquired from films scanned in different orientations, i.e., 20.3 cm side of the film parallel to the scan direction (landscape orientation) and perpendicular to the scan direction (portrait orientation). In this last case the correspondence of the normalized and scaled responses in the two orientations is illustrated in Fig. 9 where we have shown the response values in the two orientations are equivalent to about ±0.3% for all three color channels over the 0–480 cGy dose range.

IV.C. Generic calibration curve fitted by rational functions

The results indicated that the dose–response data could be fit by a set of related rational functions leading to the description of a generic calibration curve. A simplified protocol

was established where dose–response data for a specific film lot, scanner, and scanning conditions could be derived from a generic calibration curve using no more than two films exposed to known doses to adapt the curve to the specific case. In most cases only one calibrated exposure was required.

The normalized response N of the system with respect to dose can be correlated using rational functions of the form, for example,

$$\mathrm{N(D)} = \mathrm{A} + \frac{\mathrm{B}}{\mathrm{D}+\mathrm{C}} \text{ or } \mathrm{N(D)} = \mathrm{A} + \frac{\mathrm{B\,D}}{\mathrm{D}+\mathrm{C}}, \quad (1)$$

where A, B, C are parameters that can be fitted to calibration data using least square approach. For measured data (n_i, D_i), i = 1(1)I, n normalized system response, D dose, the equation

$$\sum_i (\mathrm{N(D}_i) - \mathrm{n}_i)^2 \rightarrow \min_{\mathrm{A,B,C}} \quad (2)$$

is minimized to determine the calibration parameters A, B, C.

A specific calibration can be derived from the normalized system response N using the rescaling relation

$$\mathrm{X(D)} = \mathrm{a} + \mathrm{b\,N(D)}, \quad (3)$$

where X is the response in one of the color channel R, G, or B. The two parameters a and b can be calculated as

$$\mathrm{a} = \frac{\mathrm{N_1X_2} - \mathrm{N_1X_1}}{\mathrm{N_1} - \mathrm{N_2}} \quad (4)$$

and

$$\mathrm{b} = \frac{\mathrm{X_1} - \mathrm{X_2}}{\mathrm{N_1} - \mathrm{N_2}} \quad (5)$$

if two data points (X_i, D_i), i = 1, 2, are available using $\mathrm{N}_i = \mathrm{N(D}_i)$. For larger sets of data points the least square solution solving

$$\sum_i (\mathrm{X(D}_i) - \mathrm{X}_i)^2 \rightarrow \min_{\mathrm{a,b}} \quad (6)$$

is calculated. Higher correlation order is achieved when using the extension

$$\mathrm{X(D)} = \mathrm{a} + \mathrm{b\,N(c\,D)} \quad (7)$$

of Eq. (3). The three parameters are determined using Eq. (6).

IV.D. Evaluating the new protocol using IMRT and VMAT delivery

The results described before led us to develop a simplified dosimetry protocol. In testing the protocol we used a Varian Trilogy Linac to expose IMRT and VMAT fields on EBT3 films from different production lots. We also exposed reference film samples from the same production lots of film as used for the treatment field to doses about 20% greater than the maximum in the plan for that field or arc. All three films were exposed within a 5-min time window and scanned, together with an unexposed reference film, on various Epson 10000XL scanners at times-after-exposure between 30 min and 72 h. The response images were converted to dose using FilmQA Pro software and a triple-channel method and using calibration data acquired for the film production lot at various times after exposure and on different scanners, etc., as described before. Using measurements acquired from a dose image, the doses in that image were scaled to bring the measured dose values of the reference films to their actual values.

TABLE I. The dose maps calculated for different times after exposure as compared to the treatment plan.

Time after exposure		Gamma % passing for 2% @ 2 mm		
Calibration (h)	Patient film and reference	Red	Green	Blue
2	30 min	97.9	97.0	97.6
2	60 min	97.6	96.2	97.3
2	4 h	97.7	96.3	97.3
2	24 h	97.9	97.0	97.8
2	72 h	97.9	97.6	97.9

Having exposed the films, a number of observations and comparisons were made of the fit between the measured dose maps calculated from the acquired data and the IMRT plan. In the first instance, we explored the affect of elapsed time between film exposure and scanning. To obtain the data presented in Table I the dose calculations were performed using calibration data acquired from a set of calibration films exposed within a 5-min time window and scanned about 2 h after exposure. The choice to use a calibration at 2 h was deliberate to allow calculation of dose maps from application films scanned substantially earlier and later in the postexposure period. The results in Table I demonstrate that the dose maps calculated for different times after exposure are in equally good agreement with the treatment plan. Figure 10(a) shows the close correspondence of the isodose contour maps calculated from scans at 30 min (thick lines) and 72 h (thin lines) after exposure. Compared using the gamma function more than 99.5% of pixels met the test criterion of 2% agreement within 2 mm. This shows effective compensation for postexposure growth is provided by scanning the reference films with the application film and applying values from the reference films to rescale the calibration function. For comparison, dose maps were calculated from the scans taken 30 min and 72 h after exposure using a calibration obtained from scans 2 h after exposure, but without using the rescaling protocol. In these cases the results showed poorer correspondence to the plan. Thus, the scans after 30 min and 72 h after exposure provided gamma passing rates (2% at 2 mm) of 91.9% and 89.2%, respectively. Inspection of profiles at a number of locations across the maps showed that the dose values from the 30 min scan were generally 1%–2% lower than the plan values while for the scan taken 3 days after exposure yielded results generally about 2%–3% above the plan values. These observations are consistent with the postexposure characteristics of radiochromic film, i.e., the film gets progressively darker with increasing dose and with increasing time-after-exposure.

As a second example, a set of four calibration filmstrips was prepared from EBT3 film, lot A101711, using three films exposed to 6 MV photons within a time window of ~5 min plus an unexposed film. About 2 h later the four films were scanned together on an Epson 10000XL scanner.

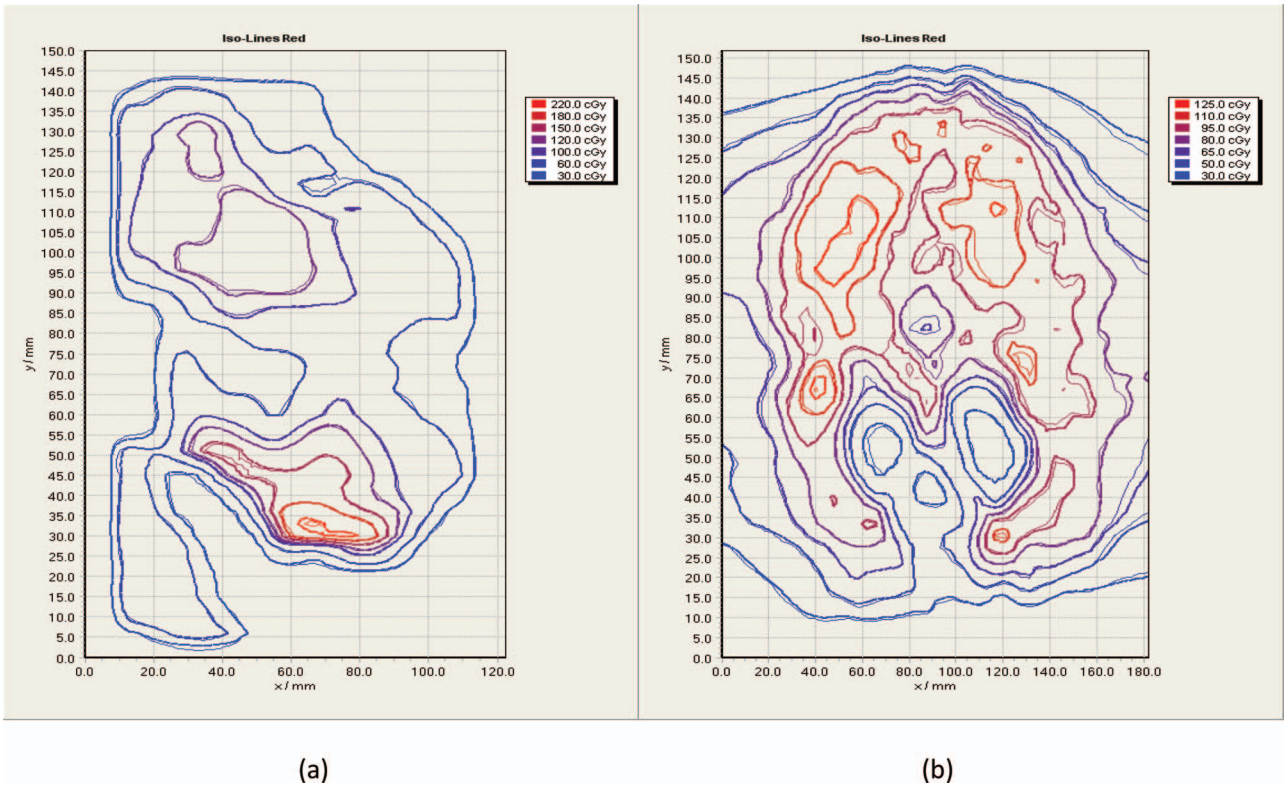

FIG. 10. Comparison of isodose maps (a) IMRT field with doses calculated from scans 30 min and 72 h after exposure; (b) VMAT beam with doses calculated using calibration in portrait (thick lines) and landscape (thin lines) orientations.

Measurements of the exposed areas were obtained and the dose–response data was plotted and fitted to the function X(D) = a + b/(D − c) described in Sec. II. Using a 6 MV photon beam, one field of an IMRT plan was exposed onto a sheet of application film and ∼3 min later a reference filmstrip was exposed to a dose of 313 cGy. About 72 h after exposure the application film and the reference filmstrips were scanned together on three different Epson scanner models—10000XL, V700, and 1680. All the response images were converted to dose images using the calibration response curve from the 10000XL scanner and rescaled using measurements taken from the reference strips. The resulting dose maps were then compared with the IMRT plan. Using the gamma function with test criteria of 2% dose agreement within 2 mm the pixel passing rates were 97.9%, 97.5%, and 97.6% for the 10000XL, V700, and 1680 scanner models, respectively. The dose maps were recalculated without rescaling. In this case, the passing rate for the 10000XL scanner dropped to ∼89% and the profiles showed the measured doses ∼2%–3% higher than the plan. This is expected because the application film was scanned at a much later time-after-exposure (72 h) compared to the calibration films (4 h). For the V700 and 1680 scanners the dose maps without rescaling had very poor correspondence to the plan. In both cases less than 40% of pixels meet the 2% at 2 mm test criterion. This is unsurprising because the absolute response values, and particularly the ratio of the red, green, and blue response values, are very different when the same films are measured on different scanner models. For example, the RGB response values of unexposed EBT3 film measured on a 10000XL and a V750 scanner were 48 106, 45 705, 27 301 and 46 885, 43 084, 23 743, respectively.

A third example relates to calibration data obtained in two different ways and the application of the new dosimetry protocol to rescale the calibration functions and calculate dose maps from a film exposed with a single arc VMAT plan. Two sets of filmstrips were cut from 20.3 × 25.4 cm^2 sheets of EBT3 film lot number A012412. One set was cut to 3.81 × 20.3 cm^2 and the second set to 3.81 × 25.4 cm^2. When arranged on a scanner with the short edges parallel to the scan direction the configurations allow the strips to be digitized in portrait and landscape orientations, respectively. Three of the 3.81 × 20.3 cm^2 strips were exposed to doses of 69.2, 138.4, and 360.0 cGy with a 6 MV beam and together with an unexposed film strip were scanned in portrait orientation as described above on an Epson 10000XL. Dose–response measurements were fitted to the function described above. A set of calibration exposures (72.5, 159.4, and 358.9 cGy) were made on the 3.81 × 25.4 cm^2 strips and together with an unexposed strip the films were scanned on the 10000XL scanner in landscape orientation as previously described. As before, the calibration film images were measured and the data fitted to a dose–response function. A 20.3 × 25.4 cm^2 sheet of film was exposed to the single arc VMAT plan and less than 5 min later a 3.81 × 20.3 cm^2 reference strip was exposed to a dose of 170 cGy. About 16 h after the exposures the VMAT film, the exposed reference strip, and a similar unexposed reference strip were digitized in portrait orientation (20.3 cm

dimension perpendicular to scan direction) on the 10000XL scanner. Dose maps for the VMAT film were calculated using the both the portrait and landscape orientation dose–response calibration functions rescaled according to the values measured for the reference strips. For comparison purposes a dose map was also calculated using the landscape orientation calibration function, but without using the reference films for rescaling. When the dose map from this latter case was compared to the plan less than 5% of pixels met the test criterion of 2% at 2 mm. However, when portrait and landscape dose–response functions were re-scaled using the reference films the passing rates were 95.6% and 96.5%, respectively. Furthermore, when those same dose-maps were compared with one another there was 99.9% agreement with the 2% at 2 mm test criterion. Figure 10(b) shows a comparison of the isodose maps calculated using the portrait calibration function (thick lines) and landscape calibration function (thin lines).

V. DISCUSSION

V.A. Efficient dosimetry protocol for triple-channel treatment plan QA

An efficient dosimetry protocol was demonstrated wherein a film to be measured and reference films were exposed within a narrow time window and then scanned at the same time. This procedure simplifies radiochromic film dosimetry and speeds its application for patient-specific IMRT plan verification. Since the IMRT/VMAT and the reference films are scanned together, interscan variability is eliminated as a source of error. As good results were obtained from calibration data acquired under a variety of conditions the protocol could potentially be used with a single, generic calibration function specific for the manufacturing lot of the radiochromic film. In addition, EBT film response has been reported to show no angular dependence,[29] making this and similar types of film like EBT2 and EBT3 suitable as dose verification tools for rotational-delivery modalities, such as VMAT. Using the Gamma test criterion of 2%/2 mm to evaluate the measurements, passing rates ranged between 95% and 99% for all the treatment fields studied. The uncertainties of the measured doses were estimated following the method described in the EBT3 film studies.[30,31] Combining the Type A (statistical) and Type B (nonstatistical) uncertainties, the uncertainties of the measured doses at individual pixels were estimated to be ~2.2% as compared to ~4% for the traditional single-channel film dosimetry.

V.B. Postexposure change and the new dosimetry protocol

As previously described (see Sec. IV.A) the response of radiochromic film continues to change after exposure in proportion to log(time-after-exposure). The behavior illustrated in Fig. 5 is characteristic of the active component in EBT2 and EBT3 films showing the rate of the postexposure change is about 0.05%/min at 60 min after exposure and about 0.01%/min at 4 h after exposure. This means that if dose–response calibration is established by scanning calibration films at a given time-after-exposure, an error in dose will result if the application film is scanned at a different time-after-exposure. However, the dose error diminishes rapidly as the ratio of the timing error to the time-after-exposure decreases. Using the data from Fig. 5, it was calculated that at a time-after-exposure of 30 min a 5-min timing error would result in a dose error of about 0.3%, while a 10-min timing error would result in a dose error about 0.6%. If the time-after-exposure increases to 60 min the dose error for a given timing error decreases by a factor of two. The new protocol employs a single scan to make dose measurements of application film and reference film exposed at different times. To keep dose errors small (<0.5%) film scanning should be delayed for a time period a minimum about four times longer than the interval between the exposure of the application film and the reference film. For example, if the exposures of the films were 5 min apart the films could be scanned 20 min later or any time thereafter. The user's efficiency increases when the time window is minimized. For single IMRT field we were always able to complete the plan and reference film exposures within 3 min. For a single VMAT beam delivery the time window for exposure was 2–3 min, rising to 4–6 min for a two-arc plan.

V.C. Lot-specific calibration characteristics of radiochromic film

Radiochromic film has been established as an accurate quantitative 2D dosimeter with fine spatial resolution for applications in external beam and brachytherapy, including IMRT QA, commissioning of treatment modalities, and verification of TPS.[32–41] Our work with a calibration film set from a lot of EBT3 film showed that the dose–response functions obtained under a variety of scanning conditions are equivalent to one another. That is, the shapes of the response curves are similar and can be adapted to one another by a simple two-point rescaling. This suggests that the dose–response of a single lot of EBT3 film, at least for the Epson scanners we used, could be represented by a generic response function and that generic function could be adapted for a specific instance by using a two-point rescaling based on one exposed reference film plus an unexposed reference film.

We repeated many of the measurements using five other lots of EBT3 film as well as three lots of EBT2 film and obtained similar results for each individual lot. However, when we compared the dose–response functions lot-to-lot and product-to-product we found that although the curves had a strong similarity they could not be adapted to one another with two-point rescaling. A similar conclusion regarding the response curves for batches of GafChromic EBT film was made by Xu.[42] The hope for describing the shape of the dose–response of EBT2 or EBT3 with a generic calibration function adaptable by two-point rescaling was not realized. Lot-to-lot differences must be described with a different generic calibration function for each lot or adapted to one another by three-point rescaling. The response functions we used are described by defining the values of three coefficients so three-point rescaling is equivalent to recalibration.

The concept of the generic and adaptable response function for each EBT2 or EBT3 film lot was developed into new protocols for dose calibration and dose measurement with these films. In Secs. IV.A–IV.D we described results showing that these protocols could result in the profound easing of the postexposure time restriction that previously has made it difficult to obtain dose measurement results without waiting for many hours. With the new measurement protocol it is possible to obtain results within a few minutes of exposure depending on the time window within which the application film and a reference film can be exposed.

Our work raises the possibility of publishing a generic calibration curve for each lot of EBT2 or EBT3 film applicable under a defined set of conditions. A user would have to adhere to the proscribed conditions and use reference films exposed at known doses to adapt the generic calibration for their case. The idea is supported by the results we present from using the new protocol to calculate dose maps from application films digitized on different scanners and in different orientations. In this way we have obtained equivalent results under a wide range of conditions under which the calibration function for the lot of film was adapted for a specific situation by scanning and measuring two reference films. While we do not present specific results in this paper, our work has also shown that the protocol appears to extend to cases where there are multiple differences between the way calibration data and measurement data were acquired. For instance, the calibration film data could be collected on scanner at a given time-after-exposure, a given orientation and a given temperature while the application film data can be collected on a different scanner, different time-after-exposure, different orientation, and different temperature. As long as the application film is scanned together with an unexposed reference film and a reference film exposed soon after the application film, the measurement protocol delivers dose results equivalent to those that would be obtained if the application film had been scanned under identical conditions to the calibration films.

VI. CONCLUSIONS

We have demonstrated a simplified protocol to measure doses delivered by an IMRT or VMAT plan using only the patient film, one reference film, one unexposed film, and applying a single scan to acquire a digital image for calculation and analysis. The simplification and timesaving provide a practical solution for using radiochromic film for routine treatment plan QA without sacrificing spatial resolution for convenience.

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