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Evaluation of a LED-based flatbed document scanner for radiochromic film dosimetry in transmission mode

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ABSTRACT

Flatbed scanners are the most frequently used reading instrument for radiochromic film dosimetry because its low cost, high spatial resolution, among other advantages. These scanners use a fluorescent lamp and a CCD array as light source and detector, respectively. Recently, manufacturers of flatbed scanners replaced the fluorescent lamp by light emission diodes (LED) as a light source. The goal of this work is to evaluate the performance of a commercial flatbed scanner with LED based source light for radiochromic film dosimetry. Film read out consistency, response uniformity, film-scanner sensitivity, long term stability and total dose uncertainty was evaluated. In overall, the performance of the LED flatbed scanner is comparable to that of a cold cathode fluorescent lamp (CCFL). There are important spectral differences between LED and CCFL lamps that results in a higher sensitivity of the LED scanner in the green channel. Total dose uncertainty, film response reproducibility and long-term stability of LED scanner are slightly better than those of the CCFL. However, the LED based scanner has a strong non-uniform response, up to 9%, that must be adequately corrected for radiotherapy dosimetry QA. The differences in light emission spectra between LED and CCFL lamps and its potential impact on film-scanner sensitivity suggest that the design of a dedicated flat-bed scanner with LEDs may improve sensitivity and dose uncertainty in radiochromic film dosimetry.

1. Introduction

Radiochromic films have become an excellent tool for dosimetry in modern radiotherapy due to its high spatial resolution, near tissue-equivalence and relatively easy handling. It has been used for dosimetry of X-ray photon, electron, and protons in external beam radiotherapy and also for the dosimetry of radioactive source in brachytherapy. Nowadays, it can be found in the literature a large number of radiochromic film protocols for the dosimetry of IMRT, VMAT and SRS plans, among other radiotherapy techniques. The establishment of a radiochromic film protocol does not only requires the definition of the radiochromic film model, but also requires the definition of the scanner to be used for film readout. In fact, the scanner directly or indirectly defines a great number of film properties, such as film reading noise, dose uncertainty, film response uniformity and film sensitivity. The scanners used most frequently for radiochromic film dosimetry are flatbed document scanners capable of digitizing transparent media with 48-bit in red-green-blue (RGB) mode (16-bit per color channel).

For many years, flatbed document scanners utilized a fluorescent lamp as a light source and several reports may found in the literature evaluating their performance for radiochromic film dosimetry [1–6]. However, recently flatbed scanners manufacturers have replaced the fluorescent lamp by light emission diodes (LED) as light source. The light production mechanism between fluorescent and LED light sources are different. The fluorescent lamps produce light through the excitation of electrons of a phosphor coating inside the lamp. Usually, the lamps are filled with a noble gas (xenon or argon) with mercury traces. An electric current in the gas excites the mercury within the gas that produces a great amount of ultra violet (UV) light. The UV light is absorbed by the phosphor which releases this energy as white light through fluorescence. The LED sources use the principle of electroluminescence in a semiconductor material to produce light. A current flows through a *p-n* junction diode exciting the electrons within the junction. Depending on the *p-n* junction material is the amount and spectrum of the produced light. For white light LEDs, it is used yttrium aluminum garnet (YAG, $Y_3Al_5O_{12}$) in combination with a phosphor

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coating. Despite similarities between fluorescent and LED based lamps, it is expected that the emission spectrum will be different and it may affect the overall response of radiochromic film dosimetry.

The goal of this work is to evaluate the performance of a commercial flatbed scanner with LED based source light for radiochromic film dosimetry. Film read out consistency, response uniformity, film-scanner sensitivity, long term stability and total dose uncertainty was evaluated for an Epson Perfection V800 (Epson, Inc., Japan) LED based scanner. The performance of the Epson Perfection V800 was compared with that of an Epson Expression 11000XL (fluorescent lamp based). Also for comparison, it was measured the emission spectra of each scanner.

2. Materials and methods

2.1. Radiochromic film and irradiation setup

The radiochromic film used in this work was the model EBT3 (Ashland, USA) with batch number A03071602. The characteristics of the film are widely reported in the literature. The response of the film was assessed using the net optical density defined as follows [6],

$$netOD = \log_{10} \left(\frac{I - I_{bckg}}{I_0 - I_{bckg}} \right) \quad (1)$$

where I and I_0 are the readings for irradiated and unirradiated films, respectively. I_{bckg} is the intrinsic background signal (zero light) of the scanner which is measured by scanning an opaque film. The associated uncertainty to Eq. (1) is,

$$\sigma_{netOD} = \frac{1}{\ln 10} \sqrt{\frac{\sigma_{I_0}^2 + \sigma_{bckg}^2}{(I_0 - I_{bckg})^2} + \frac{\sigma_I^2 + \sigma_{bckg}^2}{(I - I_{bckg})^2}} \quad (2)$$

Film irradiation was carried out using a TrueBeam STx® (Varian Medical Systems, USA) linear accelerator with a 6 MV (with flattening filter) photon beam. All irradiations were performed in a solid water phantom slab with total dimensions of 30 cm × 30 cm × 30 cm. If it is not explicitly mentioned, the irradiation geometry was SAD (source to axis distance) of 100 cm at 5 cm depth. The radiochromic film was handled according with the recommendations published on the literature [7,8].

2.2. Document scanners and emission spectrum measurement

For this work, two commercial available flatbed scanners were used from the manufacturer Seiko Epson Corporation (Japan). The Epson Perfection v800 employs a white LED light source with an emission spectrum from 400 to 725 nm. The light source is coupled with a 6-line CCD sensor array with a nominal digitizing spatial resolution of 4800 dpi. This scanner has a maximum scanning area of 20 cm width and 25 cm height, approximately. The Epson Expression 11000XL scanner employs a Xenon gas cold cathode fluorescent lamp coupled with a line CCD sensor array with a nominal scan resolution of 2400 dpi. The emission spectra covers the range from 400 to 725 nm. The maximum scanning area is 31 cm width and 42 cm height, approximately. Both scanners are capable of digitizing films with a color depth of 48-bit (16-bit per color channel). The parameters used for radiochromic film digitization for both scanners were 72 dpi resolution, 48-bit color depth and all color correction turned off. The digitized films were saved in TIFF (tagged image file format) without compression. The digitization was carried out using the Epson Scan v. 3.9 software for both scanners. All the films pieces were digitized 5 days after irradiation to avoid film post-colorization effects to film response [9].

The emission spectrum for each scanner was measured using a spectrometer model USB2000+ (OceanView Optics, USA). The spectrometer uses a fiber optic probe of 1 m length connect to the spectrometer at one end and a metal pin-hole cap for collimation and

handling to the other end. The optic fiber was oriented towards the transparent unit of each scanner in vertical position at a distance of 10 cm. Since the Epson Scan software does not have an option to turn on the light of the scanner, the preview option of the software was used with high-resolution option turned on. After the initial sensor calibration of the scanner, the transparent unit was positioned vertically (perpendicular to the scanner) and proceed with the measurement. An initial spectrum was recorded, and then this experiment was repeated 50 times for long term stability of the light source for each scanner.

A semi-quantitative analysis was performed on the measured emission spectra. Three wavelength bands were defined to mimic the RGB channels [10] and they are based on the absorption spectra of radiochromic film EBT-3 [11]. The bands are defined as follows: 636 ± 25 nm (main absorption peak), 575 ± 25 nm (includes peaks at 560 and 585 nm) and 450 ± 50 nm for red, green and blue channels, respectively. The emission spectra of both scanners were integrated over each band to calculate the emission proportion for each color channel.

2.3. Scanner performance evaluation

2.3.1. Sensitivity

The sensitivity of EBT3-scanner system was assessed using the first derivative of the sensitometric curve for each color channel and scanner. For that purpose, radiochromic film was irradiated within a dose range from 0 to 800 cGy. The sensitometric curve consisted of 16 dose points with 3 independent measurements each. For each scanner and color channel, the sensitometric curve was the weighted average of the 3 measurements per dose point. The weighted average and its associated uncertainty were assessed as following [6,12,13],

$$netOD(D) = \frac{\sum_{i=1}^3 netOD_i(D) / (\sigma_{netOD}^i)^2}{\sum_{i=1}^3 (1 / (\sigma_{netOD}^i)^2)} \quad (3)$$

and

$$(\sigma_{netOD})^2 = 1 / \sum_{i=1}^3 (1 / (\sigma_{netOD}^i)^2) \quad (4)$$

In this work, if it is not explicitly stated, the reported uncertainty is 1σ. The sensitometric curve for each color channel was fitted using the universal dose response model equation [14]:

$$netOD(D) = A_x \left[1 - \left(1 + \frac{D}{k} \right)^{-\vartheta} \right] \quad (5)$$

where A_x and k (cGy) are fitting parameters depending on the color channel and scanner system, and $\vartheta = 0.436 \pm 0.005$ is a universal constant that only depends on the sensitive material. The parameter A_x is related to the saturation netOD and k is related to the sensitive of the system. The first derivative of Eq. (5) was used to assess the overall sensitivity of the system. One of the advantage to use the universal-dose response model resides on the use of reduced units to express the sensitometric curve and sensitivity of the scanner-film system. On such units, the sensitivity of the system is expressed as [14],

$$\frac{dnetOD}{dD} = \frac{A_x}{k} \frac{dy}{dd} \quad (6)$$

where $y = netOD/A_x$ and $d = D/k$ are the reduced quantities. The Eq. (6) shows that the sensitivity can be separated in two factors, an intrinsic film sensitivity that only depends on its properties as a function of delivered dose (dy/dd), and a sensitivity depending of the scanner-channel used (A_x/k) for readout. Since the same films were digitized on both scanners, only the A_x/k factor was used to evaluate the scanner-film sensitivity.

2.3.2. Total dose uncertainty

The total dose uncertainty analysis was performed using the dose

calibration function of the form,

$$D(\text{netOD}) = b \cdot \text{netOD} + c \cdot \text{netOD}^n \quad (7)$$

where b and c are fitting parameters and n is a power constant determined by minimizing the uncertainty of the b and c parameters. Following the recommendations and previous results from the literature [6,14,15], the total dose uncertainty is expressed as,

$$\sigma_{D_{\text{tot}}}^2 = \sigma_{D_{\text{exp}}}^2 + \sigma_{D_{\text{fit}}}^2 \quad (8)$$

where,

$$\sigma_{D_{\text{exp}}} = \frac{\sqrt{(b + n \cdot c \cdot \text{netOD}^{n-1})^2 \cdot \sigma_{\text{netOD}}^2}}{D_{\text{fit}}} \times 100 \quad (9)$$

and

$$\sigma_{D_{\text{fit}}} = \frac{\sqrt{\text{netOD}^2 \cdot \sigma_b^2 + \text{netOD}^{2n} \cdot \sigma_c^2 + \text{netOD}^{n+1} \cdot \sigma_{bc}}}{D_{\text{fit}}} \times 100 \quad (10)$$

The σ_b and σ_c are the associated uncertainties of the fitting parameters b and c , respectively. The term $\text{netOD}^{n+1} \cdot \sigma_{bc}$ in Eq. (10) is the contribution to the total uncertainty of the covariance between the parameters b and c . The σ_{netOD} is the associated uncertainty of the experimental netOD. The dose uncertainty was estimated for the 3 color channels and both scanners.

2.3.3. Film uniformity response

The film uniformity response analysis was determined by scanning whole films that were uniformly irradiated at different doses. The films were irradiated using a 30 cm × 30 cm field size at a depth of 10 cm in solid water. The doses used for irradiation were 50, 200, 500 and 800 cGy. The irradiated films and an unirradiated film were digitized using each scanner. The software ImageJ® was used to acquire intensity profiles perpendicular to the source-sensor movement of the scanner. The profiles were normalized relative to each scanner center and plotted as a function of off-center distance for comparison.

2.3.4. Polarization effect

For this experiment, film pieces were used with dimensions of 4 cm × 4 cm; they were marked such that it was possible to distinguish between portrait (0°) and landscape (90°) orientations. Five batches were organized containing 5 film pieces, each batch was selected to be irradiated to a single dose of 50, 200, 500 and 800 cGy. All the films were digitized at 0° and 90° in both scanners and the readings for each dose-orientation were weighted averaged using Eq. (3). The ratio between readings at each orientation was used to determine the polarization effect as a function of dose.

2.3.5. Film read-out consistency

A non-radiochromic film was scanned 50 times on each scanner to register possible changes in scanner response. It was used a KODAK IT8™ target template which is a transparent film with a grid of colors and gray tones used to calibrate transmission scanners for color reliability. The 50 digitized film images were analyzed using ImageJ® by recording the color intensity of 20G (red) in the red channel, 20H in the green channel and 20I in the blue channel. The data was analyzed by using the mean and standard deviation for the mean of the 50 readings.

2.3.6. Long term stability

It has been reported in the literature that the scanner light emitting source may impact the reading of the film. The long term stability is related to thermal effects of the film after long working session with the scanner [6]. The effect of the light source on the film response is commonly assessed by scanning a single film piece for a fixed dose several times (continuously). It was selected 5 pieces of the irradiated radiochromic film (one per exposition dose) from the polarization experiment. Each film was digitized 50 times and the color intensity

Fig. 1. Emission spectra from V800 (solid) and 11000XL (dashed) flatbed scanners. The horizontal arrows (at the top of the graph) show the position of the bands defined for area integration. From left to right are the blue, green and red bands.

recorded for each channel in one scanner. The above was repeated with another 5 film pieces in the other scanner. The readings were analyzed using the mean and the standard deviation of the mean of 50 readings [3].

3. Results

3.1. Light emission spectra

The measured light emission spectra for each scanner was normalized to its maximum for displaying purposes. Fig. 1 shows the normalized spectra for the Epson Perfection V800 (LED based) and Epson Expression 11000XL (CCFL based). It can be observed that the V800 spectrum shows two peaks, one narrow and one wider, located at 444 and 556 nm. The spectrum showed by the 11000XL scanner present several emission peaks. It can be identified 5 narrowed peaks located at 486, 542, 592, 610 and 626 nm.

The Table 1 shows the results of the spectrum integration over the defined bands. It can be observed that for blue and red bands, the area fractions for the 11000XL scanner are greater than the corresponding ones for the V800 scanner. In the other hand, for the green channel occurs the opposite, its area fraction for the V800 scanner is greater than the area fraction of the 11000XL scanner. These differences in area fraction may impact the sensitivity of the film-scanner system.

The 50 spectra resulting of the 50 consecutive spectrum measurements were normalized and analyzed. For both scanners, it was not found any appreciable difference in the shape of the spectra.

3.2. Sensitivity

Fig. 2 shows the sensitometric curves and their fitting functions using the universal-dose response model for V800 (Fig. 2a) and 11000XL (Fig. 2b) scanners. It can be observed the usual sensitometric curves for EBT3 film, with a higher sensitivity as expected for the green

Table 1

Normalized area fraction spectra for each scanner. The normalization was relative to the total area of each spectrum. The sum is not unity due that the 3 bands do not cover the whole spectrum.

Band	V800 (LED)	11000XL (CCFL)
611 nm–661 nm (R)	0.11	0.18
500 nm–600 nm (G)	0.36	0.22
400 nm–500 nm (B)	0.19	0.24

Fig. 2. Sensitometric curves of red (●), green (▼) and blue (■) channels for both scanners V800 (solid symbols) and 11000XL (open symbols). The continuous and dashed lines represent the fitting curves of the universal-dose response model. The uncertainty for each sensitometric curve is less than the size of the symbols.

Table 2

Parameters from the universal-dose response model and the scanner-channel sensitivity defined as the ratio A_x/k . The magnitudes were rounded to one digit. The value within parenthesis is the uncertainty associated to each fit parameter. In the case of A_x/k ratio, the value within parenthesis is the combined total uncertainty.

Parameter	Epson Perfection V800			Epson Expression 11000XL		
	R	G	B	R	G	B
A_x	1.1 (1.3%)	1.8 (1.7%)	0.9 (2.0%)	1.4 (2.4%)	1.7 (2.8%)	1.1 (9.2%)
k (cGy)	500.3 (2.2%)	1159.0 (2.5%)	1170.2 (2.5%)	518.8 (4.2%)	1206.3 (3.6%)	1570.5 (11.3%)
A_x/k (10^{-3} cGy $^{-1}$)	2.2 (2.6%)	1.6 (3.0%)	0.8 (3.2%)	2.7 (4.8%)	1.4 (4.6%)	0.7 (14.6%)

channel (relative to the red channel) for the V800 scanner. The Table 2 show the fitting parameters of the universal-dose response model. It can be observed that, if it is used the ratio A_x/k as a measure of sensitivity, the red channel of the V800 is less sensitivity that for the 11000XL, but for the green channel the V800 is more sensitive that the 11000XL scanner. In the case of blue channel, the sensitivity of both scanners is comparable.

3.3. Total dose uncertainty

The Fig. 3 shows the total dose uncertainty as a function of the delivered dose to the film. It can be observed that both flat-bed scanners show similar dose uncertainty levels. The film-scanner system may achieve uncertainties less than 2% for doses above 100 cGy and less than 1% for doses higher than 200 cGy. In the case of blue channel, there is a discrepancy between V800 and 11000XL scanner. The V800 blue channel may achieve uncertainties less than 1% for delivered doses above 300 cGy, while 11000XL shows an uncertainty total dose greater or equal than 1% for the whole dose interval. The fitting contribution (σ_{fit} , see Eq. (4)) for both scanners and channels is less than 0.5% for the whole does interval, with the exception of the blue channel for 11000XL scanner that shows a $\sigma_{fit} > 1\%$.

3.4. Film response uniformity

The Fig. 4a and b show the normalized horizontal profiles for the uniformly irradiated films for V800 and 11000XL scanner, respectively. The profiles were normalized to the scanner center. It can be observed

Fig. 3. Total dose uncertainty as a function of delivered dose for Epson Perfection v800 (solid symbols) and Epson Expression 11000XL (open symbols) for red (●), green (▼) and blue (■) channels. The dashed horizontal lines show the 2 and 1% uncertainty levels, respectively. The dotted and dashed lines between symbols are for visual purposes.

(a)

(b)

Fig. 4. Lateral profiles normalized to unity at the center of the scanner for (a) Epson Perfection V800 and (b) Epson Expression 11000XL. The profiles were fitted to second order polynomials with the exception of the V800 scanner where a third order polynomial was used for doses greater than 200 cGy. The y-axis scale was chosen to be comparable with lateral response functions reported in the literature [16].

Fig. 5. Polarization effect for v800 (solid symbols) and 11000XL (open symbols). The dotted and dashed lines between symbols are for visual purposes. Uncertainty bars are 1 σ level.

that V800 flat-bed scanner has a strong lateral response function compared to 11000XL. For the V800 scanner, the un-irradiated profile (0 cGy dose) shows a center to off-axis ratio down to 0.960 while for the 11000XL is about 0.995. In the case of 800 cGy, the differences showed at 0 cGy decreasing for values of 0.92–0.94 for V800 and 11000XL, respectively.

3.5. Polarization effect, read-out consistency and long-term stability

Fig. 5 shows the film response ratio between portrait and landscape orientations. It can be observed no appreciable differences between the results of both scanners within the uncertainty bars. Both scanner show the same trend for the three color channels. Fig. 6 shows the results of consistency (Fig. 6a) and effect of the light scanner on film response (Fig. 6b).

From Fig. 6a, it can be observed that V800 scanner does not show any appreciable change in OD as a function of number of consecutive scans when non-radiochromic media are digitized. The 11000XL shows a change in OD of $\sim 2\%$ between the first and fifth scan. The calculated SNR shows that V800 and 11000XL scanners have values of 1100 and 600 for the transparent media, respectively. For black media, SNR values are 950 and 400 for V800 and 11000XL scanners, respectively. Fig. 6b shows no appreciable effect on radiochromic film response for both scanners. However, the statistical analysis shows a significant trend ($r^2 > 0.69$ and $p < 0.05$) to slightly decrease the pixel value (increase OD) for irradiated and non-irradiated films using 11000XL scanner.

4. Discussion

This work shows the performance of a LED based flatbed scanner and its comparison with that of a CCFL based flatbed scanner which is commonly used for radiochromic film dosimetry in research and clinical applications. The measured LED emission spectra showed that the light source of the V800 scanner is consistent to that of YAG:Ce based white LEDs [17]. The results from Table 1 suggest that V800 scanners may have a potential greater sensitivity for the green channel than 11000XL scanner (see Table 2). The later is supported by direct comparison of the sensitometric curves. From Fig. 2, it can be observed that the 11000XL scanner has a higher sensitivity than the V800 for red and blue channels. However, as mentioned above the V800 green channel has a higher sensitivity than the 11000XL green channel. Comparing channel relative area from Table 1 with scanner channel sensitivity from Table 2, it can be inferred that channel relative area is a good

Fig. 6. (a) Readout consistency for V800 (circles) and 11000XL (triangles). A black ($OD > 1.2$) and transparent ($OD < 0.096$) non-radiochromic media were scanned. (b) Effect of scanner light on film response after 50 consecutive scans for V800 (circles) and 11000XL scanners (triangles). A 200 cGy (pixel value < 27000) and non-irradiated (pixel value > 38000) radiochromic films were scanned. The uncertainty is $< 0.6\%$ for all points and both graphs.

parameter to estimate scanner channel sensitivity. The results of total dose uncertainty shows a slightly advantage of V800 over 11000XL scanner. Both scanners may provide dose uncertainties less than 1% for absorbed doses greater than 2 Gy for red and green channels. In the case of the blue channel, V800 scanner shows total dose uncertainties less than 1% after 3 Gy while the dose uncertainties for 11000XL scanner is greater than 1% for the whole dose interval. Blue channel shown a higher σ_{fit} than red and green channels for both scanner, but more noticeable for the 11000XL scanner.

The non-uniform response of the V800 scanner is consistent to that of the V750 scanner [16] which is a previous version of the V800 scanner with CCFL lamp (see Fig. 4). The latter is due that the non-uniform response of the scanner is mainly affected by its optical system (the lenses) [18]. The above results suggest that non-uniform response of the scanner is not influence by the light source. However, V800 scanner has a higher degree of non-uniformity compared to the 11000XL scanner. It can be observed from Fig. 5 that for a dose of 200 cGy, the V800 had an under-response of $\sim 5\%$ compared to $\sim 2.5\%$ of the 11000XL scanner. These differences may be attributed to the length of the lamp/CCD array (rather than the differences between LED and CCFL lamps) of the 11000XL scanner which is 11 cm greater than the V800 lamp/CCD array, thus decreasing the edge effects in the analyzed length (500 pixels ~ 17.5 cm).

It was not observed important differences in polarization effects between both scanners, despite the difference in light source. The later indicates that initial polarization of the light for both scanners lamps is identical [18]. However, the read-out consistency of V800 scanner is higher than 11000XL. It can be observed from Fig. 6a that for V800 scanner there is no appreciable changes in OD as a function of consecutive scan number while for the 11000XL scanner there is a change of 2.2% within the first 5 scans [19]. Fig. 6b shows that the LEDs light source had no effect on the radiochromic film response as a function of consecutive scans. Also, it can be observed that CCFL lamp has a small effect on radiochromic film response which is consistent with findings reported in the literature [3,19]. CCFL lamps increase the temperature of the scanner glass tray which cause a change in radiochromic film optical properties.

The results of this work show that, in overall, the performance of the V800 scanner is comparable to that of the 11000XL scanner. The V800 scanner has three advantages over 11000XL, 1) smaller total dose uncertainty for R, G, B color channels, 2) no appreciable changes in lamp spectra due to lamp warm-up and 3) the LED lamp does not affect the film response in 50 consecutive scans. One result to highlight, is the comparison of the green channel sensitivity between V800 and 11000XL scanners which is strong related to the light emission spectra of LED and CCFL lamps. It was found in this work that the magnitude of area fraction is a good predictor of the final film-scanner sensitivity. The above may be used to design future dedicated flat-bed scanners for film dosimetry which optimize the sensitivity for each channel. The latter may be possible by using LEDs with emission spectrum compatible with the radiochromic film absorption spectra.

5. Conclusions

In overall, the performance of the LED document scanner is comparable to that of a cold cathode fluorescent lamp (CCFL). There are important spectral differences between LED and CCFL lamps that results in a higher sensitivity of the LED scanner in the green channel. Total dose uncertainty, film response reproducibility and long-term stability of LED scanner are slightly better than those of the CCFL. However, the LED based scanner has a strong non-uniform response that must be adequately corrected for the measurement of dose distributions. The differences in light emission spectra between LED and CCFL lamps and its potential impact on film-scanner sensitivity suggest that the design of a dedicated flat-bed scanner with LEDs may improve sensitivity and total dose uncertainty in radiochromic film dosimetry.

Declarations of interest

The authors have no conflicts of interest.

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