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Precautions and strategies in using a commercial flatbed scanner for radiochromic film dosimetry

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Abstract

The purpose of this study was to investigate the value of a commercially available flatbed scanner for film dosimetry with radiochromic film for external radiotherapy. The EPSON Pro 1680 Expression scanner was examined as a densitometer for two-dimensional film dosimetry with Gafchromic EBT film. An accurate and efficient scanning procedure was established. Possible drift and warm-up effects of the scanner were studied and the direct physical influence of the scanner light on the radiochromic film was assessed. Next, we investigated the scan field uniformity. Also, we examined if the accuracy of radiochromic film was improved by subtracting the optical density of the unirradiated blank film from the optical density of the irradiated film. To assess the accuracy of Gafchromic EBT film when the EPSON scanner was used as a densitometer, the depth dose of a 2×15 cm^2 field and the in-plane and cross-plane profiles of a 15×15 cm^2 field were measured and compared with diamond detector measurements. When taking consecutive scans, we found that the optical density taken from the first scan was about 1% higher than the optical density taken from subsequent scans. We attribute this to the warming up of the lamp of the scanner. Longer-term drift of the scanner was found to be absent. We found that the use of a correction matrix was necessary to correct for the non-uniform scanner response over the scan field. Subtracting the optical density of the unirradiated blank film from the irradiated film improves the precision of the Gafchromic EBT film. Depth dose and profile measurements with Gafchromic EBT film and the diamond detector are in agreement within 2.5%. The EPSON Pro 1680 Expression scanner is an excellent tool for accurate two-dimensional film dosimetry with Gafchromic EBT film provided that some precautions and corrections are taken into account.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

New techniques in radiotherapy, such as IMRT and IMAT, increase the planning and delivery complexities. Therefore, there is a growing need for entire treatment dose verification. The presence of sharp dose gradients around organs at risk, which lead to important volume effects for many detectors, and the contribution of low-energy scattered photons to the absorbed dose make accurate dose measurements difficult. Two-dimensional radiochromic film dosimetry is appropriate for entire treatment dose verification because of its high spatial resolution, nearly tissue-equivalency and low energy dependence (Niroomand-Rad *et al* 1998).

The recently developed radiochromic film Gafchromic EBT (International Specialty Products Corporation, Wayne, NJ, USA) is almost free of the drawbacks of the previous types of radiochromic film, such as high cost, inhomogeneous dose response, post-irradiation colouration and low sensitivity (Niroomand-Rad *et al* 1998, Rink *et al* 2005, Cheung *et al* 2005).

There are several types of densitometers in use for two-dimensional film dosimetry and each of them has its own specific characteristics (Devic *et al* 2004). The EPSON Pro 1680 Expression scanner is frequently recommended as a densitometer to perform two-dimensional film dosimetry with Gafchromic EBT film. This is a commercially available flatbed document scanner equipped with a transparency unit which allows the acquisition of images in transmission mode.

The aim of this study is to examine the characteristics of the EPSON Pro 1680 Expression scanner in combination with Gafchromic EBT film and to optimize the accuracy of the film acquisition process. First, an accurate and efficient scanning procedure was determined and possible drift and warm-up effects of the lamp of the scanner were studied. The direct influence of the fluorescent scanner light on the radiochromic film was assessed. Next, the scan field uniformity was investigated. Furthermore, we examined if the precision of the radiochromic film can be improved by subtracting the optical density of the unirradiated blank film from the optical density of the irradiated film. Finally, to determine the resulting accuracy of Gafchromic EBT film in combination with the EPSON scanner, the depth dose of a 2×15 cm^2 field and the in-plane and cross-plane profiles of a 15×15 cm^2 field were measured and compared with diamond detector measurements.

2. Materials and methods

To examine the characteristics of the EPSON Pro 1680 Expression scanner (Seiko Epson Corporation, Nagano, Japan), we make use of 2×2 cm^2 pieces of Gafchromic EBT film, with sheet dimensions of 8×10 (Lot no 34267-004). The film pieces were irradiated at the Elekta SL*i*plus (Elekta, Crawley, UK) linear accelerator equipped with the standard multileaf collimator. The film pieces were placed in the central part of a 10×10 cm^2 field in a polystyrene slab phantom at a depth of 5 cm and an SSD of 95 cm. A beam quality of 6 MV was used. The maximum available output rate of 400 MU min^{-1} was applied. Due to post-irradiation colouration of the films, we waited at least 6 h before scanning the films (Cheung *et al* 2005).

2.1. Image acquisition

Since the white fluorescent light of the scanner may directly affect the optical density of radiochromic film, both radiographic and radiochromic films are used to investigate the characteristics of the scanner. The two types of films were scanned with the software package

'EPSON scan', which is used in professional mode with all image adjustments and colour corrections turned off. A resolution of 72 dpi was applied. Radiochromic films were scanned in the 48 bit red-green-blue (RGB) mode (16 bits per colour) and radiographic films were scanned in the 16 bit greyscale mode. Data were saved in a tagged image file (TIFF). Each scan was taken over the whole scan field, even if only a small piece of film was scanned. The portrait orientation of the original (rectangular) film sheets was maintained since pixel values obtained from films scanned in landscape orientation were systematically higher due to polarization effects (Butson *et al* 2003). Film analysis was performed using in-house written routines in the Matlab environment (The Math Works, Inc., Natwick, MA, USA, Matlab 6.5). For radiochromic film, only the red component was extracted from the image file, since the sensitivity of the blue radiochromic film was found to be higher in red. Measured transmission values were converted into raw optical density—further denoted as optical density (OD)—by using the formula

$$\mathrm{OD} = \log_{10}(I_0/I_\mathrm{t})$$

where I_0 ($I_0 = 2^{16}$) is a reference for the light intensity incident on the film and I_t is the measured light intensity transmitted through the film.

2.2. Drift of the scanner on short term

In contrast to some other scanners, such as the Vidar VXR-12 (Mersseman and De Wagter 1998) and the Agfa Arcus II (Devic *et al* 2005), there is no possibility of warming up the lamp of the EPSON scanner prior to scanning. So, the lamp of the scanner is only turned 'on' during previewing or scanning. Therefore, the short-term effect of the warming up of the lamp of the scanner has to be assessed to establish an accurate and efficient scanning procedure.

In view of the fact that the radiochromic film is possibly sensitive to the light of the scanner lamp, this analysis was first conducted with radiographic film type EDR2 (Eastman Kodak Co., Rochester, NY, USA). An unirradiated (but developed) piece of 2×2 cm^2 of radiographic film was placed in the centre of the scan field. First, the film was scanned rapidly ten times after each other, without taking a preview. After waiting for 15 min, to let the scanner lamp cool down, the film was again scanned ten consecutive times, but now a preview was taken before scanning. The optical density of the film was obtained as the average over the central 1.4×1.4 cm^2 (40×40 pixels) of the film.

In parallel, exactly the same procedure was followed for a 2×2 cm^2 piece of radiochromic film that was irradiated to a dose of 128 cGy.

2.3. Drift of the scanner on long term

Since the fluorescent scanner light might influence the optical density of radiochromic film, we make use of radiographic film to assess the long-term drift of the scanner. An unirradiated (but developed) piece of EDR2 film of 2×2 cm^2 was placed in the centre of the scan field and 100 scans were taken consecutively with only a few seconds in between. The time needed to take 100 consecutive scans was about 1 h. No preview was taken before scanning. The optical density was obtained as the average over the central 1.4×1.4 cm^2 of the film.

2.4. Influence of the fluorescent light of the scanner lamp on EBT

To investigate the influence of the fluorescent lamp of the scanner on EBT, six film pieces of 2×2 cm^2 were irradiated to a dose of 0, 29, 70, 128, 201, 290 and 396 cGy respectively. The films were arranged all together on the scan field and 105 consecutive scans were taken. The optical density was obtained as the average over the central 1.4×1.4 cm^2 of the film.

2.5. Uniformity of the scan field

Preliminary research revealed that the response over the scan field is not uniform. The measured optical density is larger at the long side of the scan field than in the centre. Each type of transparent medium, for instance radiochromic film, radiographic film or overhead sheet, gives cause to different deviations. Furthermore the deviations are dependent on the optical density and the colour channel. The magnitude of the observed deviations makes it necessary to determine a correction matrix for the non-uniform response over the scan field. It is not preferable to use a whole EBT film sheet to determine the correction matrix, because it is not possible to irradiate the whole area of the film with a homogenous field and because the film manufacturer warrants only homogeneity within 2%. Therefore, we prefer a straightforward approach to determine the correction matrix for the non-uniform response over the scan field. To that end, we defined 11×7 equally distributed positions over the scan field for which the correction factors, defined as the ratio of the optical density at these points and at the centre of the scan field, were determined with use of small pieces of EBT film of 2×2 cm^2. The optical density was assessed as the average optical density over the central 1.4×1.4 cm^2 part of the 2×2 cm^2 film. In the scan direction (vertical direction) and perpendicular to it (horizontal direction), we distinguish 11 rows and 7 columns. We created a paper template with 11×7 cut-aways of 2.1×2.1 cm^2 to allow a reproducible positioning of the films within the scan field. The paper template was removed after the positioning of the film pieces.

We developed an accurate and time efficient scanning protocol to determine the correction factors at these 11×7 positions. To reduce the number of scans (and thus the time needed) we make use of seven films, i.e. one film per column. In total we need 21 scans to determine the correction factors. (In fact, each scan is the average of the last three scans from a series of five consecutive scans, see section 3.1.) The film and scan number are denoted by f1 to f7 and s1 to s21 respectively. First, each film fx was placed at the centre of the scan field (row 6, column 4). Next, six scans were taken, with the film fx placed subsequently on row 1 till 6. Thereafter, the film fx was again placed at the centre (row 6, column 4) of the scan field. This allows us to correct for the increase in optical density of the film due to the environment light and the light of the lamp of the scanner (sections 2.5 and 3.3) received during the previous scans. Then, the film fx was subsequently placed on row 7 till 11. Finally, the film fx was again placed at the centre, which again allows us to correct for the increase in optical density due to light. So, a possible direct influence of the scanner light on the EBT film is not an issue in this experiment.

The correction factors of these 11×7 positions for four optical densities, i.e. for films irradiated to 0, 29, 128 and 396 cGy, were determined as the average of five independent measurements with different films.

Starting from the correction factors of the four optical densities of these 11×7 positions, the correction matrices over the entire scan field, i.e. 843×611 points/pixels, were determined by cubic interpolation and extrapolation.

2.6. Pre-scanning of the EBT film

To check whether the precision of radiochromic EBT film dosimetry is increased when the optical density of the unirradiated film is subtracted from the optical density of the irradiated film, 100 unirradiated film pieces of 2×2 cm^2 were scanned, irradiated to a dose of 128 cGy and subsequently scanned again (after waiting at least 2 h). For the 100 irradiated film pieces, the standard deviation on the optical density is assessed and compared with the standard deviation on the optical density when the optical densities of the unirradiated film pieces were subtracted.

2.7. Measurement accuracy for regular fields

To assess the accuracy of Gafchromic EBT film in combination with the EPSON scanner, the depth dose of a small elongated 2×15 cm^2 field typically used in IMAT (Duthoy *et al* 2003) and the in-plane and cross-plane profiles of a 15×15 cm^2 field were measured and compared with diamond detector measurements. A beam quality of 6 MV was applied.

Our previous findings were taken into account to perform the EBT film measurements and the image analysis. Film measurements were performed in a polystyrene phantom. An SSD of 95 cm was applied. The depth dose of a 2×15 cm^2 field is measured with an EBT film strip of 4×25 cm^2. The film was placed in the centre of the field parallel to the central axis and 200 MU were delivered to the phantom. To measure the in-plane and cross-plane profiles of a 15×15 cm^2 field a whole EBT film sheet was irradiated with a 15×15 cm^2 field. The film was placed at a depth of 5 cm and again 200 MU were delivered to the phantom. A calibration curve was used to convert the optical density to dose. This curve was obtained by irradiating films of 2×2 cm^2 perpendicular to the central beam axis to doses of 0, 14, 29, 48, 70, 97, 128, 162, 201, 244, 290, 341 and 396 cGy in a polystyrene phantom at 5 cm depth. A calibration curve was then obtained using a third-order polynomial fit through the data.

Measurements with the diamond detector (PTW, Freiburg, type 60003, nr 994582) were carried out in an MP3 water phantom (PTW, Freiburg). The diamond detector was positioned with its axis in the scan direction to obtain the highest possible spatial resolution. A correction for dose rate dependence was performed (Hoban *et al* 1994, Laub *et al* 1997).

3. Results and discussion

3.1. Drift of the scanner on short time

The effect of the warming up of the scanner lamp on the optical density of EDR2 and EBT is illustrated in figures 1 and 2 respectively. For radiographic film, the optical density of the first scan is 2.3% higher than the second scan and 2.6% higher than the third scan when no preview is taken (solid line in figure 1). The optical density is stable within 0.07% for the third to the tenth scan. So, the optical densities resulting from the first two scans are too high and are not reliable. This can be explained by the warming up of the lamp on short time. When a preview is taken before scanning, the lamp is already partly warmed up and the optical density resulting from the first scan is not more than 0.6% and 0.7% higher than the second and third scans respectively (dashed line in figure 1).

Similar results are found for radiochromic film. The optical density of the first scan is 0.9% higher than the second scan and 1.0% higher than the third scan when no preview is taken (solid line in figure 2). The optical density is stable within 0.046% for the third till tenth scan. When a preview is taken before scanning, the optical density resulting from the first scan is not more than 0.2% and 0.3% higher than the second scan and third scan respectively (dashed line in figure 2).

From figure 2 it is seen that the optical density of EBT has the tendency to rise for the final scans, 7–10. This effect was not observed for radiographic film (figure 1), so we ascribe it to the influence of the light of the lamp of the scanner on the radiochromic film.

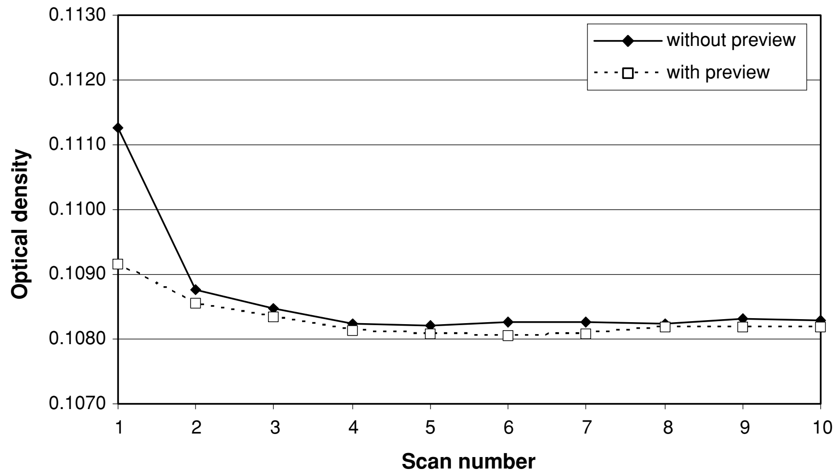


Figure 1. Effect of preview on the optical density: EDR2.

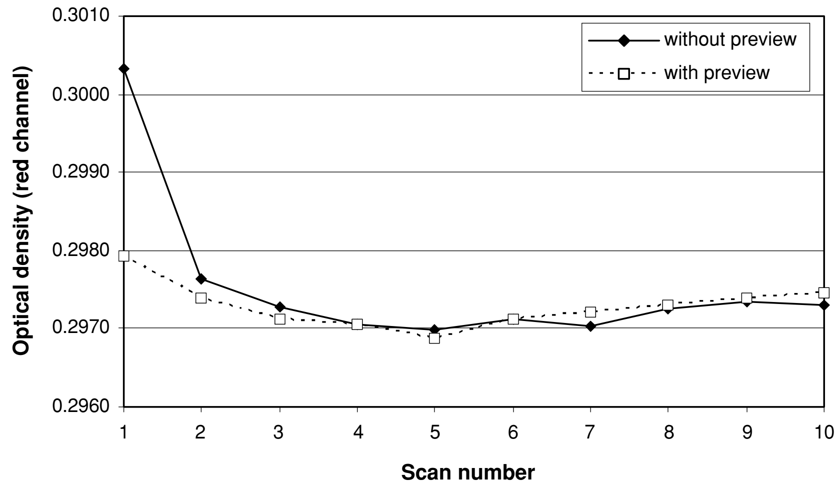


Figure 2. Effect of preview on the optical density: EBT.

We performed these experiments with several films and on several days, and we found always the same trend as presented in figures 1 and 2. Based on these results, we decided that scanning every film five times (with or without preview) rapidly after each other and averaging the last three scans, is an accurate and time efficient scanning procedure.

3.2. Drift of the scanner on long term

The optical densities of the film, taken from 100 successive scans, are presented in figure 3. The high optical density resulting from the first scan is due to the warming up of the lamp of the scanner (see section 3.1). The standard deviation on the optical density resulting from scans 3 to 100 is 0.13%. We conclude that drift of the scanner is absent.

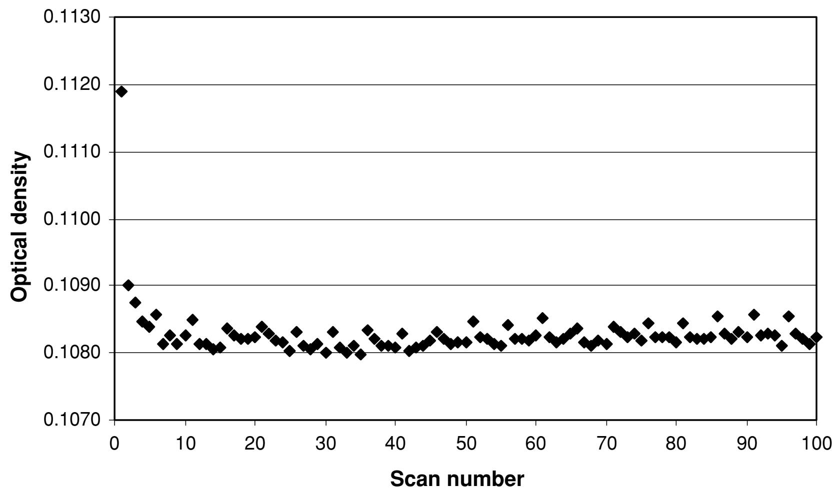


Figure 3. Long-term drift of the scanner (EDR2). The total time span to take the 100 consecutive scans is about 1 h.

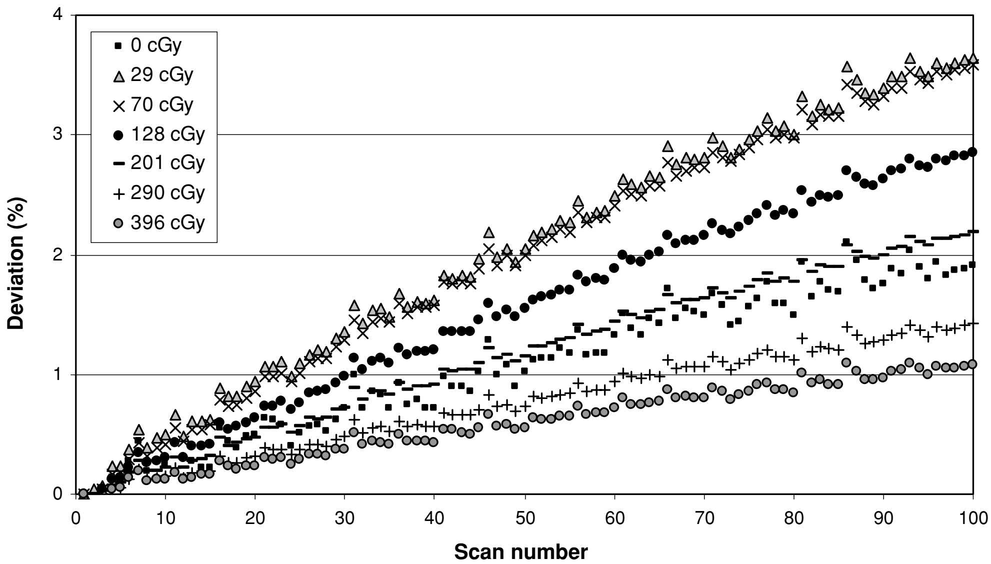


Figure 4. Influence of the fluorescent light of the scanner lamp on the optical density for EBT.

3.3. Direct influence of the scanner lamp on EBT

To exclude the effect of the warm-up of the lamp of the scanner, the first five scans were ignored in the data analyses (see sections 2.2 and 2.3). Figure 4 represents the percentage increase of the optical density for the resulting 100 scans. From this figure it is seen that the influence of the lamp of the scanner on EBT is dependent on the initial optical density. The increase of the optical density for a film irradiated with 0, 29, 70, 128, 201, 290 and 396 cGy is 1.91, 3.64, 3.59, 2.86, 2.19, 1.42 and 1.08% respectively. The influence of the

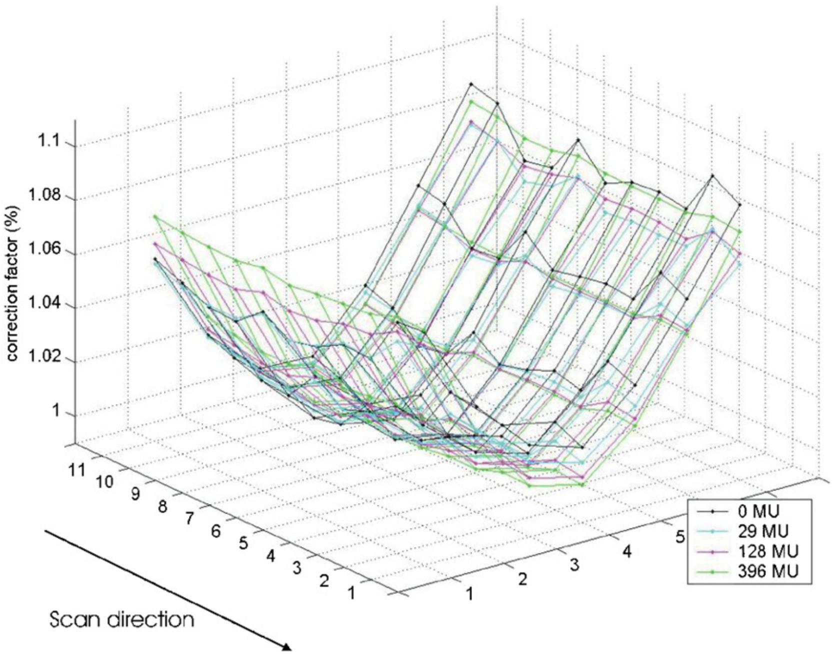


Figure 5. Correction factors for the 11 × 7 positions measured with films irradiated to 0, 29, 128, 396 MU in the red colour channel.

scanner lamp on EBT is most likely due to the UV from the fluorescent light causing extra chemical reactions and colouration. The increase of OD for the blank film is limited because the polymerization reaction was not already initiated.

3.4. Uniformity of the scan field

Figure 5 represents the correction factors for the non-uniform response of the scan field for the 11 × 7 positions for the four optical densities in the red colour channel. Each measurement point is the average of five independent measurements. The correction factors for the green and blue colour channels are different from those of the red colour channel. The average standard deviation at each measurement point for the red, green and blue colour channels is 0.0021, 0.0022 and 0.0025 respectively.

In table 1(A) the maximal percentage deviations for the measured optical density over the 11 × 7 positions are presented for the four optical densities and the three colour channels. The maximal deviations for the four optical densities vary from 7.7% (128 cGy) to 9.8% (0 cGy) for the red colour channel. For the green and blue colour channels the maximal deviations for the four optical densities vary from 4.1% (396 cGy) to 9.0% (0 cGy) and from 5.9% (396 cGy) to 11.2% (0 cGy) respectively. The maximal deviations, and thus also the non-uniformity of the scan field, are the lowest for the green colour channel. Large non-uniformities were observed in OD measurements, especially perpendicular to the scan direction (along the rows). Table 1(B) and (C) represents the maximal deviations for the measured optical density in terms of percentage along the direction perpendicular (along the rows) and parallel (along the columns) to the scan direction for the four optical densities and the three colour channels. The deviations described here are obtained within a single row/column. For example, for the

Table 1. Percentage deviations: (A) maximum deviation over the 11 × 7 positions, (B) deviation perpendicular to the scan direction (along the rows) and (C) deviation parallel to the scan direction (along the columns).

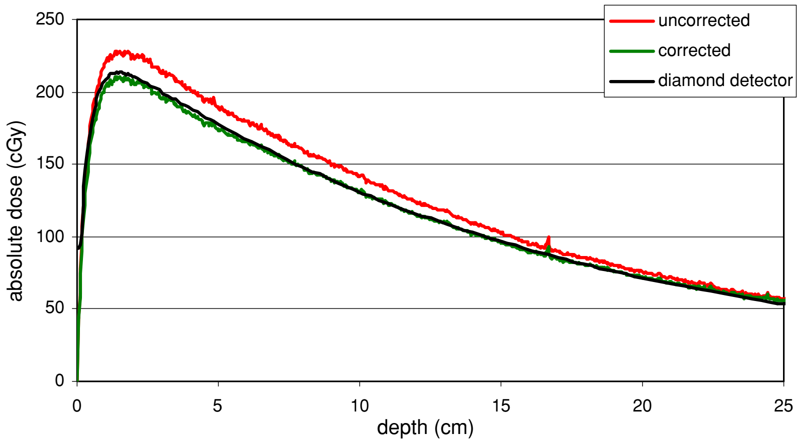
	Red				Green				Blue			
	0 cGy	29 cGy	128 cGy	396 cGy	0 cGy	29 cGy	128 cGy	396 cGy	0 cGy	29 cGy	128 cGy	396 cGy
(A) Maximal deviation												
	9.8	7.8	7.7	8.5	9.0	7.2	5.0	4.1	11.2	10.5	8.4	5.9
(B) Deviation perpendicular to the scan direction (along the rows)												
r1	7.4	5.9	6.7	7.8	6.9	5.1	3.8	3.5	8.4	6.9	5.9	4.4
r2	7.5	6.3	6.9	7.8	7.0	5.7	4.0	3.5	8.4	7.7	6.1	4.4
r3	7.5	6.2	6.8	7.9	7.0	5.7	3.9	3.6	8.6	7.8	6.2	4.6
r4	7.5	6.2	6.9	7.9	7.0	5.7	4.1	3.6	8.7	8.0	6.4	4.7
r5	7.8	6.4	7.1	8.0	7.4	5.9	4.3	3.8	9.1	8.2	6.8	4.9
r6	7.7	6.6	7.1	8.1	7.3	6.0	4.3	3.8	9.0	8.6	6.7	5.0
r7	7.9	7.0	7.2	8.1	7.4	6.3	4.3	3.9	9.1	8.9	6.8	5.0
r8	7.7	6.8	7.3	8.1	7.1	6.1	4.4	3.9	9.2	9.0	6.9	5.1
r9	7.7	6.7	7.2	8.1	7.1	6.0	4.4	3.9	9.4	8.7	7.0	5.0
r10	8.6	7.3	7.4	8.2	8.0	6.7	4.7	4.0	10.2	9.4	7.5	5.3
r11	8.5	7.2	7.5	8.2	8.0	6.7	4.7	3.9	10.1	9.4	7.6	5.2
Mean	7.8	6.6	7.1	8.0	7.3	6.0	4.3	3.8	9.1	8.4	6.7	4.9
(C) Deviation parallel to the scan direction (along the columns)												
c1	2.8	2.1	1.2	0.7	2.7	2.3	1.2	1.0	2.7	2.6	1.6	1.3
c2	2.9	1.9	1.2	0.7	2.5	1.8	1.2	0.9	1.7	1.7	1.4	1.1
c3	2.9	2.0	1.1	0.6	2.5	1.9	1.2	0.8	1.6	1.5	1.2	0.9
c4	2.8	1.9	1.1	0.6	2.3	1.8	1.2	0.7	1.3	1.1	1.0	0.7
c5	2.6	1.5	1.0	0.5	2.1	1.4	1.1	0.6	1.5	1.5	1.0	0.6
c6	2.3	1.4	0.8	0.4	1.8	1.1	0.8	0.4	1.7	2.0	1.4	0.9
c7	2.6	1.4	0.8	0.5	2.2	1.5	0.9	0.4	2.4	2.9	2.1	1.2
Mean	2.7	1.7	1.0	0.6	2.3	1.7	1.1	0.7	1.9	1.9	1.4	1.0

red colour channel, the average maximal deviation in the horizontal direction is 7.8, 6.6, 7.1 and 8.0% for films irradiated with 0, 29, 128 and 396 cGy respectively whereas the average maximal deviation in the vertical direction is only 2.7, 1.7, 1.0 and 0.6% respectively.

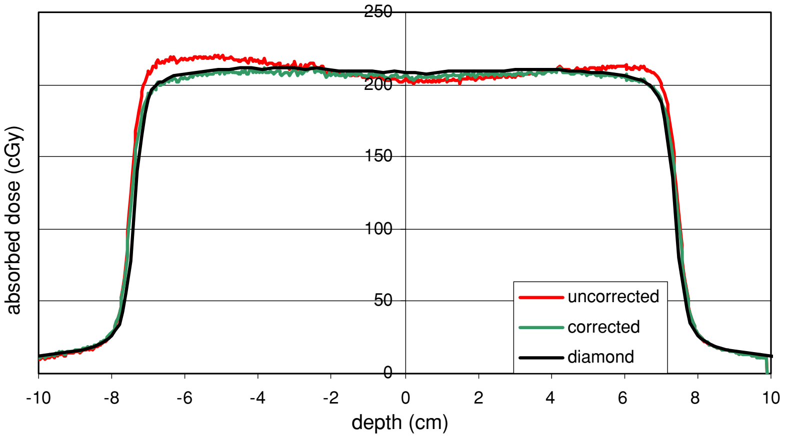
The correction factors in the red colour channel are almost the same for the four optical densities. To construct a correction matrix for the non-uniform response of the scan field which is representative for an irradiated EBT film, the correction factors for the optical densities associated with 29, 128 and 396 cGy were averaged for each of the 11 × 7 positions. Subsequently, starting from the correction factors of these 11 × 7 positions a correction matrix for the entire scan field, i.e. 843 × 611 points/pixels, was constructed by cubic interpolation and extrapolation. This method to construct the correction matrix would not be possible if the correction factors in the red colour channel were highly dependent on the optical density, as is the case for the green and blue colour channels. The maximum deviation between the average correction matrix (average of the correction matrices for 29, 128 and 396 cGy) and the individual correction matrices for 29, 128 and 396 cGy is 1.1%.

3.5. Pre-scanning of the EBT film

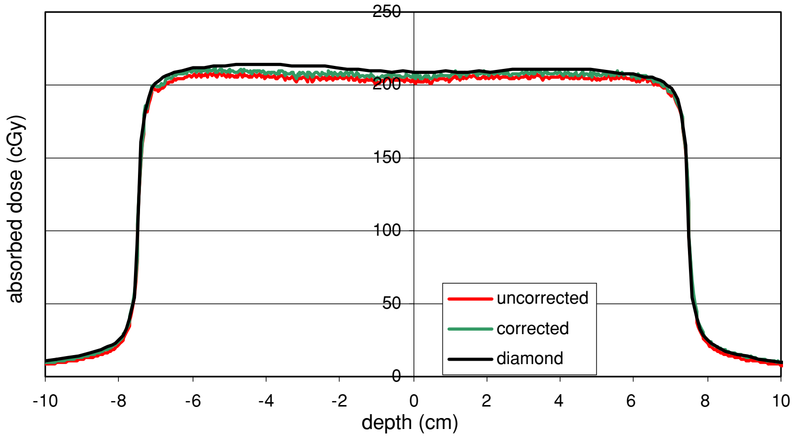
The measured optical density of the unirradiated and irradiated films is corrected for the non-uniform response of the scan field (see sections 2.5 and 3.4). The average optical density



(a)



(b)



(c)

Figure 6. Comparison of uncorrected and corrected (for the non-uniform scan field) EBT film measurements for (a) depth dose of a 2 × 15 cm^2 filed, (b) cross-plane profile of a 15 × 15 cm^2 field and (c) in-plane profile of a 15 × 15 cm^2 field with diamond detector measurements.

over the 100 irradiated films is 0.273 82 with a standard deviation of 0.0015. The average optical density over the 100 irradiated films from which the optical density of the unirradiated films is subtracted is 0.175 75 with a standard deviation of 0.0011. The Levene test rejects the assumption of equality of variances (p-value = 0.001 62). We conclude that subtracting the optical density of an unirradiated film from the irradiated film improves the precision of EBT film dosimetry.

3.6. Assessment of measurement accuracy

All films, including calibration films, were scanned before irradiation in order to later subtract the optical density of the unirradiated films from the irradiated films (see sections 2.6 and 3.5). The optical density was calculated as the average optical density from the last three subsequent scans from a series of five (see sections 2.2 and 3.1). The optical density of the unirradiated and irradiated films was corrected for the non-uniform response of the scan field. For the unirradiated films we used a correction matrix based on the correction factors measured with unirradiated films. The irradiated films were corrected with a correction matrix based on the average correction factors measured with films irradiated to 29, 128 and 396 cGy (see section 3.4).

Figure 6 presents the comparison of the EBT film with diamond detector measurements for (a) the depth dose of a 2 × 15 cm^2 field, (b) the cross-plane profile of a 15 × 15 cm^2 field and (c) the in-plane profile of a 15 × 15 cm^2 field. To illustrate the importance of the correction for the non-uniform response of the scan field, both the uncorrected and corrected EBT film measurements were presented. In the direction perpendicular to the movement of the lamp, in this example the cross-plane profile, the deviations are the largest, whereas in the direction of the movement of the lamp, in this example the in-plane profile, the deviations are relatively small. The EBT measurements are in agreement with the diamond detector within 2.5%, except in the field penumbra where small deviations in the positioning of the leafs or the collimators give rise to large deviations.

4. Conclusion

The EPSON Pro 1680 Expression scanner is an excellent device to perform accurate two-dimensional film dosimetry with Gafchromic EBT. However some precautions and corrections have to be taken into account. The optical density resulting from the first scan is unreliable due to warm-up effects. Therefore, each film is consecutively scanned five times and the optical density of the last three scans is averaged. A correction matrix allows us to correct for the non-uniform response over the scan field. Especially in the direction perpendicular to the scan direction, deviations in optical density up to 8% are corrected in that way. Subtracting the optical density of the unirradiated film from the irradiated film improves the precision of EBT film dosimetry.

Comparison of depth dose measurements and in-plane and cross-plane dose profiles with diamond detector measurements revealed that EBT films dosimetry with use of the EPSON scanner is accurate within 2.5% if some precautions and corrections are taken into account.

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