Measurement of high energy x-ray beam penumbra with Gafchromic™ EBT radiochromic film

Tsang Cheung
Department of Physics and Materials Science, City University of Hong Kong, Kowloon Tong, Hong Kong

Martin J. Butson[a)]
Department of Physics and Materials Science, City University of Hong Kong, Kowloon Tong, Hong Kong and Department of Medical Physics, Illawarra Cancer Care Centre, Crown St., Wollongong, N.S.W 2500, Australia

Peter K. N. Yu
Department of Physics and Materials Science, City University of Hong Kong, Kowloon Tong, Hong Kong

High energy x-ray beam penumbra are measured using Gafchromic™ EBT film. Gafchromic™ EBT, due to its limited energy dependence and high spatial resolution provide a high level of accuracy for dose assessment in penumbral regions. The spatial resolution of film detector systems is normally limited by the scanning resolution of the densitometer. Penumbral widths (80%/20%) measured at D_{max} were found to be 2.8, 3.0, 3.2, and 3.4 mm (± 0.2 mm) using 5, 10, 20, and 30 cm square field sizes, respectively, for a 6 MV linear accelerator produced x-ray beam. This is compared to 3.2 mm ± 0.2 mm (Kodak EDR2) and 3.6 mm ± 0.2 mm (Kodak X-Omat V) at 10 cm $\times$ 10 cm measured using radiographic film. Using a zero volume extrapolation technique for ionization chamber measurements, the 10 cm $\times$ 10 cm field penumbra at D_{max} was measured to be 3.1 mm, a close match to Gafchromic™ EBT results. Penumbral measurements can also be made at other depths, including the surface, as the film does not suffer significantly from dosimetric variations caused by changing x-ray energy spectra. Gafchromic™ EBT film provides an adequate measure of penumbral dose for high energy x-ray beams. © *2006 American Association of Physicists in Medicine*. [DOI: 10.1118/1.2218318]

INTRODUCTION

The accuracy of penumbral measurements in radiotherapy is important.[1–3] Dose planning computers require accurate data to adequately model beams, which in turn are used to calculate patient dose distributions. This is especially important with the use of devices such as multileaf collimators, because penumbral shapes can vary as seen by comparison of collimator jaw defined fields and rounded leaf ends[4,5] fields. Measurement of penumbra with finite volume ionization chambers produce an inaccurate penumbra result, due to the physical size of the detector. Smaller ion chambers, having spatial resolutions as low as 1 mm, provide minimal error for penumbra dose assessment compared to larger farmer type chambers, however, these still introduce inaccuracies in the actual penumbra size. Radiographic film offers a high spatial resolution for measurement but depending on film type, can be affected by its inherent energy dependence.[6–8] In turn, this can produce an overestimation of dose, specifically in the penumbral and peripheral regions. Radiographic film types like Kodak EDR2 have improved this feature due to reduced energy dependence and higher accuracy.[9,10] The newly released Gafchromic™ EBT film[11–13] offers both low energy dependence and high spatial resolution, making it ideal for penumbra dose assessment. This note investigates the ability of Gafchromic™ EBT to measure penumbral doses in high energy x-ray beams.

MATERIALS AND METHODS

Gafchromic™ EBT (ISP Corp, Wayne, NJ) radiochromic film is used to study penumbral doses in high energy x-ray beams. EBT film is constructed using multilayers, consisting of an active polymer coated by polyester, which allows the film to be easily handled and minimizes effects from ultraviolet exposure.[14] The effective atomic number of EBT film is $Z_{eff} = 6.98$ and when compared to water, $Z_{eff} = 7.3$, provides a comparatively good match.[15] Its energy dependence was found to be less than 10% over the energy range of 50 kVp to 6 MV.[16] The films were used to measure penumbral regions of 6 MV x-ray beams produced by a Varian 2100EX linear accelerator. For dose delivery, the films were positioned in a solid water[17] phantom with dimensions of 30 cm $\times$ 30 cm $\times$ 30 cm. The phantom was placed on the linear accelerator couch at 100 cm SSD and films were given a 2 Gy dose at the central axis using various depths for penumbral analysis. Various field sizes were tested ranging from 5 cm $\times$ 5 cm up to 30 cm $\times$ 30 cm. Measured penumbral
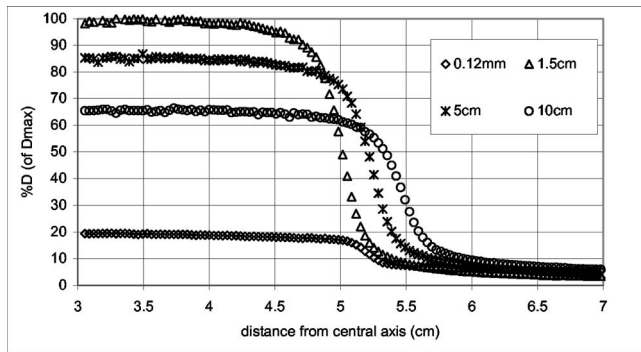
FIG. 1. Profile measurements of a 10 cm×10 cm 6 MV x-ray beam with Gafchromic™ EBT film. Results show profile as well as relative %D at depth.

FIG. 2. Normalized penumbral data for a 10×10 cm field (a) and a 20 cm ×20 cm field (b).

doses were compared to the central axis dose measurements and the penumbral results quoted as 80%/20%.

The Gafchromic™ EBT films were analyzed using a personal computer desktop scanner and Image J software. The scanner used was a Hewlett Packard ScanJet with a scanning resolution of 2400 pixels per inch. Analysis was performed using a 20×20 pixel region of interest and provided a measurement resolution of 0.2 mm. The 16 bit images were a combination of the red, green, and blue components, with the combined image studied for analysis. Doses were calculated using a dose calibration curve produced for each field size. Less than 2% variation was seen in the dose response curves over the field sizes measured. The profile measurements of penumbra were made in the same direction as the charge coupled device (CCD) scanning direction. No corrections were made for transversal sensitivity of the CCD. Results were also compared to Kodak X-omat V and Kodak EDR2 radiographic film. Extrapolated, zero volume ionization chamber measurements[18] were also made and compared.

Radiographic film is used as a direct comparison for film dosimetry and results have been analyzed using the same densitometry system as Gafchromic™ EBT film. The extrapolated zero volume chamber results have been calculated using a technique outlined by Laub and Wong[18] where a series of penumbra measurements are performed with various chambers of different spatial resolutions and an extrapolation is performed to predict the measured penumbra with a zero volume detector. Ionization chambers used in the technique were a Markus parallel plate chamber, NE 0.6 cm^3 cylindrical thimble chamber, IC13 and IC10 Wellhofer small volume ionization chambers. This technique can produce the gold standard for penumbra measurements, however, it is a very time consuming and demanding process.

RESULTS AND DISCUSSION

Figure 1 shows the percentage profile measurements for a 10 cm×10 cm x-ray beam at 0.12 mm (physical depth), 1.5, 5, and 10 cm depth relative to dose at the D_{max} central axis as measured by Gafchromic™ EBT film. Results were normalized to 100% at central axis D_{max}. The measured surface dose (0.12 mm physical depth of the EBT) is approximately
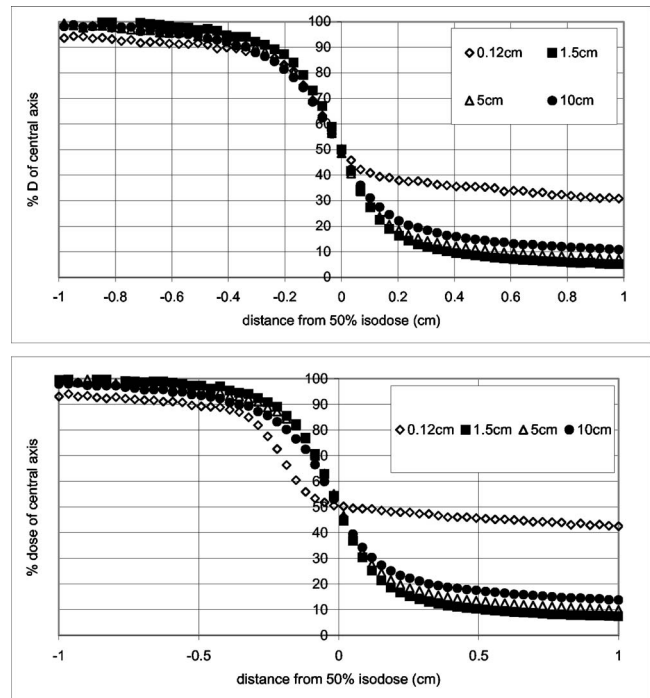
22% at the central axis and slowly reduced in the peripheral regions (as seen in Fig. 1) with an increased contribution compared to dose at depth outside the treatment field. This is specifically due to the electron contamination component of the beam. Central axis %DD measurements were found to be 100%, 85%, and 66% at 1.5, 5, and 10 cm, respectively (when normalized to 100% at the D_{max} position). This is compared to 100%, 86.1%, and 66.1% when measured with a Farmer ionization chamber, again showing a relatively good match to chamber measurements in this region. The measured penumbra revealed a spreading which is a combination of beam divergence and increased scatter contributions at depth. Similar results were seen at other field sizes ranging from 5 to 30 cm squares.

Figure 2(a) shows the normalized 80%/20% penumbra for the 6 MV 10 cm×10 cm x-ray beam. To perform the normalization, the off axis dose is compared to the central axis dose at each specific depth and normalized to 100% at central axis. Results are shown at the surface (0.12 mm physical depth), D_{max} (1.5 cm), 5, and 10 cm. The 80%/20% penumbra widths for this field size are 3.0 mm at 1.5 cm, 3.5 mm at 5 cm, and 4.4 mm at 10 cm. Similar results are shown in Fig. 2(b) which is for a 20 cm×20 cm 6 MV x-ray beam. Results here are 3.1 mm at 1.5 cm, 3.7 mm at 5 cm, and 5.1 mm at 10 cm depth. Of note is the increased peripheral dose as a ratio of the central axis for all depths, which shows a larger degree of scatter contributions in the peripheral regions from larger field sizes. Table I highlights the measured 80%/20% penumbra for various field sizes using EBT film compared to radiographic film and results from the zero volume chamber extrapolation predicted penumbra.

TABLE I. Comparison of penumbral widths for various x-ray field sizes and a zero volume chamber measurement.

Measurement device	Field size (cm)	80%/20% penumbral width (mm) at D_{max}
EBT (Radiochromic)	5×5	2.8±0.2
EDR2 (Radiographic)	5×5	2.9±0.2
X-Omat V (Radiographic)	5×5	3.3±0.2
EBT (Radiochromic)	10×10	3.0±0.2
Ion chamber (Extrapolated)	10×10	3.1±0.2
EDR2 (Radiographic)	10×10	3.2+0.2
EDR2 (Radiographic)	10×10	3.6±0.2
EBT (Radiochromic)	20×20	3.2±0.2
EDR2 (Radiographic)	20×20	3.4±0.2
X-Omat V (Radiographic)	20×20	3.7±0.2
EBT (Radiochromic)	30×30	3.4±0.2
EDR2 (Radiographic)	30×30	3.6±0.2
X-Omat V (Radiographic)	30×30	4.0±0.2

Results show that EBT film measured penumbra match closely to extrapolated chamber values. This is assumed to be mainly due to the low energy dependence of the EBT film.[14] Kodak EDR2 radiographic film also produces results, which are relatively close to zero volume chamber results. This is expected due to the lower level of energy dependence of this film type, whereas X-Omat V film produces a significant difference, which can be attributed to the large energy dependence of the films response to x rays. This characteristic of EBT makes it ideal for measurements in areas such as the penumbra where a significant change in spectra components of an x-ray beam can occur. This quality could also be effective in other areas such as measurement of interleaf leakage or where spectral changes effect measurements and a high spatial resolution is required. The accurate measurement of penumbra is especially important for beam modeling where the models are used to predict doses for step and shoot, or segmented field treatments.

CONCLUSION

EBT provides a low energy dependence and high spatial resolution detector, which are two properties necessary for penumbral dose measurements. Penumbral dose measurements require a dosimeter with low energy dependence due to the changing x-ray spectra in this region. Radiographic films such as Kodak X-Omat V are not ideal as they exhibit large energy dependence. EDR2 radiographic film produced a better match to penumbral data, however, it still has a larger energy dependence than EBT Gafchromic and also

requires a development process. High energy x-ray beam penumbra can be accurately measured with Gafchromic™ EBT, radiochromic film.

[a] Author to whom correspondence should be addressed. Present address: Department of Medical Physics, Illawarra Cancer Care Centre, Crown St, Wollongong, N.S.W 2500, Australia. Electronic address: butsonm@iahs.nsw.gov.au

[1] M. Arnfield, V. Arounougame, and R. Alkins, "The use of film dosimetry of the penumbra region to improve the accuracy of intensity modulated radiotherapy," Med. Phys. **32**, 12–18 (2005).

[2] A. Olch, "Dosimetric performance of an enhanced dose range radiographic film for intensity-modulated radiation therapy quality assurance," Med. Phys. **29**, 2159–2168 (2002).

[3] M. Butson, T. Cheung, and P. K. N. Yu, "Spatial resolution of a stacked radiochromic film dosimeter," Radiother. Oncol. **61**, 211–213 (2001).

[4] M. Butson, P. K. N. Yu, and T. Cheung, "Rounded end multi-leaf penumbral measurements with radiochromic film," Phys. Med. Biol. **48**, N247–N252 (2003).

[5] M. Huq, I. Das, T. Steinberg, and J. Galvin, "A dosimetric comparison of various multileaf collimators," Phys. Med. Biol. **47**, N159–N170 (2002).

[6] T. Cheung, M. J. Butson, and P. K. N. Yu, "Experimental energy response verification of XR type T radiochromic film," Phys. Med. Biol. **49**, N371–N376 (2004).

[7] T. Kron, L. Duggan, I. Smith, A. Rosenfeld, M. Butson, G. Kaplan, S. Howlett, and J. Hyodo, "Dose response of various radiation detectors to synchrotron radiation," Phys. Med. Biol. **43**, 3235–3250 (1998).

[8] N. Suchowerska, A. Davison, J. Drew, and P. Metcalfe, "The validity of using radiographic film for radiotherapy dosimetry," Australas. Phys. Eng. Sci. Med. **20**, 20–26 (1997).

[9] N. L. Childress, L. Dong, and I. I. Rosen, "Rapid radiographic film calibration for IMRT verification using automated MLC fields," Med. Phys. **29**, 2384–2390 (2002).

[10] X. R. Zhu, S. Yoo, P. A. Jursinic, D. F. Grimm, F. Lopez, J. J. Rownd, and M. T. Gillin, "Characteristics of sensitometric curves of radiographic films," Med. Phys. **30**, 912–919 (2003).

[11] A. Rink, I. Vitkin, and D. Jaffray, "Characterization and real-time optical measurements of the ionizing radiation dose response for a new radiochromic medium," Med. Phys. **32**, 2510–2516 (2005).

[12] T. Cheung, M. Butson, and P. K. N. Yu, "Post-irradiation colouration of Gafchromic™ EBT radiochromic film," Phys. Med. Biol. **50**, N281–N285 (2005).

[13] M. Butson, T. Cheung, and P. K. N. Yu, "Absorption spectra variations of EBT radiochromic film from radiation exposure," Phys. Med. Biol. **50**, N135–N140 (2005).

[14] M. J. Butson, P. K. N. Yu, T. Cheung, and P. E. Metcalfe, "Radiochromic film for medical radiation dosimetry," Mater. Sci. Eng., R. **41**, 61–120 (2003).

[15] ISP Web Web, www.ispcorp.com, 2006.

[16] M. Butson, T. Cheung, and P. K. N. Yu, "Weak energy dependence of EBT Gafchromic™ film dose response in the 50 kVp–10 MVp x-ray range," Appl. Radiat. Isot. **64**, 60–62 (2006).

[17] C. Constantinou, F. H. Attix, and B. R. Paliwal, "A solid water phantom material for radiotherapy x-ray and gamma-ray beam calibrations," Med. Phys. **9**, 436–441 (1982).

[18] W. U. Laub and T. Wong, "The volume effect of detectors in the dosimetry of small fields used in IMRT," Med. Phys. **30**, 341–347 (2003).