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 measured at $D_{\text{max}}$ 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 × 10 cm measured using radiographic film. Using a zero volume extrapolation technique for ionization chamber measurements, the 10 cm × 10 cm field penumbra at $D_{\text{max}}$ 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]

**Key words:** radiochromic film, Gafchromic™ EBT, surface dose, penumbral measurements

**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 ends4,5 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 penumbral dose assessment compared to larger farmer type chambers, however, these still introduce inaccuracies in the actual penumbral 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 film11–13 offers both low energy dependence and high spatial resolution, making it ideal for penumbral 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 $Z_{\text{eff}}=6.98$ and when compared to water, $Z_{\text{eff}}=7.3$, 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 water17 phantom with dimensions of 30 cm × 30 cm × 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 × 5 cm up to 30 cm × 30 cm. Measured penumbral...
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 measurements18 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 ionization chamber measurements18 were also made and compared.

RESULTS AND DISCUSSION

Figure 1 shows the percentage profile measurements for a 10 cm×10 cm 6 MV x-ray beam with Gafchromic™ EBT film. Results show profile as well as relative %D at depth. 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 Dmax 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% penumbral data for a 10×10 cm field (a) and a 20 cm×20 cm field (b).
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.\textsuperscript{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\textsuperscript{TM} EBT, radiographic film.

**ACKNOWLEDGMENTS**

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

<table>
<thead>
<tr>
<th>Measurement device</th>
<th>Field size (cm)</th>
<th>80%/20% penumbral width (mm) at $P_{max}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EBT (Radiographic)</td>
<td>5 $\times$ 5</td>
<td>2.8±0.2</td>
</tr>
<tr>
<td>EDR2 (Radiographic)</td>
<td>5 $\times$ 5</td>
<td>2.9±0.2</td>
</tr>
<tr>
<td>X-Omat V (Radiographic)</td>
<td>5 $\times$ 5</td>
<td>3.3±0.2</td>
</tr>
<tr>
<td>EBT (Radiographic)</td>
<td>10 $\times$ 10</td>
<td>3.0±0.2</td>
</tr>
<tr>
<td>Ion chamber</td>
<td>10 $\times$ 10</td>
<td>3.1±0.2</td>
</tr>
<tr>
<td>EDR2 (Radiographic)</td>
<td>10 $\times$ 10</td>
<td>3.2±0.2</td>
</tr>
<tr>
<td>EBT (Radiographic)</td>
<td>20 $\times$ 20</td>
<td>3.2±0.2</td>
</tr>
<tr>
<td>EDR2 (Radiographic)</td>
<td>20 $\times$ 20</td>
<td>3.4±0.2</td>
</tr>
<tr>
<td>X-Omat V (Radiographic)</td>
<td>20 $\times$ 20</td>
<td>3.7±0.2</td>
</tr>
<tr>
<td>EBT (Radiographic)</td>
<td>30 $\times$ 30</td>
<td>3.4±0.2</td>
</tr>
<tr>
<td>EDR2 (Radiographic)</td>
<td>30 $\times$ 30</td>
<td>3.6±0.2</td>
</tr>
<tr>
<td>X-Omat V (Radiographic)</td>
<td>30 $\times$ 30</td>
<td>4.0±0.2</td>
</tr>
</tbody>
</table>

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