Radiochromic film thickness correction with convergent cone-beam optical CT scanner

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Abstract. A cone-beam optical computed tomography (CT) scanner was modified by replacing the diffuse planar yellow light emitting diode (LED) source with violet and red LEDs and a large Fresnel lens. The narrow band sources provided transmission images of radiochromic EBT2 film at 420 and 633 nm, with air as a reference. The dose image was not detectable with the violet source. This demonstrated spectral independence of the two images. Assuming attenuation at 420 nm was dominated by absorption from yellow dye in the active film layer allowed a relative thickness image to be calculated. By scaling the 633 nm optical density image for relative thickness, non-uniformities in the recorded dose distribution due to film thickness variations, were removed.

1. Introduction
Self-developing radiochromic film is a versatile, tissue-equivalent dosimeter. The commercially available Gafchromic® EBT2 film from Ashland Chemicals has acceptable spatial resolution and dose sensitivity for measuring most radiotherapy dose distributions. Bending the film sheet allows sampling a surface within a 3D dose distribution. The main problem with this dosimeter is the non-uniform thickness of the active layer. Until this manufacturing limitation is resolved, methods to measure and correct for thickness variations will be required. A yellow dye is included in the active layer to provide strong absorption of violet and ultraviolet light to reduce film sensitivity to light at these wavelengths. This allows the film to be handled in typical indoor lighting conditions without initiating a photochromic response. By measuring the absorption in the violet or blue spectrum a relative film thickness map can be determined, assuming the dye doping is uniform throughout the film. White papers on the manufacturer’s website provide information for scanning the film for accurate dosimetry [1]. Micke et al have also developed a commercial program for analyzing EBT2 transmission data from Epson flatbed document scanners using the red, green and blue channels to correct for film uniformity and optimize dynamic range of the combined film-scanner system [2]. These document scanners have limitations for quantitative spectral imaging. One of the largest issues is the cross-talk between the blue and red channels which limits accurate measurement of the recorded dose distribution. In this study a prototype light source for a convergent, cone-beam, optical CT scanner is evaluated for imaging of EBT2 radiochromic film.

By choosing a violet light source, in the spectral range of 400 to 430 nm, it is expected that EBT2 film attenuation will be primarily due to absorption from the yellow dye. It is also anticipated that violet light absorption by the dose-induced chromophores will be minimal. The red source, 633 nm, fwhm = 10 nm is near the dose product absorption peak at 635 nm. It is expected that spectrally
independent violet and red transmission images obtained with this light source will provide higher quality images for dosimetry compared to the Epson document scanner.

2. Instrumentation and methods
A schematic of the modified Vista10, Modus Medical Devices Inc., cone-beam optical CT scanner is shown in figure 1. The red source consisted of a Luxeon III, 3W LED operating at 0.8 mA (note maximum recommended current is 1.3 A). The LED light was pseudo-collimated with a composite optic to a beam divergence of 20 degrees, filtered by a 10 nm bandpass filter with centre wavelength of 633 nm and then focused to a 2 mm spot at a white diffuser. The spot source was aligned with the optic axis of the Vista scanner. A Fresnel lens, 25 cm diameter, was located ~ 30 cm from the rotation axis of the scanner and the source position was adjusted to provide a cone of light focused at the camera position. The violet source was realized by substituting a 3W, 420 nm LED, operating at 0.2 mA (StevesLEDs, note maximum recommended current is 1 A) and a dark blue glass filter. The optimum source position was closer to the Fresnel lens for the violet source because of dispersion.

Figure 1. Schematic top view of modified Vista10 convergent cone-beam optical CT scanner with beam: 1) LED, 2) bandpass filter, 3) lens, 4) diffuser, 5) Fresnel lens, 6) film, 7) digital camera.

A reference air image for the red source was acquired with an exposure time of 3 msec (note the equivalent exposure with the planar, diffuser source required ~60 msec). The camera lens was focused to the scanner’s rotation axis plane and an f4 aperture was used for all images. An EBT2 film sample that had been previously exposed for another measurement, was attached to a frame and placed in the rotation axis plane and centred on the optic axis. The sequence was repeated with the violet source. Dark images were acquired by blocking the light at the LED. Images were processed in Matlab. Optical density images were calculated with air as reference, since the film had been exposed.

3. Results
Power measurements, with a calibrated silicon photodiode, determined blue and red LED light temporal stabilities to within 1% during the experiment. Figure 2a, shows the violet, optical density image. The mean optical density is 2.5. No filtering was applied. By comparison the zero-dose, blue-channel OD with the Epson scanner was 0.48, see figure 2 of reference 2. No image of the dose distribution is evident in the violet image. In contrast, the blue channel has ~25% the dose sensitivity of the red channel with the Epson scanner see figure 2 of reference 2. The relative thickness correction image was generated by spatially filtering the normalized, violet, OD image with a 5x5 median filter, see figure 2b. Note the horizontal features are similar in magnitude (+1% to -1% of the mean), to those reported with the Epson scanner, see figure 3 of reference 2.
The red OD image shows a 6 MV dose distribution with an average maximum dose of 2.2 Gy, see figure 3a. At this dose, the maximum optical density is approximately 2.0 compared to 0.28 for the Epson scanner, see figure 2 of reference 2. Features present in the relative thickness map are also observed in red OD image. Correction for relative thickness was performed by dividing the red OD image by the relative thickness image, pixel by pixel. This ratio removed non-uniformity features, see figure 3 (right panel).

**Figure 2.** Optical density image of EBT2 film at 420 nm with air reference (a), relative thickness image (b), pixel size 0.235 x 0.235 mm.

**Figure 3.** Optical density images of EBT2 film at 633 nm: (a) reference is air, (b) corrected for non-uniform film thickness, pixel size 0.235 x 0.235 mm.

### 4. Discussion

This sevenfold signal increase, compared to Epson scanner, is similar to EBT film data from 633 nm scanning laser film densitometers [3]. The impact of film scatter requires further investigation.
However, point measurements with a 633nm laser (polarization at 45 degree, to approximate non-polarized light) are similar. This indicates that scatter is minimal in these images. This result is consistent with the fact that the irradiance is approximately 100 times lower in the film plane compared to the diffuse planar source. Imaging efficiency is much greater with the small source-lens combination compared to the previous planar diffuser source again indicating the primary to stray light ratio has increased with this more collimated source. Multiple slot array images will be used to quantify magnitude and spatial distribution of stray light in this system [4]. Since the violet image is insensitive to dose, previously irradiated EBT2 films can be rescanned to provide high-resolution thickness corrections to the dose images. Acquiring multiple images and averaging would decrease the noise. Polarization effects with EBT2 film are large and will be reported with ongoing paired measurements for EBT3 film.

5. Acknowledgements
Disclosure: The author has a research agreement with Modus Medical Devices Inc concerning optical CT scanners and dosimetry applications.

6. References
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