2011

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Publication Details

Williams, M. and Metcalfe, P. (2011). Radiochromic film dosimetry and its applications in radiotherapy. 4th SSD Summer School: Concepts and Trends in Medical Radiation Dosimetry (pp. 75-99). Wollongong: AIP.

Radiochromic Film Dosimetry and its Applications in Radiotherapy

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Abstract. Radiochromic film can be a fast and inexpensive means for performing accurate quantitative radiation dosimetry. The development of new radiochromic compositions that have greater dose sensitivity and fewer environmental dependencies has led to an ever increasing use of the film in radiotherapy applications. In this report the various physical and dosimetric properties of radiochromic film are presented and the strategies to adequately manage these properties when using radiochromic film for radiotherapy applications are discussed.

Keywords: Radiochromic film; Medical dosimetry; Film dosimetry; Film scanners; Densitometry.
PACS: 87.53.Bn

INTRODUCTION

In radiotherapy, dosimetry is concerned with quantifying the energy deposited in terms of absorbed dose to water. The ideal dosimeter has numerous features, both physical and radiation, that make it so. It should have fast kinetics to provide real time information that is stable, insensitive or predictable in response to environmental factors such as temperature pressure and humidity. The ideal dosimeter should be small in size to provide high spatial information as well as producing minimal perturbations of the beam. It should be water equivalent to allow interpretation of dose relative to tissue and also to avoid perturbations and other artifacts. The response to radiation should be independent of energy and dose rate; and ideally be linear in its response, with sensitivity to both small and large doses. Other more practical considerations include that it be non-toxic for in vivo dosimetry purposes, cheap, reliable and reproducible.

Radiochromic dosimeters are solid state detectors in the sense that the structural properties of their crystalline solid undergo a change when exposed to radiation. The polymerization results in a color (chromatic) change. Radiochromic dosimeters can exist in various forms such as liquids, gels, films and pellets. Radiochromic films are increasingly being used in radiotherapy centers for the measurement of 2D dose distributions; this is due partly to the improved dose sensitivity of newer radiochromic films but also to the decline in the use of processor based radiographic film.

There have been several comprehensive reviews conducted on radiochromic film over the last decade[1-3]. In this report some of the material from previous reviews is presented to provide a holistic overview of radiochromic film; and additional information is provided on the current types of film and methods for performing radiochromic film dosimetry.

HISTORICAL BACKGROUND

One of the earliest documented radiochromic processes was demonstrated by Jospeh Niepce in 1826, in which he projected the view from a window onto a pewter plate coated with a light sensitive solution of "bitumen of Judea". After approximately 8 hours of exposure to sunlight a permanent bitumen image was produced on the plate[4]. The image production was attributed to an unsaturated hydrocarbon polymeric mixture in the bitumen that underwent cross-linking upon irradiation[2].

Concepts and Trends in Medical Radiation Dosimetry
AIP Conf. Proc. 1345, 75-99 (2011); doi: 10.1063/1.3576160

In 1965 McLaughlin *et al.* reported on the development of colorless solid solutions of particular materials, namely derivatives of the triphenyl methane molecule, that underwent radio-synthesis to produce dyes[5]. Much of the early work on radiochromic materials can be attributed to the National Institute of Standards and Technology (NIST, US). The early forms of radiochromic media had a useful dose range of 10^3 to 10^6Gy, and as such there use was limited to high dose applications such as food irradiation, medical instrument sterilization, and other industrial applications.

The opportunity for non-industrial applications of radiochromic media came with the development of a new radiochromic film medium in 1986[6]. The film was known as GAFchromic™, and was produced by ISP Technology a division of GAF Chemical corporation (GAF Corporation, Wayne, NJ). The acronym GAF was derived from the company's pre-1968 name of General Aniline and Film Corporation. In 1991 the GAF Chemical Corporation was publicly listed and is now known as International Specialty Products Inc. (ISP). The particular dye in GAFchromic™ film was found to be an order of magnitude more sensitive than previous types and could be used for mapping dose distributions above 5Gy[7, 8]. The early uses of this particular film included the dosimetry of radioactive hot particles (or spheres) of ^{60}Co and ^{90}Sr/^{90}Y with activities ranging from 1 to 300 MBq [9, 10] and its use was further extended to ^{90}Sr/^{90}Y ophthalmic applicators[11]. Other uses have included the dosimetry of small stereotactic radiosurgery fields and intravascular brachytherapy sources[12],. Other radiochromic films were also being developed at this time and were used for electron and proton dosimetry[13, 14]

PRINCIPLES OF RADIOCHROMIC POLYMER REACTIONS

The materials in radiochromic film responsible for the coloration are known as crystalline polyacetylenes, in particular diacetylenes, and upon thermal annealing or radiation exposure they undergo polyermerization, turning blue or red depending on their specific composition[15, 16]. The particular diacetylene monomer used in GAFchromic™ EBT film is the lithium salt of pentacosa-10,12-diyonic acid (LiPCDA) [17]. In the raw manufactured form diacetylene crystals are too large to provide useful sensitivity therefore they are dissolved in a solvent, such as n-butanol solvent, which has the added advantage of improving the light resistance of the polyacetylenic crystals. The dissolved crystals are then dispersed in a binder such as an aqueous gelatin solution. After further processing to remove the alcohol solvent the binder is coated onto a substrate, upon drying the crystals become fixed in orientation. The drying and aging process may take several months. Possible substrate materials include polyester, ceramics, glass, or metals and an adhesive may also need to be used[18]. Additional coatings may be added to the active layer to reduce UV sensitivity and to act as an anti-oxidizing layer[16, 19]. Films may be constructed as laminates with single, double or triple emulsion layers coated onto intervening substrate layers.

McLaughlin *et al.* demonstrated that the mechanism of color production in GAFchromic™ films was a first order solid state polymerization of the diacetylene monomer, and reported that propagation of the polymerization was complete within 2 ms of a single 20Gy 50ns electron pulse [20]. In a subsequent publication McLaughlin *et al.* also observed that post-irradiation polymerization continued to occur, most notably within the first 24 hours following exposure[21]. The diacetylene monomers upon heating, UV or ionizing radiation exposure undergo progressive 1,4-polymerisation leading to the production of colored polymer chains that grow in length with level of exposure, FIGURE 1[15, 20, 22]. The packing of the diacetylene monomers in the crystal lattice depends on the particular end groups (R_1 and R_2 in FIGURE 1), the monomers in GAFchromic™ films are approximately 0.75μm in diameter and for the polymerization to occur the triple bonds of adjacent monomers should be within 0.4nm of each other[17]. The radiation sensitivity of the crystal is also dependent on the particular end groups, with the lithium salt of PCDA used in GAFchromic™ EBT film being sensitive to doses as low as 1cGy, several orders of magnitude more sensitive than the earlier radiochromic films.

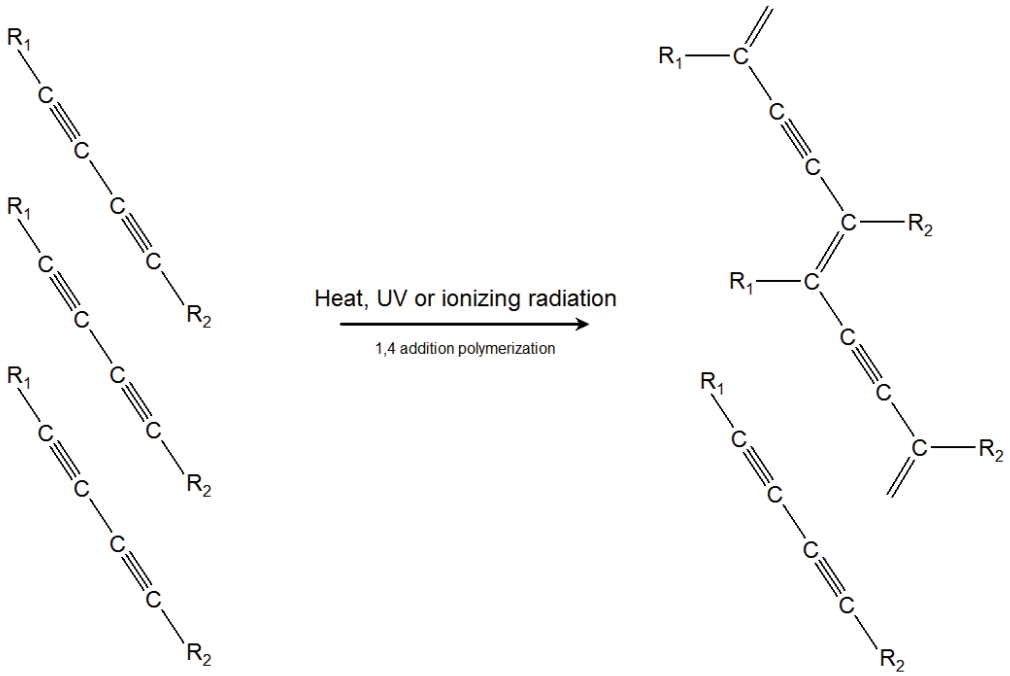

FIGURE 1. The diacetylene monomers undergo a 1,4 polymerization upon exposure to heat, UV or ionizing radiation.

RADIOCHROMIC FILMS

There are several companies that produce a range of radiochromic films and media for a variety of applications. The majority of these radiochromic films require doses greatly in excess of clinically useful ranges, however there are some that are suitable for use in radiotherapy.

International Specialty Products Inc., Wayne, NJ, USA

ISP manufacturers a range of radiochromic films under the product name GAFchromic™. The difference between each type of film relates to whether it is constructed with a single or double active layer film, if it is reflective or transmissive film, its physical dimension, and the specific chemical composition of the active layer.

The HD-810 film, also known as DM-1260, consists of a single 7μm layer of the GAFchromic™ emulsion coated on 100μm thick polyester base. It has a dose range of 10-400Gy. MD-55-2 contains two 16μm layers of GAFchromic™ emulsion separated by a 25μm layer of polyester and 2 x 25μm layers of adhesive, all sandwiched between two 66 μm polyester layers. The total active layer is over double that of the HD-810 films making it sensitive to a dose range of 2-100Gy. The HS films have a single 40μm layer of GAFchromic™ emulsion layered between two 97μm thick layers of polyester. The outer layers provide a water barrier and again the greater thickness of active layer increases the sensitivity, HS film having a dose range of 0.5-40Gy. The sensitivity of HD, MD and HS film decreases with decreasing energy, therefore ISP developed XR type T and R (reflective and transmissive) specifically for use in the low energy range, 20-200 kVp. The film has the same active layer as the previous films but includes a high Z material and has a dose range of 0.1–15Gy.

A new film was released in the mid 2000's called GAFchromic™ EBT. The active layer was a variation of the monomer used in the previous films, and was a hair like version of the LiPCDA crystal[17]. The atomic composition of EBT is (42.3% C, 39.7% H, 16.2% O, 1.1% N, 0.3% Li and 0.3% Cl). The inclusion of the moderate atomic number element chlorine (Z = 17), provided a Z_{eff} of 6.98 making it near tissue equivalent. The new active layer was also found to be more sensitive, providing a dose range of 0.01-8Gy.

In 2009 the production of EBT film was discontinued and replaced by EBT2. The EBT2 film had the same active component as EBT but with a yellow dye added to the active layer and it was also constructed as a single layer instead of double, FIGURE 2. The film has a slightly narrower active layer than EBT and slightly different overall atomic composition (42.37% C, 40.85% H, 16.59% O, 0.01% N, 0.10% Li, 0.04% Cl, 0.01% K, 0.01% Br). The Z_{eff} of EBT2 is 6.84 compared to 6.98 for EBT, and close to Z_{eff} of water (7.3).

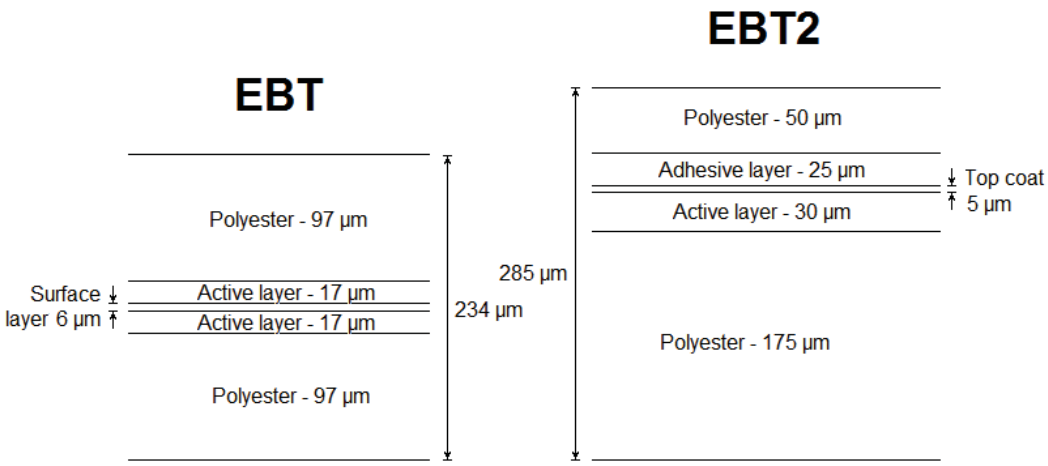

FIGURE 2. An illustration of the physical construction of GAFchromic™ EBT compared to EBT2, EBT2 has a slightly thinner active layer and an asymmetric design

Far West Technology Inc, Goleta, California, USA

FWT-60 film is based on hydrophobic substituted triphenylmethane leucocyanides, and is used for high-dose applications such as radiation processing, food irradiation, and sterilization; with a dose range of 0.5-200kGy it has limited use for radiotherapy applications. The substrate that holds the dye is nylon. The film has a density of approximately 1.15 g/cm3 and an atomic composition of (C 63.7%, N 12.0%, H 9.5%and O 14.8%). The film has a physical thickness of approximately 0.05 mm.

GEX Corporation, Centennial, Colorado, USA

The GEX Corporation produces B3 film, which is a thin and flexible polymeric film consisting of a pararosaniline radiochromic dye embedded in a polyvinyl butyral matrix. Ionizing radiation events activate the B3 dye centers which in turn cause the B3 film to undergo a predictable color change from clear to deepening shades of pink. The amount of color change is proportional to dose and is influenced by the temperature during irradiation. The post-irradiation color change can take several hours to stabilize and heat treatment of the film is recommended. The dose range of B3 is approximately 1-150kGy, again well above the clinically useful dose range.

Other

JP Laboratories (Middlesex, NJ, USA) have developed a range of radiochromic films, called SIRAD (Self-indicating Instant Radiation Alert Dosimeters). The film consists of a diacetylene monomer in a polymeric binder coated on polyester base and laminated with an outer polyester-layer film. The intended use of SIRAD films is for personal dose monitoring to record high dose unintentional exposure.

RADIOCHROMIC FILM DOSIMETRY

In the following sections the use of radiochromic film for performing dosimetric measurements will be discussed in detail. The majority of discussion will focus on the behavior of the GAFchromic™ range of film; however the majority of observed behavior and properties are also present to some degree in the other types of film. Unless specified otherwise data that is presented for illustrating the behavior of film has been collected with an EPSON 10000XL scanner, using 16-bit red channel data. Film batches used were EBT lot number 47277-061 and EBT2 lot number F06110901.

Irradiated and unirradiated absorption spectra

The feature of radiochromic film that makes it useful as a dosimeter is that the amount of color change or darkening is proportional to the absorbed dose. As light traverses the active layer the polymerized monomer chains will absorb some of the light, this will vary with the concentration of dye centers. The amount of light that is absorbed will also be dependent on the wavelength of light. The absorbance spectrum describes the variation in absorbance of radiation as a function of wavelength. The absorbance spectrum for MD-55-2 is shown in FIGURE 3, it has two main absorption peaks, with λ_{max}, occurring at 617nm and 675nm. There is a small dependence of λ_{max} on the absorbed dose, with it shifting to higher values as the dose increases[23]. The absorbance spectra for EBT and EBT2 are shown in FIGURE 4 and FIGURE 5 respectively. Both EBT and EBT2 show much greater absorbance than the MD-55-2 when exposed to similar doses. There is also a shift in the absorbance peaks, for EBT and EBT2 these are centered at 583nm and 635nm. The most obvious difference in the absorbance spectrum of EBT and EBT2 is the presence of a large broad peak centered at approximately 450nm for the EBT2. This is due to the introduction of the yellow dye into the EBT2; its purpose will be discussed later.

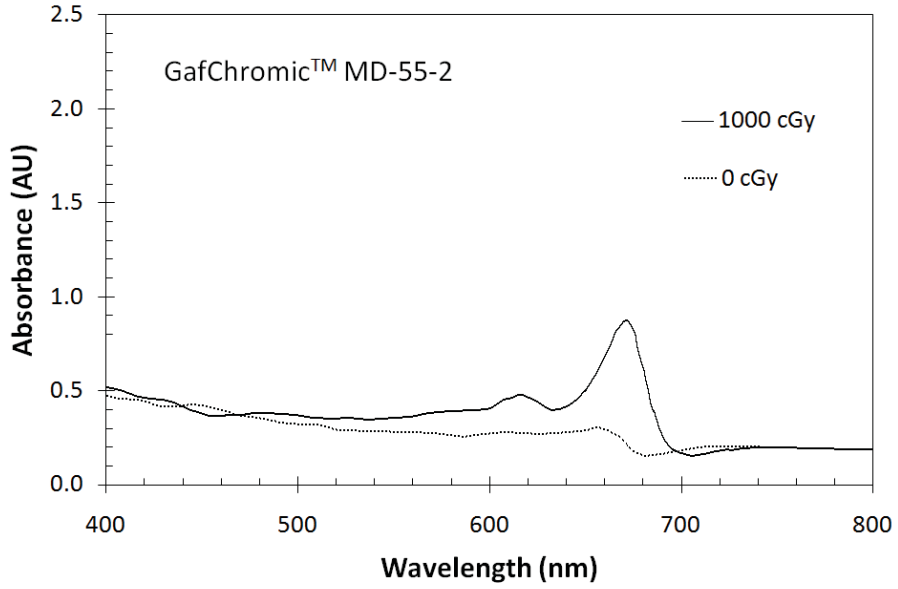

FIGURE 3. The absorbance spectrum for GAFchromic™ MD-55-2, pre and post irradiation to 1000cGy.

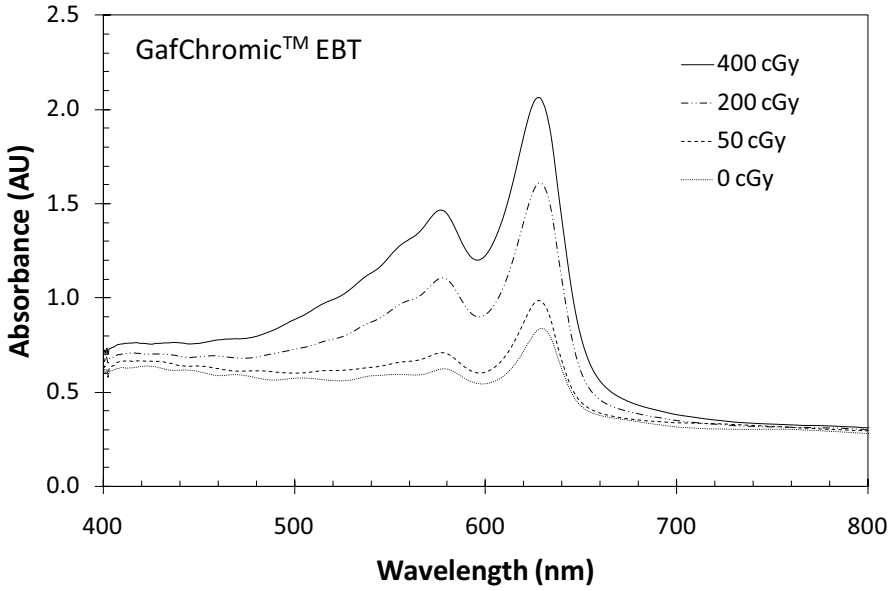

FIGURE 4. The absorbance spectrum for GAFchromic™ EBT, pre exposure and following exposure to 50, 200 and 400cGy.

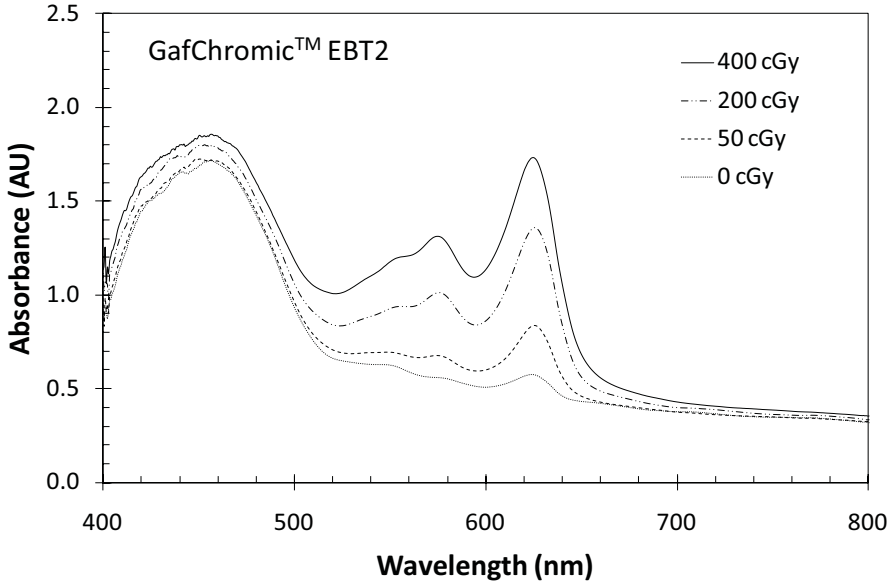

FIGURE 5. The absorbance spectrum for GAFchromic™ EBT2, pre exposure and following exposure to 50, 200 and 400cGy.

Optical density

To determine the amount of dose delivered to the film the change in the films absorbance is measured. To quantify this change the optical density of the film is measured. The optical density (OD) is defined as, $OD = \log_{10}(I_0/I)$, with I_0 as the initial intensity and I as the transmitted (or reflected) intensity. Fusi *et al* investigated the optical properties of MD-55-2 and have described the complex interaction of light within the various layers of the film [24]. To accurately measure the change in OD of the radiochromic material only the transmitted light should be recorded, most densitometry techniques are actually measuring a combination of reflection, absorbance and transmission through the various layers of films. Importantly, the OD values measured are only valid for the specific wavelength or waveband of light analysed[25], and will be dependent on both the emission spectrum of the light source and spectral sensitivity of the light detector, these are discussed later.

Unexposed films have a background optical density (fog), the change in optical density above the background level as a result of radiation exposure can be expressed as the net optical density. Net optical density has been defined in several ways[26-28]. A common method, based on the technique described by Devic *et* al, for calculating net OD when performing 2D radiochromic dosimetry is shown in Equation 1 [27].

$$netOD^{i}(D_j) = \log_{10}\frac{I^{i}_{un\exp}(D_j) - I_{bckg}}{I^{i}_{\exp}(D_j) - I_{bckg}} \quad (1)$$

Where $I^{i}_{un\exp}(D_j)$ and $I^{i}_{\exp}(D_j)$ are the intensities measured for the unexposed and exposed pieces of the i[th] film, and I_{bckg} is the reading when no light is transmitted. To apply this technique the film must first be scanned prior to irradiation and then following radiation, and requires a method for accurate repositioning of the film.

The particular wavelength used for film analysis will influence the OD that is measured and will impact on the effective dose range of the film. Selecting a light source centered on the λ_{max} will provide the highest dose sensitivity for the film. For example EBT has peak absorption at 635nm therefore a helium neon laser which has wavelength of 633nm will provide good sensitivity [29, 30].

Film calibration and OD

To perform accurate dosimetry with radiochromic films it is necessary to characterize the dose response of the film to the particular radiation source that is being measured. A range of known doses, preferably encompassing the dose region of interest, should be delivered to the film and the change in OD of the film measured. Ideally the relationship between dose and OD should be linear but generally it is not, and various methods are used to describe the OD-dose relationship, including polynomial fits, or empirical models with variable coefficients. An example of calibration curves for EBT and EBT2 is shown in FIGURE 6. By characterizing OD response of film to known doses, the measured OD of the unknown dose can be used to calculate the actual dose delivered to the film.

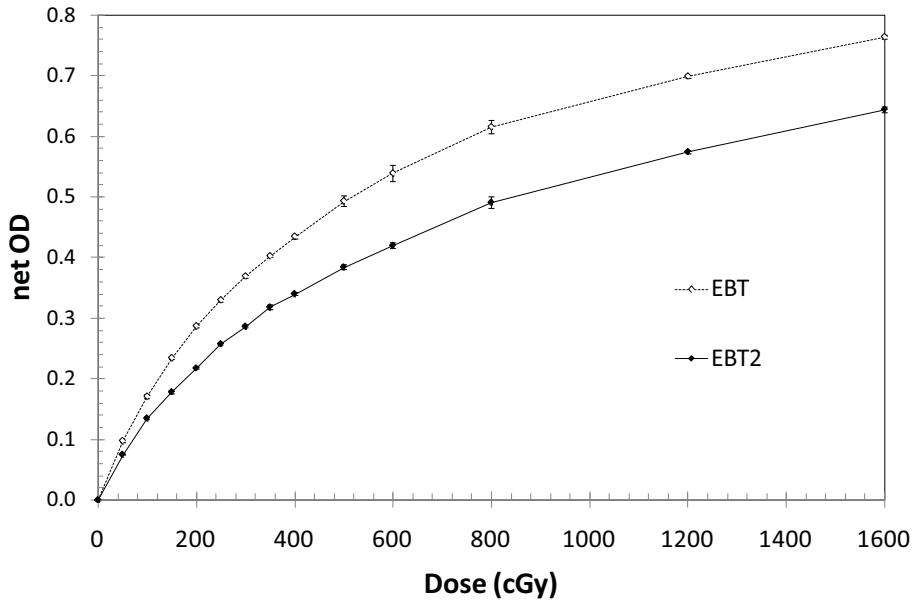

FIGURE 6: Optical density versus dose characteristic curve for GAFchromic[TM] EBT and EBT2, EBT with the greater thickness of active layer material is more sensitive than EBT2.

Energy dependence and tissue equivalence

The energy dependence of radiochromic film relies on the specific composition of the various layers, the specific composition of a particular film type has been shown to vary between batches[31]. Unlike radiographic film which

relied on radiation interaction with silver halides and therefore had a high Z_{eff}, GAFchromic™ films are closer to tissue equivalent and therefore have a near linear energy dependence over the range of clinical energies, FIGURE 7. The exception is GAFchromic™ XR which includes higher Z material to improve response at lower energies. The near tissue equivalence of GAFchromic™ films also means that the angular dependence is greatly reduced compared to radiographic films, a 1-2% increase in optical density has been reported as the angle of incidence approaches parallel to the film[32, 33]

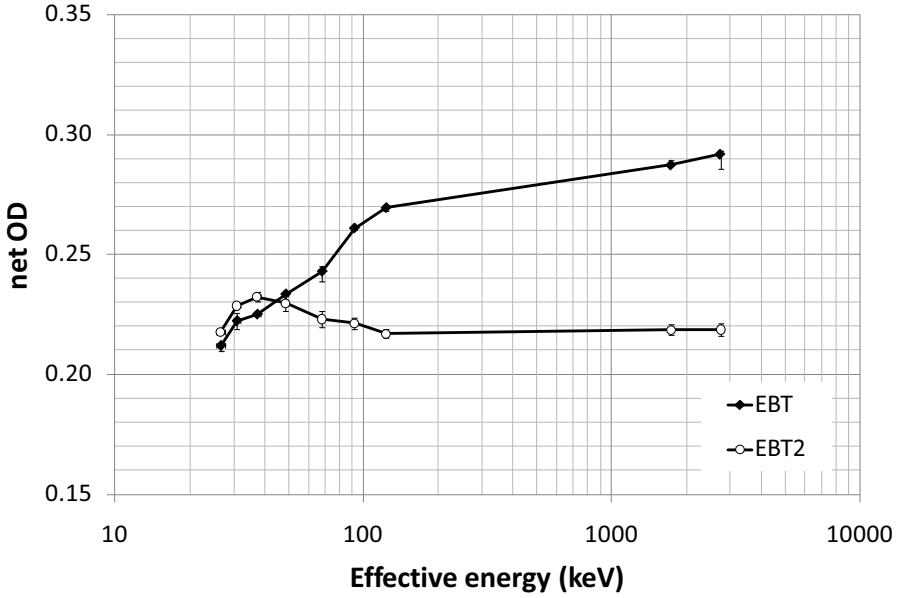

FIGURE 7: The variation in net OD for a dose of 2Gy delivered with radiation beams of different qualities for GAFchromic™ EBT and EBT2.

Ultraviolet radiation and ambient lighting

The active layers of most radiochromic films are sensitive to UV light, as found in sunlight and fluorescent light, and depending on the coatings used this will affect the sensitivity of the film to environmental lighting conditions [21, 30, 34-36]. Reinstein *et al* found that for GAFchromic™ MD-55-2 fluorescent light increased the optical density at a rate of $0.0007h^{-1}$, which equated to a dose effective sensitivity of 3.5cGy/h. Butson *et al* reported on the successful use of MD-55-2 for performing dosimetry of UVA radiation, wavelength 320–400nm[35]. According to ISP one of the advantages of EBT2 over EBT is that the inclusion of the yellow dye has decreased the film sensitivity to ambient lighting. In FIGURE 8 the decreased sensitivity of EBT2 to ambient fluorescent light as compared to EBT has been shown. Both unexposed and exposed pieces of film were used to investigate if the presence of already polymerized chains affected the sensitivity to fluorescent light, no significant difference was observed.

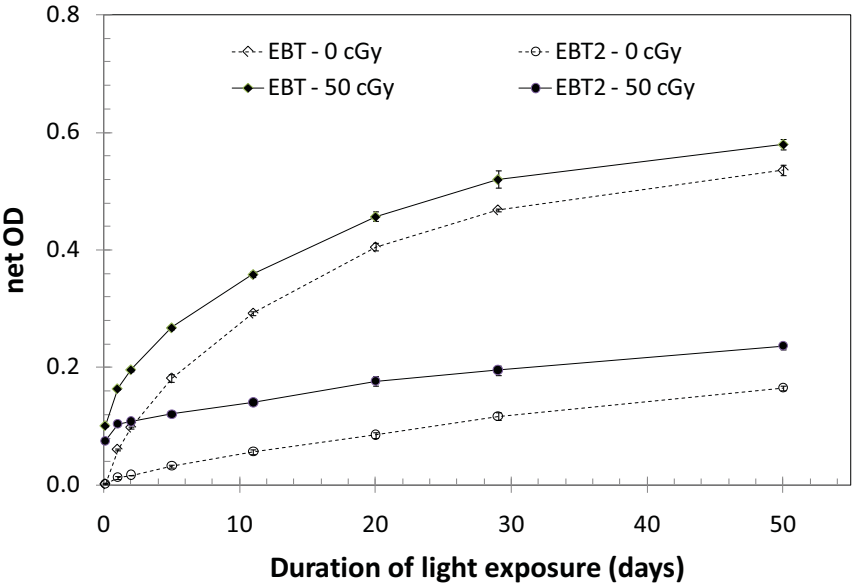

FIGURE 8: Sensitivity of GAFchromic^{TM} EBT and EBT2 to fluorescent light. The change in OD was measured for unexposed film as well as for film that had already commenced polymerization.

Dose fractionation and dose rate dependence

It has been reported that at clinical doses there are no dose rate or fractionation dependences for MD-55-2 [21, 22, 37]. However if using GAFchromic^{TM} as a real-time dosimeter or not allowing sufficient post-irradiation time, than significant differences in OD response may occur for the same dose delivered at different rates or intervals[38]. Rink *et al* have reported on the dose rate dependence of EBT and exploring its use of as a real-time dosimeter[28, 39].

Stability

Post-irradiation color stability

The polymerization process in radiochromic film continues for considerable time after irradiation [2, 38, 40]. The consequence of the continued polymerization is that the OD grows over time; therefore films should be left for at least 6 hours and preferably 24 hours before scanning. To minimize uncertainties associated with post-irradiation coloration both the calibration films and experimental films should be scanned after approximately the same time interval following irradiation.

Temperature effects

For MD-55-2 McLaughlin *et al* observed an increase in sensitivity with increasing temperature equivalent to a change in absorbance of +0.6-0.7% °C^{-1} between 20-30°C[21]. For EBT there is a decrease in λ_{max} with increasing temperature, changing from 635nm at 22°C to 630nm at 38°C, these changes were found to be reversible with temperature [17, 41]. Lynch *et al* reported an OD increase with rising temperature[42], whereas Rink *et al* found the opposite, showing a decrease in OD with increasing temperature[17]. Rink reconciles the two observations by attributing the difference to the readout methods, and when evaluating the increase in OD based solely on the newly formed polymers the net OD decreases with increasing temperature. Rink *et al* also suggested that the observed negative change in net OD was unlikely to be due to a decrease in the intrinsic sensitivity or polymerization kinetics of the active component and was possibly caused by temperature induced changes in absorption or reflection coefficients of the various layers in the film[17].

FWT-60 and B3 were investigated by Abdel-Fattah *et al* [43], and they reported that the absorbance had a temperature dependence during irradiation of 0.25°C^{-1} for FWT-60 and 0.5°C^{-1} for B3 dosimeters, this was for temperatures between 20 and 50°C with relative humidifies ranging from 20 and 53%.

A post-irradiation heat treatment technique has been reported as method to assist in stabilizing the polymerization process [44]. Heating MD-55-2 to 45°C for 2 hours following irradiation reduced the increase in net OD in the first 24 hr to less than 0.5% compared to 6% without. A similar technique is recommended for use with B3 (GEX) heating the film to 60°C for 5 minutes[45].

Humidity

The level of hydration is linked to the temperature dependence; with the temperature influencing the level of film hydration. Janovsky *et al* reported on the hydration effects for FWT-60 and GAFChromic™ HD-810, and for a relative humidity range from 0-90% the effect on dose response was less than 2% for the HD-810 and up to 30% for FWT-60[46]. Rink et al studied the impact of hydration levels on EBT using a calcium chloride desiccant to dry out EBT film. Two configurations of EBT film were studied, one with the active layer exposed and the other with the outer polyester layer in place. For the unlaminated film there was a 66% drop in sensitivity (based on change in net OD) after 24 hrs of desiccation at 50°C and it remained stable at that value, for the EBT in standard configuration the sensitivity dropped by 25% in 24 hrs and then reached 66% after 126 hours of drying time[17]. Spectral analysis of the dried films revealed a change in the absorbance spectrum suggesting that the water molecules were an integral part of the molecular composition of the LiPCDA. Rehydration resulted in a different absorbance spectrum suggesting that a different PCDA polymer was formed when the water molecules were reincorporated.

Laminated design – cutting and water penetration

Radiochromic films are constructed in layers, partly to provide a supporting structure and protective coating for the active layer but also to increase the thickness of sensitive material and thus improve its sensitivity[47]. The layers are held together by natural or synthetic adhesives, when films are cut the pressure can cause delamination to occur, with fractures or separation of the layers extending up to 8mm from the edge but typically 1-2mm[48]. For this reason it has been advised to avoid reading films close to the edge[2]. For non- layered construction, such as HD 810 where the active layer is coated directly onto the polyester base, this is less of a problem.

Another implication of the layered design is water permeability. GAFchromic™ films have polyester outer layers. The water permeability of polyester is lower than that of the adhesive and active layers, and the sandwich type GAFchromic™ films are water resistant, but there is water penetration from the sides between the layers. For MD-55-2 this was reported at a rate of approximately 0.34mm per hour[49] and similar rates have been specified by the manufacturer for EBT and EBT2[50]. Up to 9 mm after 24hours of immersion has been reported for EBT2[51]. The slow penetration rate makes it feasible to use GAFchromic™ films to perform measurements in water. Immersion in water over night has also been reported as a simple means of separating the layers to gain access to the individual components [23].

Batch variation

As discussed earlier the manufacturing process for radiochromic films is complex and time consuming. There are numerous phases in the production process, with a variety of chemicals used and the whole process can extend for several months. It is not surprising that there may be small variations between the production of different batches. However it has been suggested that there can be significant, intentional and unreported changes in chemical composition between batches made by the manufacturer. This has been demonstrated by Lindsay *et a*l when investigating the energy dependence of EBT and EBT2 by using neutron activation analysis of the chlorine and bromine in different batches of film[31]. Therefore it is recommended that along with the type of GAFchromic™ film used the particular batch or lot number of the film should also be reported [2, 23].

Resolution and uniformity

It has been suggested that the active component of GAFchromic™ film is capable of resolving greater than 1200 lines/mm, this is based on the physical size of the crystal[7]. When dispersed in emulsions of different thickness the true resolution is likely to deviate from this value. In either case GAFchromic™ film is capable of very high spatial resolution, and for accurate dosimetry the film response should be uniform over very small and large distances. This can be described as local and regional uniformity or alternatively as microscopic and macroscopic uniformity [1, 2]. The local uniformity concerns high spatial frequency variation within a region of interest and is best quantified as a

relative standard deviation. It is influenced by the thickness of active layer, spatial and signal resolution of the scanner, pixel size, signal and detector noise. Ferreira *et al* reported that as the resolution of the scanning system decreased the amount of noise also decreased, as determined by the relative standard deviation within an ROI ($2x2mm^2$). This has been illustrated in FIGURE 9, with profiles taken across a sheet of EBT2 in the same location using the different scan resolutions of 72, 96 and 200 dpi.

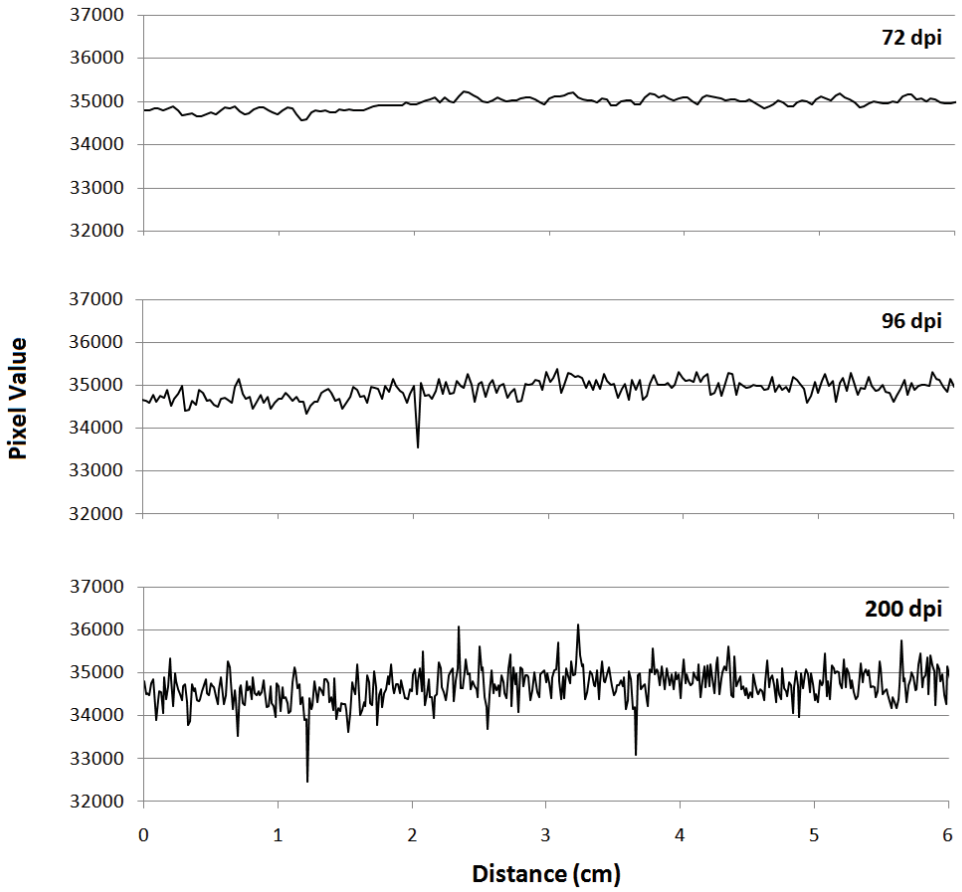

FIGURE 9: Profiles measured across the same region of GAFchromic™ EBT2 film using different scan resolutions. As the scan resolution decreases the amount of noise also decreases.

Macroscopic or regional uniformity relates to the consistency of film response from one region of the film to another, and is dependent on active layer composition and consistency within the region. For early versions of GAFchromic™ films non-uniformities of between 4-15% in response were reported [52, 53].

More recent work on GAFchromic™ EBT has reported OD variations of 1.5% equating to 2-2.5% in dose at 2Gy[54, 55]. Data from Saur *et al* suggest an intra-film variability or uniformity of 2% in dose at 2Gy and film to film variation of 3.2% at 2Gy[56].The EBT2 film reportedly has poorer uniformity than the EBT[57]. A recent paper on EBT2 determined an intra-sheet uniformity of 2.4% in ADC value equivalent to approx 4.8% at 2Gy (2 sd of ADC) and between sheets of 1.2% which equates to approximately 2.4% at 2 Gy [58]. However Hartman et al using the same type of scanning equipment report a much poorer uniformity for EBT2 of 8.7% at 1Gy compared to 1.1% for EBT [59]. The uniformity was based on the maximum and minimum pixel value detected within an 1.4 x 1.4 cm ROI whereas Richley *et al* were reporting the mean value of pixels within a 0.5x0.5 cm^2 ROI. Arjomandy *et al* also investigated the uniformity of EBT2 and reported an inter-film variability of 1.8% of OD (2 s.d.) at a dose higher than 10 Gy equating to approximately 1% in dose. This was measured using a densitometer with a green light source which accounts for the higher dose range and possibly also for the improved uniformity with green light as it has a lower sensitivity to inherent variations in film response [60].

To negate the effects of non-uniformity several methods have been proposed. For the earlier version of film that required significantly higher doses and had poorer uniformity, a double exposure technique was suggested[23, 53]. In

the double exposure technique a known dose is delivered to the film and the relative response or sensitivity of the film is measured. The unknown dose is then delivered to the same film and the data is then corrected for the changes in relative response throughout the film. This technique is used for other dosimetry systems, such as TLD's and 2D diode arrays. For MD-55-2 using a double exposure technique improved the uniformity from 8-15% OD variations down to 2-5% variations[53].

The improved uniformity of GAFchromic™ EBT meant that it could be used without the double exposure technique[55], however pre-scanning the film may still have been performed to provide a background reading, and would incorporate some of the non-uniformities [27]. A supposed advantage of including the yellow dye in the active layer of EBT2 is that it allows for a correction to be performed for the non-uniformity in thickness of the active layer. The technique relies upon analysis of different wavebands. The active layer of EBT2 has its highest absorbance in the red part of the spectrum, whilst the yellow dye absorbs in the blue part (see FIGURE 5). The suggested correction technique relies on the use of a flatbed scanner and involves taking the ratio of the outputs of the red and blue channels, the blue channel providing a measure of the active layer variation. Kairn *et al* reported that when using this correction method for EBT2 local deviations of 5% were present, but if using a net OD method correction method based on the red channel only the local variations decreased to 2%[57].

SCANNING DENSITOMETER SYSTEMS

Scanning densitometer systems were originally fixed point by point systems, meaning that both the light source and light detector were fixed in position and the film had to be manually translated between them. These systems evolved into motorized versions with the light sources and detector being driven across the film or conversely the film being mechanically scanned. A major limitation of the point by point systems was the amount of time required to collect and generate high resolution data, with each data point requiring a incremental shifts in position. The development of charge coupled device (CCD) arrays has resulted in a wider range of imaging densitometers being used for film dosimetry. These may have a line of CCD detectors or a 2D array of CCDs similar to that found in digital cameras. A variety of scanning densitometry systems are described in the following sections.

Spectrophotometer

A spectrophotometer is a device used for measuring light intensity and it measures intensity as a function of wavelength[13]. Important features of spectrophotometers are its spectral bandwidth and the linear range for the measurement of absorption. The spectrophotometer quantitatively compares the fraction of light that passes through a reference sample and a test sample. Broad polychromatic light is passed through a monochromator, which diffracts the light into a spectrum and outputs narrow bandwidths of the diffracted spectrum. Discrete wavelengths are transmitted through the test sample. The intensity of transmitted light is measured with a photodiode, and the transmittance value for this wavelength is then compared with the transmission through a reference sample. When using a spectrophotometer for radiochromic dosimetry it is important to consider if it has a UV filter in place to prevent contamination of the film sample.

Scanning laser densitometer

A transmission scanning-laser densitometer is described by Dempsey *et al* [61]. The device measures the charge produced in a photomultiplier tube by collecting the light from a He–Ne laser that has passed through the film into a collimated light integrating cylinder. The laser beam is focused down to a width of 50 to 100 μm and rastered across the film.

A converted infrared film densitometer

Carolan *et al* describe a novel technique for performing radiochromic film dosimetry using infrared densitometry system by replacing the infrared light source with a red light emitting diode (LED) [62]. Infrared film densitometers traditionally involved an infrared light source and photodiode mounted on opposite sides of a glass plate with both attached to a motorized arm. The source and detector would then be translated across the film and incrementally stepped along the film to provide 2D scans of the film.

VIDAR scanners

The VIDAR scanner (VIDAR Systems Corporation, Herndon, VA, USA) consists of a white fluorescent tube adjacent to a linear CCD array, the film is translated past the CCD using a set of rollers. Suboptimal performance of this scanner for film dosimetry has been reported due to its low OD range, inability to perform averaging of scans and artifacts caused by the motion of rollers flexing the film [63-65]. A new version of the VIDAR scanner has been developed specifically for radiochromic film dosimetry, Dosimetry Pro Advantage (Red)™. It employs a red LED light source with a peak emission at 627nm and FWHM bandwidth of 20nm, which encompasses the absorption peak of EBT and EBT2 film. The LEDs illuminate a translucent diffuser adjacent to the film to reduce unwanted light scatter, and rollers have also been attached to the LED lamp cartridge to reduce flexing of the film. These scanners are considerably expensive and little data is presently available on their use.

Flatbed scanners

The ready availability and low cost of flatbed scanners make them attractive for use as densitometers. One particular make and model, the EPSON 10000XL, has been specifically recommended by ISP for use with their GAFchromic™ EBT films. Flat bed scanners typically consist of a white light fluorescent source and CCD detection system that move together to scan the film. Azuma *et al* replaced the white light with an infra-red tube to better target the specific peak absorption of EBT[66]. These devices have the ability to operate in reflectance mode as used for scanning documents and also in transmission mode, which are designed for scanning of photographic films. Flat bed scanners now represent a large proportion of the film densitometry systems in use, and some of the particular issues associated with their use are discussed in the following sections.

Light sources

Types

Spectrophotometers provide a specific wavelength and have a very narrow waveband 3.5nm[23]. He-Ne lasers are at the specific wavelength of 632.816 nm (in air). Light emitting diodes (LEDs) are available over a range of wavelengths from infra-red down to ultraviolet and have spectral bandwidths of approximately 30nm. A special subgroup of LEDs known as laser diodes are available at particular wavelengths and have narrower bandwidths than standard LEDs, at 1-10nm [67-69]. Fluorescent light sources can have an emission spectrum that covers the entire visible spectrum and may include ultraviolet and infra-red. FIGURE 10 shows the emission spectrum for the Xenon cold cathode ray tube that is found in the Epson 10000 XL flatbed scanner, also shown are the spectral sensitivities in the red, green and blue channel for the CCDs typically used in flatbed scanners. It is also possible to apply a variety of filters to the light source, this might be done to reduce the UV component[25], or a physical filter to eliminate a broad spectrum of wavebands[70] or by using an LED light source coupled to a band pass filter to provide a specific narrow waveband[29].

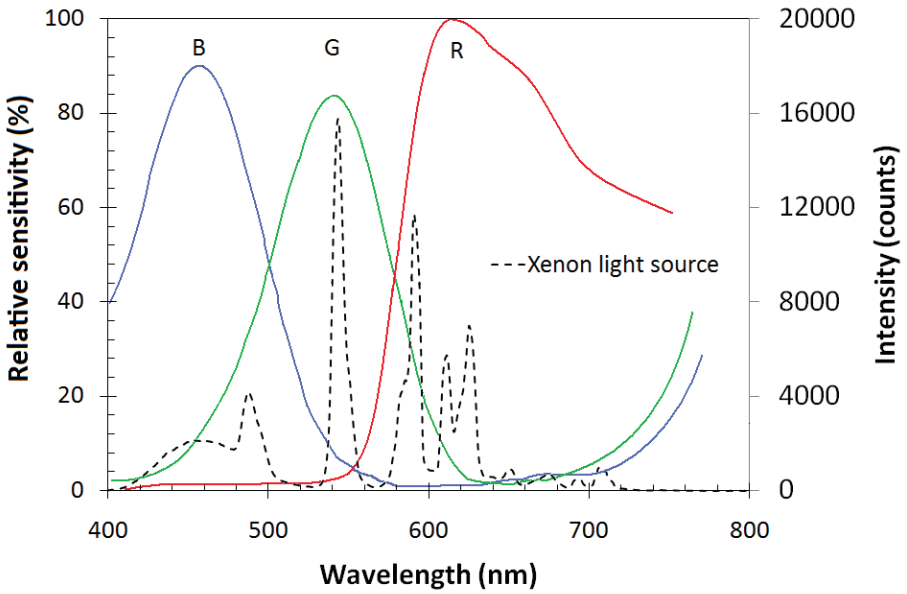

FIGURE 10: Typical spectral sensitivities of the red, green and blue channels of a CCD of the type used in flatbed scanners, also shown is the emission spectrum of the Xenon cold cathode ray tube used in the EPSON 10000XL flatbed scanner.

Polarization

The needle-like polymers in GAFchromic™ film have a preferred orientation and tend to align with each other, this results in anisotropic light scattering. In addition the various layers of film may cause polarization of the incident light. Klassen *et al* using MD-55-2 found large variations (> 50%) in OD depending on the films orientation relative to a polarized He-Ne laser light source[69]. The majority of the polarization was attributed to the middle mylar layer specific to MD-55-2 film, other GAFchromic™ films have shown less polarisation[71]. Even when not using a polarized light source, the anisotropic scattering means that the orientation of the film can affect the measured OD. Lynch *et al* detected an 8% variation in OD when rotating EBT film through 360° on a flat-bed scanner[42]. It is recommended that radiochromic films are always scanned using the same orientation between calibration and measurement[72].

Interference fringes

Lasers produce a coherent light, this results in interference patterns being produced at the interface between layers in the film that have different refractive indices. These interference fringes, known as Moiré patterns, are considered reproducible and are dependent on the specific wavelength of the light source[63]. Another interference pattern can occur when radiochromic film is readout on a glass plate, such as in a flatbed scanner. These patterns are known as Newton's rings and result from multiple reflections of light between the film and glass, FIGURE 11. They are considered non-reproducible as they will change each time the film is repositioned on the glass plate. This effect can be eliminated by elevating the film off the plate using a mask[56], replacing the glass with a diffusing glass plate[61] or by removing the glass plate all together and suspending the film in air[53].

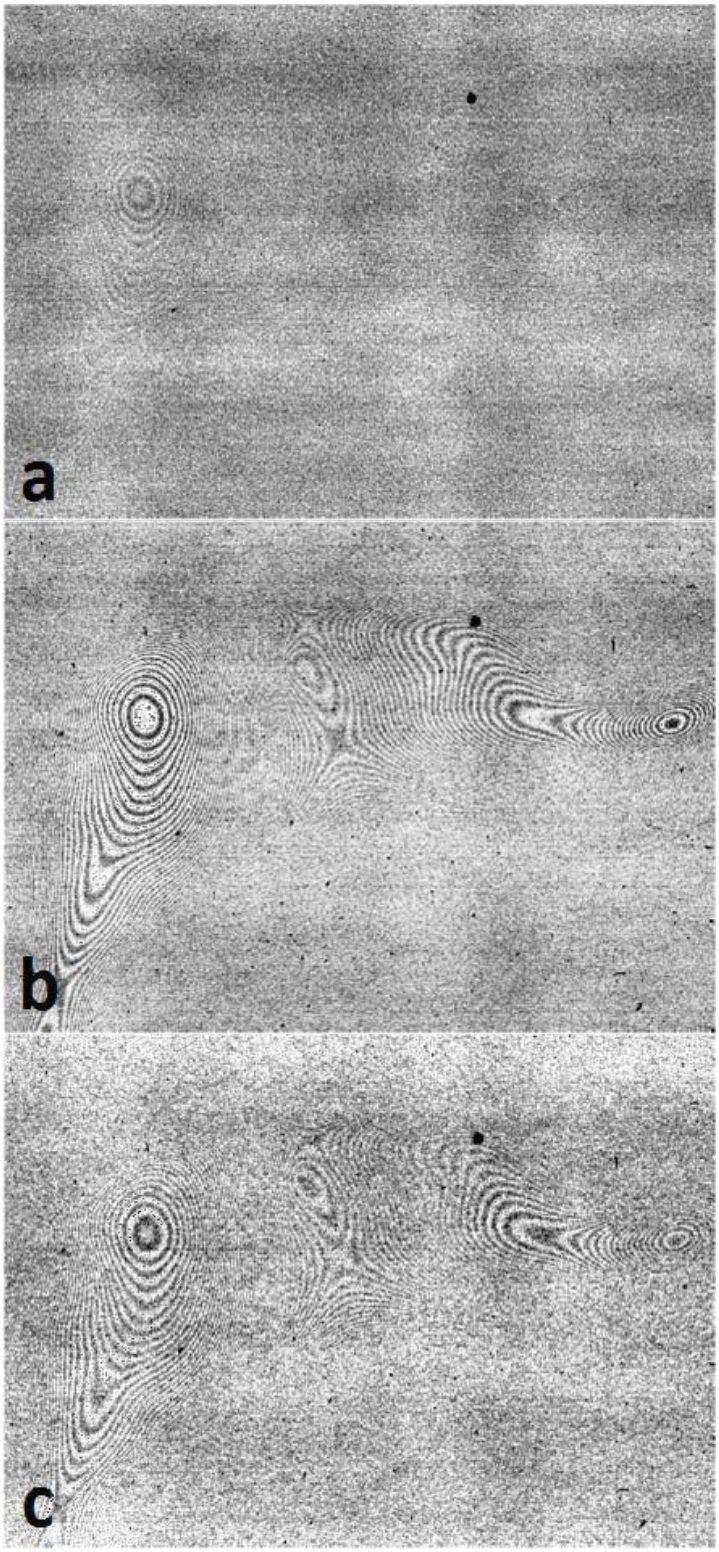

FIGURE 11: Interference patterns known as Newton's rings occur due to the multiple reflections at the interface between the film and glass plate of the flatbed scanner. These images are of GAFchromic^{TM} EBT2 film and show the difference in appearance of the rings when analyzing the (a) blue, (b) green and (c) red channel data.

Emission spectrum

An important consideration for selection of an appropriate light source is the absorption spectrum of the particular radiochromic film and the particular OD range that is required[30, 73]. FWT-60 has a broad skewed absorption peak at 605nm ranging from approximately 480nm to 650nm. For low doses (1-30 kGy) the most sensitive wavelength 605nm should be used but if higher doses are to be measured then it is suggested that a shorter wavelength in the less sensitive region 510nm be used[74]. B3 has an absorption peak at 552nm, and the GAFchromic™ films (HD, MD, HS) have two peaks at 617nm and 675nm. GAFchromic™ EBT and EBT2 have absorption peaks at 583nm and 635nm. For high dose applications selecting the most sensitive absorbance peak may result in saturation of the densitometer.

Another important consideration is how the absorption peak or λ_{max} varies with different doses and other environmental factors such as temperature. Devic *et al* studied the absorption spectra for EBT and EBT2[75, 76], decomposing the spectrum into 8 Lorentzian profiles and found that 3 out of the 8 absorption bands varied with dose. Selecting a waveband that samples too narrow an emission spectrum may introduce additional inaccuracies if the position of λ_{max} shifts in to or out of the waveband during measurement [41].

Light detectors

Types

The moving light source systems typically use either a photomultiplier tube or the less sensitive silicon photodiode[77]. As with photomultiplier tubes most photodiodes have specific spectral response curves. The photodiode produces a voltage in response to light and generates a current proportional to the intensity of the light striking it.

Charge coupled devices (CCDs) rely on the photoelectric effect and are fabricated from silicon. Photons coming from the object of interest strike the surface of the sensor and penetrate into the silicon up to a depth depending on their wavelength, generally shorter wavelengths (<400nm) are reflected and longer wavelengths (>1000nm) will pass through the CCD. The absorbed photon frees an electron which is stored in the depletion zone. By applying a voltage the freed electrons are transported, across adjacent pixels until they reach the charge node, where they are measured and converted into a voltage, the voltage is proportional to the number of electrons. The voltage is converted into a digital signal. CCD devices can have a single line of CCDs such as some flatbed scanners or in a 2D matrix such as cameras and in some flatbed scanners. The spectral sensitivities for the RGB channels of a CCD flatbed scanner were included in FIGURE 10, the red channel is well suited for GAFchromic™ dosimetry with a peak sensitivity between 600-650nm.

Properties

There are several properties that determine the suitability of a light detector for radiochromic film dosimetry. There is its sensitivity, this describes the ability of a light detector to differentiate between different quantities of photons and will be influenced by the amount of noise inherent to the detector. The sensitivity will influence the maximum detectable OD. Spectral efficiency is also important, as with the light source shifts in the absorbance or transmittance spectrum of the radiochromic film may have an effect on the detected signal. Most light detection systems will have a unique spectral response. For densitometry the spectral response of the detector should ideally be stable over the waveband(s) of interest. The light detector should have a linear response over a large range of light intensities. Another important consideration is signal resolution, most light detection systems produce an analogue signal in response to light and the signal is then converted into a digital output. The resolution of the digital output will determine the precision of measurement. An 8-bit image can contain 2^8 discrete pixel values ranging from 0-255. In film dosimetry systems, 16-bit and to a lesser extent 12-bit resolutions are more commonly used [63, 64, 77, 78].

Comparing the output of densitometry systems

A particular combination of light source and detector will produce a different response to that of another combination. It is possible to characterize the response of the system to known optical densities by using neutral density filters. The OD value determined by the densitometry system is compared to known value for the neutral

density filter, as shown in FIGURE 12. The neutral density filters are made of tinted glass or thin film metal coatings, that uniformly attenuate light over a broad spectral range, the level of attenuation is specified by the OD of the filter. The neutral density filters are normally specified by reference to their blocking (OD) value at a wavelength of 550nm. Film dosimetry software, such as RIT113 (Radiological Imaging Technology, Inc. Colorado Springs), may also provide a set of calibrated OD filters; these allow the user to characterize the particular response of their scanner and can also be used for monitoring the long term performance of the system.

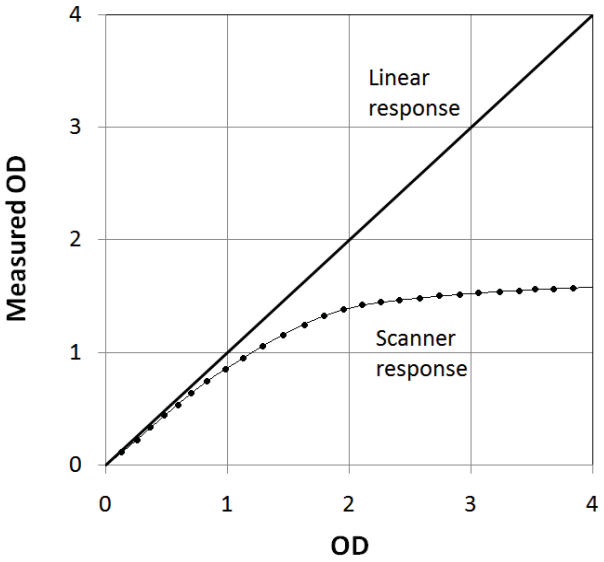

FIGURE 12: The non-linearity in response of a flatbed scanner to known optical densities**.**

FLAT BED SCANNER DOSIMETRY

In a conventional flatbed scanner, a film is placed on a glass plate, and a scanning array consisting of a lamp, a lens, and image sensors moves back and forth beneath the glass. Light from the lamp is reflected back from the film and passes through the lens, which focuses the image into the CCD. The signal from the CCD is converted into a digital signal and then stored. In transmission mode the movement of the lamp is separate to that of the lens and CCDs, and the lamp moves above the glass plate with its motion synchronized to the movement of the lens and CCD array. In high quality scanners the focus of the lens can be adjusted to accommodate objects that are not directly on the glass surface.

RGB

For film dosimetry purposes the image produced by the CCDs should be at least 16-bit resolution in the channel of interest, for a color scanner this will mean 48-bit images are required as 16-bits will be allocated to each of the red, green and blue color channels. The red channel is usually separated out for analysis because of the peak absorbance of EBT and EBT2 occurring at 635nm. However, as discussed previously, depending on the dose range being measured selecting a less sensitive spectral region may be advantageous [79, 80].

Transmission and reflectance

Flat bed scanners can operate in transmission or reflection mode. The most obvious difference between transmission and reflection mode is that in reflection mode most of the detected light has passed through the film twice, this increases the sensitivity to low doses but leads to quicker saturation at higher doses[58]. Several authors have also reported better uniformity when scanning in reflectance mode [58, 81]. The interaction of light with the multiple layers of film will be dependent on the absorption and scattering coefficients of each layer[24]. When used in reflection mode a dependence on the transparency of the surrounding media has been observed [58, 82]. Alva *et al* suggested using a black background to eliminate this unwanted reflected light from reaching the detector[82].

Desroches *et* al found that the asymmetric layer design of EBT2 meant there was a small OD dependence when scanning the film face up or face down in reflection mode[83].

OD range

As described by Gonzalez-Lopez *et al,* the OD range of a scanner used for film dosimetry is limited due to saturation and noise. As the OD increases, saturation causes the rate of change of the output to become smaller as the input signal increases, whilst at the same time the amount of noise remains fairly constant or increases. The combined effect leads to a degradation of the signal-to-noise ratio at high optical densities[84]. Flatbed scanners are generally limited to a maximum OD of approximately 3.5, and the useful range (where there is <0.5% uncertainty in OD) is smaller than this, 0.5-2.5OD [33, 85, 86].

Noise

In addition to the microscopic non-uniformity of the film, the flatbed scanner will introduce additional noise due to the electronics. By averaging multiple successive scans the amount of noise can be reduced [27, 86]. Ferreira *et al* reported a large decrease in noise was achieved by repeating scans twice, and a maximum improvement occurred after 4 scans. As the number of repeat scans increased beyond four there was degradation in image quality and the noise began to increase again.

To reduce noise caused by imperfections in the film the images can be processed using a filter, such as Wiener filter[27]. According to Devic *et al* the 2D Wiener filter uses a local estimate of the noise power spectrum and is therefore suitable for dosimetry as it preserves systematic variations in the film's optical density. Additional artifacts can be introduced due to the interference fringes caused at the interface between the film and glass surface, the simplest solution is to elevate the film off the surface by using a transparent mask[56].

To minimize film to film variations, averaging across multiple films can be done. In a study by van Battum *et al* on EBT and the uncertainties associated with using a flatbed scanner they concluded that using at least two films reduced the impact of inherent film non-uniformity and reduced the overall uncertainty of EBT dosimetry down from 1.8% to 1.3%[33]. Decreasing scanner resolution can also improve dose accuracy by averaging out the noise. Using a resolution of 72-75 dpi provides a good compromise between image resolution and noise[86, 87].

Dust/dead pixels

Any debris present on the glass plate or film will be propagated through the scans and add to noise. Similarly, dead or defective pixels caused by faulty CCD elements will introduce unwanted noise. Devic *et* al present a method to minimize the effects of these pixels by performing a series of blank scans of the scanner bed. Any pixels that differ in intensity from the blank (unattenuated) signal, equal to 2^{16}, are then ignored during filtering and thus effectively removed from the image [27]. It is advisable that all of the scanning surfaces and film are wiped clean with a soft lint free cloth prior to scanning.

Warm-up

A warming up period has been observed for scanner fluorescent lamps[27, 72]. If possible the scanner and lamp should be turned on 30 minutes prior to use to allow the temperature to stabilize. For some scanners, such as the EPSON 10000XL, it is not possible to independently switch the light source on without scanning, hence to warm up the lamp scanning must be performed. Typically the scanner response stabilizes after the first 3-4 scans. Several authors report various scanning methodologies, but each contains either a warm-up period or the rejection of the first 2-3 images, followed by the averaging of the next 3 images[27, 33, 56, 72].

Stability

The stability of scanners have been studied by performing numerous (100+) repeat scans[72, 88]. When using radiochromic film a gradual increase in OD was observed following the initial warm-up period. Several factors contribute to this increase. The response of the film is temperature dependent, as multiple scans are performed the temperature of the glass plate increases and hence the film also heats up leading to a change in response[42]. To reduce this effect Devic *et al* suggested leaving the transparency module raised during the warming up of the lamp[27]. In

FIGURE 13 the percentage change in net OD is shown for EBT and EBT2 films that were exposed to 50 and 200cGy, both film types show an increase in OD with increasing number of scans. The films that received the higher dose had a greater change in net OD, of 3-4% after 100 scans.

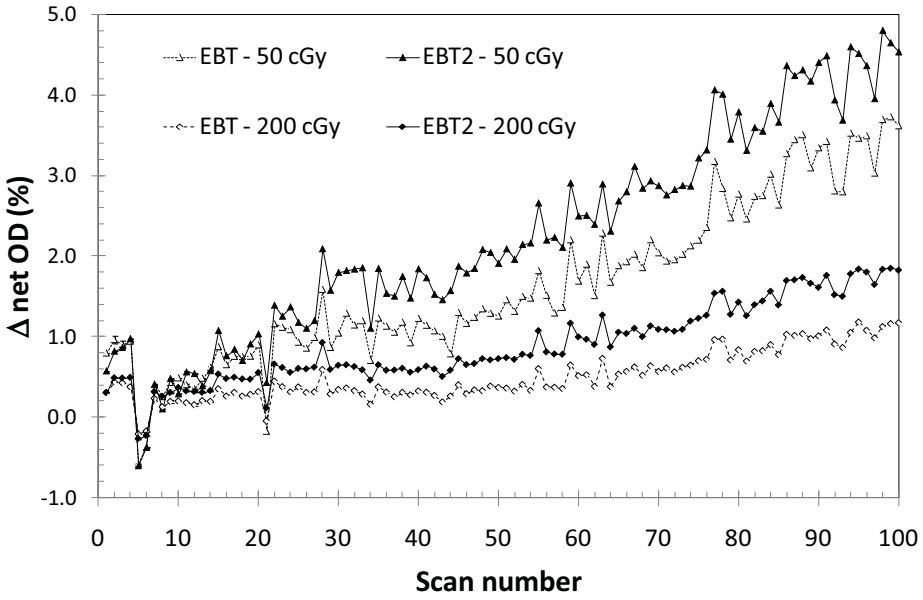

FIGURE 13: The percentage change in net optical density due to successive repeat scanning of pieces GAFchromic™ EBT and EBT2 exposed to 50 and 200cGy.

Another contributing factor to the increase in OD with multiple successive scans is the presence of UV wavelengths in the fluorescent light. Most radiochromic films demonstrate some sensitivity to UV light, and when they are scanned using the standard white light fluorescent tube the UV component results in additional polymerisation[72, 88]. Limiting the number of multiple scans to fewer than 10 will minimize this effect. Martisikova *et al* also observed large jumps in the scanner response, where it appeared the scanner was switching between two operating states[88]. A method for quality control of scanner stability is to include a transparent filter that has a constant optical density in every scan and monitor the measured pixel value of the filter.

Uniformity

The non-uniformity of the scanned light field on flatbed scanners has been well documented and is one of largest sources of error if left uncorrected [42, 56, 72, 89-91]. The non-uniformity is essentially limited to the direction perpendicular to the scan direction, this being parallel to the light source. The non-uniformity has been shown to be dependent on OD and can be greater than 10% across the entire scan area. The uniformity across an EPSON 10000XL scanner is shown in FIGURE 14, deviations of up to 4% were measured across the scan area. Devic *et al* suggest several possible contributing factors to the non-uniformity; geometrical inefficiency with CCD elements at the edge capturing fewer photons, non-uniformity in light production along the length of the fluorescence light source, light leakage, differences between reflections in the central region and in region close to the edges of the scanning bed and the optics used to focus the light at the CCD array[89].

To minimize the uncertainty associated with light non-uniformity, several options have been proposed. The simplest method is to restrict the scanning of films to the centre of the scanner which has minimal non-uniformity. For large A3 type scanners this is practical but for smaller A4 scanners this may be too restrictive on the size of films that can be used. An alternate method is to use a transparent film or filter of constant OD, and scan it over the entire flatbed producing a correction matrix. Another proposed method is the double exposure technique. It involves pre-scanning a uniformly exposed film before irradiating it with an unknown dose; the non-uniformity is inherently incorporated into the correction[53]. The pre-scanning methods are dependent on accurate repositioning of the film between scans.

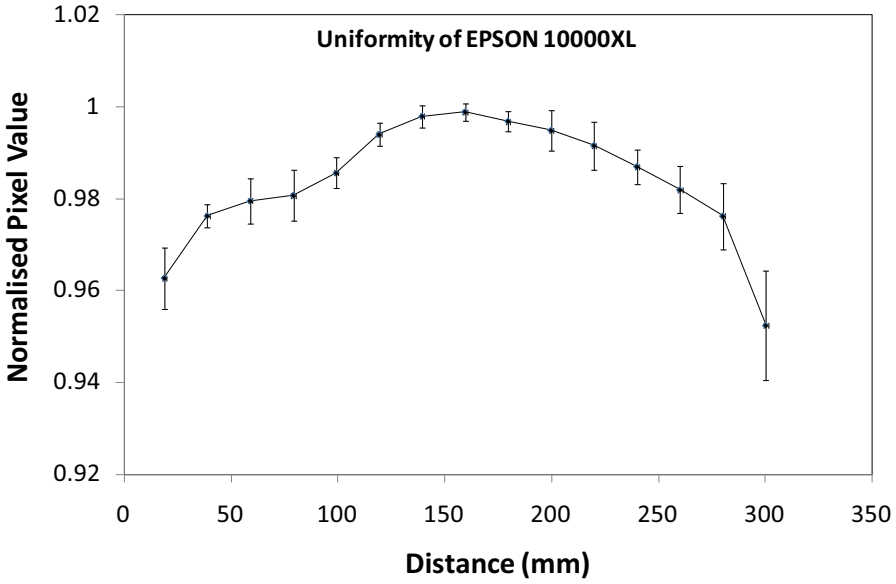

FIGURE 14: Deviations in pixel value measured across the scanner perpendicular to scan direction for the EPSON 10000XL.

Orientation

The polarization and directionally dependent light scattering effects observed for the various GAFchromic™ films mean that the placement of film on the scanning area will affect the measurement. The OD measured for GafChromic™ films show considerable difference between portrait and landscape orientations[56], and consistency between calibration and measurement must be maintained. FIGURE 15 is a plot of the calibration curve for EBT2 film when measured in portrait and landscape orientation. The manufacturer (ISP) advises scanning in landscape orientation.

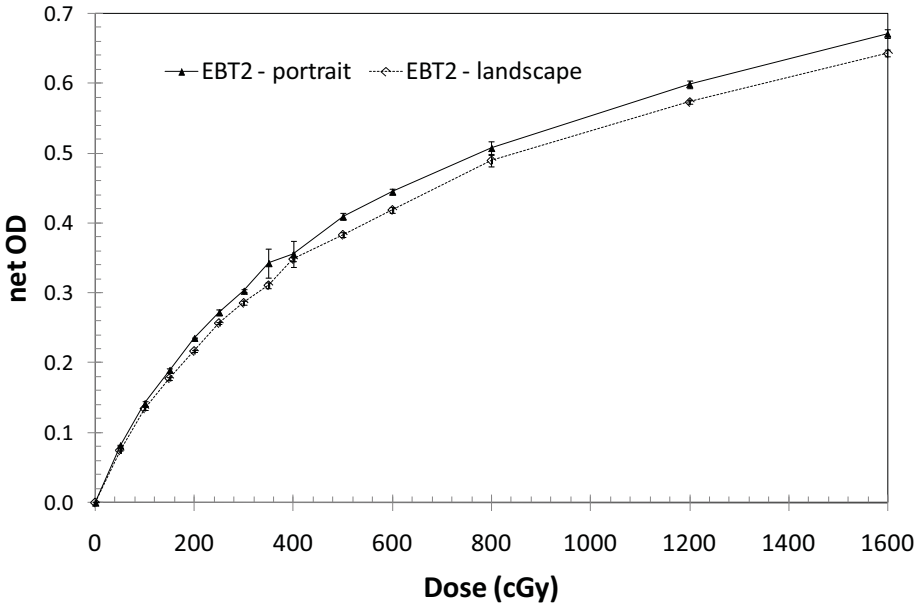

FIGURE 15: Calibration curves for GAFchromic™ EBT2 film in portrait and landscape orientations.

Additional considerations when scanning

File format - when scanning films it is ideal to preserve as much data as possible when saving the image, hence a lossless file format such as TIFF should be used.

Color management and filters - Most flatbed scanners come equipped with specific scanning software. The software is generally designed for the reproduction of photographic quality images or image presentation that is best suited for interpretation by the human eye. To produce these images various filters and color management techniques are employed. It is essential for accurate film dosimetry that all color management features and filters are disabled when scanning images.

Analysis software – there are several commercial products available for analysis of radiochromic films. An important feature is their ability to incorporate the various correction and calibration techniques required for accurate radiochromic film dosimetry. A common feature of analysis software is the use of gamma analysis[92]. Gamma analysis combines the measures of dose agreement and distance to agreement into a single index. A pixel in the measured dose distribution that satisfies the dose agreement tolerance or distance to agreement tolerance has a gamma value less than or equal to 1. For 2D dosimetry, such as performed with radiochromic film, typical gamma criteria used are 3%/3mm with the requirement that at least 90% of points must satisfy those criteria[93].

A documented scanning procedure – to ensure consistent high quality radiochromic film dosimetry it is advisable to develop a robust scanning and image processing procedure, several comprehensive documents on scanning techniques have been published [2, 27, 33, 72].

RADIOTHERAPY APPLICATIONS

Radiochromic film has been used for a variety of medical applications for many years, and until recently the dose range of radiochromic film restricted its use to high dose applications. These have been comprehensively summarized in the literature[2, 3, 94]. With the advent of the GAFChromic™ media and the even more sensitive EBT and EBT2 products, along with the demise of processor based radiographic imaging for patient treatments, there has been a rapid uptake of radiochromic film for use in radiotherapy dosimetry. The following is a brief overview of some of these uses.

For accurate quantitative dosimetry to be performed with radiochromic film there must be adequate measures in place to account for the variety of film and densitometer dependent properties. With such measures in place radiochromic film can be used to collect high resolution data that characterizes various properties of the linear accelerator such as micro-multileaf leakage and transmission[95] and to perform small stereotactic field dosimetry[96]. The water resistance and near tissue equivalence of EBT and EBT2 film allow it to be used in water phantoms to perform accurate dosimetry [51]. The EBT film has been used to perform high resolution build-up dosimetry[97], skin dosimetry[98] and characterize the depth dose of 50 and 100 kV beams[99]

The high resolution of GAFchromic™ film makes it favorable for performing high resolution qualitative measures. GAFchromic™ film has been used to verify isocentre alignment for proton beams[100], and this could readily be extended for use on linear accelerators also. The use of film to accurately measure penumbra has been shown to improve the accuracy of dose distributions predicted by treatment planning systems[101]. The study by Arnfield *et al* used a radiographic film (Kodak XV-2) with known energy dependence issues, the improved tissue equivalence of EBT2 film potentially allows for similar or better accuracy in the data used in penumbral modeling on treatment planning systems.

One of the more common uses of GAFchromic™ film is to perform quality assurance of IMRT treatments[54, 102-104]. With the complexity of IMRT planning and delivery requiring increased verification of treatment delivery; radiochromic film provides a fast and reliable means of accurately recording the dose distribution. The insensitivity to room light and lack of chemical processing also allow it to be incorporated into a variety of phantoms. In FIGURE 16 EBT2 is shown being used to conduct dose verification in an anthropomorphic head and neck phantom.

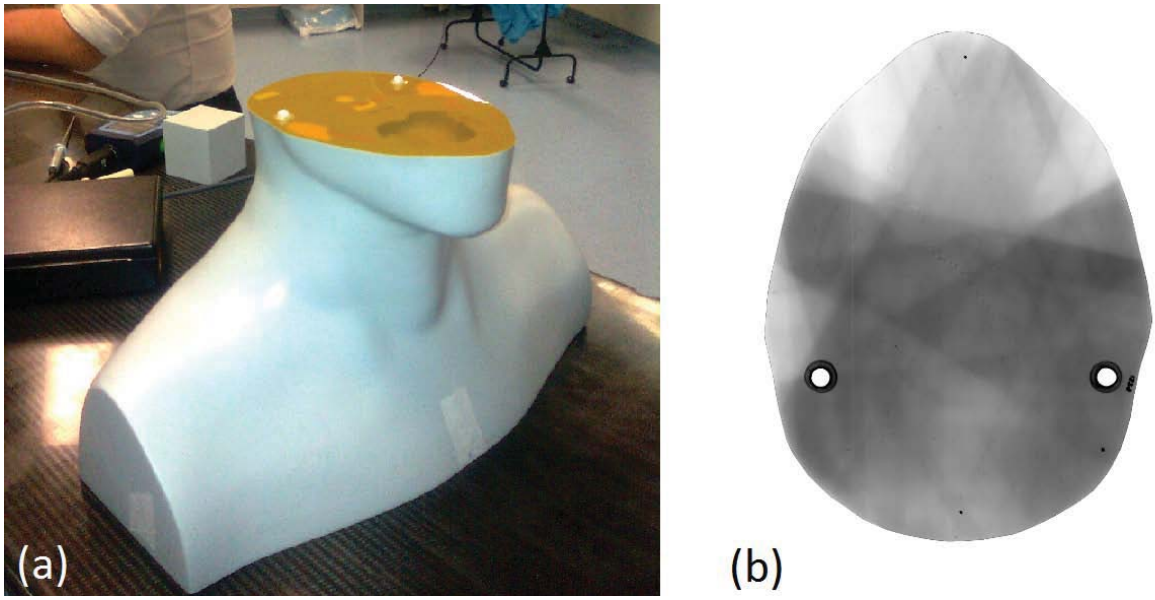

FIGURE 16: (a) EBT2 film being used to perform axial dose verification of a head and neck IMRT treatment in an anthropomorphic phantom and (b) the resulting measured distribution.

In addition to its use for verifying patient treatments, radiochromic film has also been used to perform in vivo dosimetry for total body electron[105] and total body photon treatments[106]. The ability to cut and bend the film allows it to be positioned at various locations on the patient that have challenging dosimetry, such as skin folds.

There have been several more recent publications on the use of radiochromic films for more exotic medical applications including medical ion beams[107], Cyberknife doisimetry[108], intra-operative dosimetry[109], low dose rate and high dose rate brachytherapy dosimetry[110]Ir-192 dosimetry[111], synchrotron dosimetry[112] and passive neutron dosimetry in the radiobiological irradiation of mice[113]

CONCLUSION

Radiochromic media have been in use for over half a century and a wealth of knowledge has been generated (largely by a few) on the unique behavior and properties of the various compositions. The recent development of radiochromic films that are sensitive to doses in the clinical treatment range has resulted in an explosion in the use of radiochromic film and the subsequent publications of those uses. As is the case for any dosimeter, radiochromic film is not perfect and it is important that the various characteristics and limitations of radiochromic film dosimetry systems are considered when presenting and interpreting radiochromic film data.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the support of the physicists at the Illawarra Cancer Care Centre and their assistance in the development of the ICCC radiochromic film dosimetry program. This work was supported by the Cancer Council New South Wales (Grant No. RG 09-21).

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