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Characterization and optimization of EBT2 radiochromic films dosimetry system for precise measurements of output factors in small fields used in radiotherapy

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ABSTRACT

The accurate determination of absorbed dose in small photon beams, especially for stereotactic radiation therapy, is a difficult task with commercially available detectors. As these small fields are characterized by high dose gradients, a lack of lateral particle equilibrium and a variation of energy spectra with beam sizes, a dosimeter with high resolution, tissue-equivalence and high precision is required. The new radiochromic film EBT2, which meets these criteria, was fully characterized in Institut de Radioprotection et Sûreté Nucléaire (IRSN) for this application. This type of film was tested with the reading system EPSON Dual Lens Perfection V700 flatbed scanner in transmission mode. Warm-up effects of the scanner were studied as well as the influence of the scanner light. Uniformity of unirradiated and irradiated EBT2 films in terms of pixel value was found to be respectively 0.3% (1 SD) and 0.5% (1 SD). An original, accurate and efficient radiochromic film dosimetry protocol was established. The overall uncertainty for dose measurement with EBT2 films using this protocol was estimated at less than 2% (1 SD). Encouraging measurements of output factors were performed on a Novalis system.

1. Introduction

Recently, the evolution of technology in radiation therapy has enabled small and irregular lesions to be treated. Three types of systems are used in stereotactic radiotherapy (SRT) and radiosurgery (SRS): adapted or dedicated linacs equipped with circular collimators or micro-multileaf collimators, Cyberknife and Gamma Knife. With these systems, the smallest field size ranges from 4 mm to 6 mm which leads to high dose gradient. Nevertheless, it is well known that it is difficult to accurately measure the dosimetric quantities required for the commissioning of these systems (Heydarian et al., 1996; McKerracher and Thwaites, 1999; Bucciolini et al., 2003; Paskalev et al., 2003; Das et al., 2008). In particular, the measurement of output factors is very problematic. Several studies have shown that measurements of the output factor of the smallest beams with different detectors can lead to a deviation of up to 30% (Haryanto et al., 2002; Tsai et al., 2003; Derreumaux et al., 2010). Work is in progress in order to define a new formalism for the reference dosimetry of small fields (Alfonso et al., 2008; Francescon et al., 2008) but there is still a need to find dosimeters able to accurately measure the output factors in small beams used in radiotherapy. As these small fields are characterized by high dose gradients, a lack of lateral particle equilibrium and a variation of photons and secondary electrons spectra with beam sizes; a dosimeter with a high spatial resolution and good tissue equivalence is required.

Due to their high spatial resolution, their near tissue equivalence and their low energy dependence, radiochromic films seem to be a good candidate for dose measurements in photon fields with high dose gradients (Niroomand-Rad et al., 1998; Butson et al., 2003). Radiochromic films use a radiation-sensitive dye organized into microcrystals and embedded in a gelatin binder to measure the dose of ionizing radiations. Following an irradiation, a solid-state polymerization takes place in the film and its colour progressively changes. The blue colour of the polymer becomes progressively darker as the dose increases. The advantage of radiochromic film is that no physical, chemical, or thermal processing is required to bring out this colour. The absorption spectrum of the radiochromic film exhibits a maximum in the red region of the visible spectrum (Stevens et al., 1996; McLaughlin et al., 1996). Therefore the response, upon irradiation, of radiochromic films is enhanced by measurement with red light. Radiochromic films can be measured with transmission densitometers, film scanners or spectrophotometers. Due to technical innovation, commercial

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flatbed scanners are more and more used for radiochromic films measurements. In 2004, EBT Gafchromic films were released by ISP and designed especially for radiotherapy. Several studies have been performed on EBT films (Devic et al., 2005; Butson et al., 2005; Todorovic et al., 2006; Lynch et al., 2006; Paelinck et al., 2007; Van Battum et al., 2008). These studies pointed out that the performances of this type of films are good but that as flatbed scanners are not especially designed for dosimetry, the scanning procedure has to be carefully evaluated. As a consequence, dosimetry with radiochromic films depends on the film model and the densitomer used and the scanning procedure. In May 2009, EBT Gafchromic films were replaced by EBT2 Gafchromic films. EBT2 Gafchromic films have a different structural layer and contain a yellow marker dye. This marker has two goals. Firstly, EBT2 films are supposed to be less sensitive to light than EBT films. Secondly, the marker enables differences in film thickness to be taken into account. EBT2 films are relatively new and need to be investigated as few studies are available (Butson et al., 2009, 2010; Hartmann et al., 2010; Kairn et al., 2010; Richley et al., 2010).

The aim of this study is to investigate the properties of the EBT2 Gafchromic films, to compare them with those of the EBT Gafchromic films and to present the procedure established for EBT2 Gafchromic films in combination with the EPSON Dual Lens Perfection V700 scanner in order to accurately measure the absorbed dose in small fields used in radiotherapy. Our goal is to provide a thorough description of the protocol so that it may be used by other teams and also be compared and evaluated.

2. Material and methods

2.1. EBT and EBT2 Gafchromic films

Radiochromic films EBT and EBT2 are both developed by ISP. They are recommended for a dose range between 0.01 and 8 Gy. EBT film is blue and consists in two sensitive layers separated by a surface layer and sandwiched between two polyester layers. It is composed of 42.3% C, 39.7% H, 16.2% O, 1.1% N, 0.3% Li and 0.3% Cl and its effective atomic number (Z_{eff}) is 6.98 (ISP, 2007). EBT2 film is yellow and consists of a single active layer coated with an adhesive layer and sandwiched between two polyester layers. For EBT2, the active layer incorporates a yellow dye which makes it possible to decrease the light sensitivity and also to compensate for differences in coating thickness. The atomic composition of EBT2 film is 42.37% C, 40.85% H, 16.59% O, 0.10% Li, 0.04% Cl and 0.01% N, K and Br (ISP, 2009). Its Z_{eff} is 6.84. Each box is composed of 25 sheets of 25.4×20.3 cm^2.

2.2. Scanner

EPSON Dual Lens Perfection V700 desktop scanner was used for scanning EBT and EBT2 films. This scanner is equipped with a white cold cathode fluorescent lamp. The scanner is capable of scanning in transmission and reflection modes. Films were scanned with EPSON software in transmission mode, in 48-bit colour mode without applying any image processing features and saved as TIFF image files. A preview was performed before each scan in order to define the area to scan.

2.3. Image processing

Analysis of images is performed using commercial software and an in-house graphical user interface (GUI). The commercial software called FilmQA is developed by 3Dcognition for quality assurance in IMRT. With this tool, the red component of the RGB images is extracted and the average pixel value is calculated in a given region of interest (ROI). The in-house tool was developed using Matlab. The first step in this program consists in overlaying the image of the unirradiated film and the image of the irradiated film. Then, the red component of the two overlaid RGB images is extracted pixel by pixel (Fig. 1).

The results are expressed in terms of pixel values (PV) for unirradiated and irradiated films as well as in terms of net optical density (netOD) for irradiated films. NetOD calculation is performed using the Devic et al. (2005) formula where the netOD is the difference between the optical densities of the irradiated and unirradiated film:

$$\text{netOD} = \log_{10}\left(\frac{\text{PV}_{\text{unirr}} - \text{PV}_{\text{bkg}}}{\text{PV}_{\text{irr}} - \text{PV}_{\text{bkg}}}\right) \tag{1}$$

PV_{unirr}, PV_{irr} and PV_{bkg} are respectively the measured pixel value of the unirradiated film, the measured pixel value of the irradiated film and the pixel value of the zero light transmitted intensity. The zero light transmitted intensity was determined by reading a stack of EBT2 film pieces exposed during two weeks to natural light.

For the commercial software, netOD is calculated independently on an Excel sheet from a mean pixel value for a given ROI. For the in-house tool, the netOD is calculated pixel by pixel.

2.4. Irradiation procedure

All the irradiations, except the dose and energy response, were performed at the IRSN secondary standard metrology laboratory. Samples of films were placed in the center of the field of a Co-60 irradiator (gamma photon emitter, mean energy = 1.25 MeV) and irradiated behind a Plexiglas window with the electronic equilibrium conditions in terms of air kerma (thickness = 5 mm). In this configuration, the field size on the film pieces was 10×10 cm^2.

2.5. Study of parameters influencing the scanning procedure

2.5.1. Precautions

Films were always handled with gloves. For most of the tests, except for film uniformity and scanner uniformity, the sheet was cut in pieces of 10×10 cm^2. As orientation on the scanner can affect the measurement (Butson et al., 2003; Lynch et al., 2006; Zeidan et al., 2006) the orientation of each piece was marked with a small sticky label. This sticky label was also used for the overlaying of the images in the Matlab tool. Moreover a plastic template of 10×10 cm^2 was specially designed to place the film at the same position and to maintain the film on the scanner glass. Pieces of films were cut two days before irradiation in order to allow the disturbances created mechanically to relax. As post-coloration of the films can occur up to 6 h after irradiation (Cheung et al., 2005), films were read one day after irradiation.

2.5.2. Warm-up effect of the scanner lamp and reproducibility

With this scanner, there is no possibility of warming up the scanner before scanning so the warm-up effect of the lamp must be investigated. As a matter of fact, a decrease in optical density has been observed by different authors due to the warm up of the scanner (Devic et al., 2005; Paelinck et al., 2007; Ferreira et al., 2009). As radiochromic films are known to be sensitive to light, it was decided to investigate the warm-up effect of the scanner lamp with a blue sheet used as a fictitious film. The scanner was turned on ten minutes before the first preview and then films were scanned successively with a preview followed by a scan. As the successive scans may result in a subsequent heating of the scan bed, different waiting periods between two successive scans were investigated as well as the waiting period between the preview and