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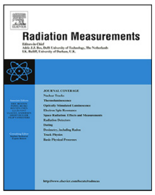

Development of a protocol for small beam bi-dimensional dose distribution measurements with radiochromic films

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HIGHLIGHTS

- Uniformity of a flatbed scanner and radiochromic films were investigated.
- A “four films” dosimeter was designed to reduce experimental uncertainties.
- An accurate bi-dimensional dose measurement protocol was developed.
- Measurements were performed in stereotactic radiotherapy conditions.
- The protocol was validated with Monte Carlo simulations.

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ABSTRACT

Gafchromic™ films have become popular due to their ease of use and their near water equivalence. This last property is crucial for stereotactic small beam dosimetry as demonstrated in recent papers. An accurate bi-dimensional dose measurement with Gafchromic™ films is very challenging mainly because of the non-uniformity response of flatbed scanners (used for films digitalization) and their own non-uniformity. The first proposal of this work is to develop bi-dimensional protocol for small beams and evaluate the associated uncertainty. The second proposal is to validate this protocol for the bi-dimensional measurements of treatment plans performed with the CyberKnife® system.

First, the uniformity of an Epson V700 flatbed scanner and a batch of EBT3 Gafchromic™ films has been investigated. A “four films” dosimeter was designed to reduce the errors (statistic and systematic) due to their non-uniformity. Then, the “four films” dosimeter protocol in both a homogeneous (RW3 material) and heterogeneous (RW3, lung-like and bone-like materials) phantoms has been used to measure the bi-dimensional dose distributions of three simple CyberKnife® treatment plans. Two tumor locations (middle of the lung and near lung/bone interface) were considered for the heterogeneous phantom. These plans were achieved with the 10 mm fixed collimator and modeled with the PENELOPE Monte Carlo code in order to calculate accurate dose distributions. Finally, the “four films” bi-dimensional dose distributions were compared to the PENELOPE Monte Carlo simulations.

Regarding the uncertainty associated to the bi-dimensional dose measurement protocol, the relative standard deviation σ_D on the dose was 1.2% in the range from 0.5 to 4.0 Gy. Regarding the protocol validation on CyberKnife® treatment plans, a very good agreement was found with all measurement points passing the {3% - 3 mm} Gamma Index criteria.

1. Introduction

Stereotactic radiation therapy (SRT) is an external radiation therapy dedicated to treat small targets. Multiple high energy photon beams with small size (small beams) are used to cover the

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small and irregular planning target volume with a high spatial accuracy. A treatment plan is achieved before the radiation dose delivery by calculating the number of beams, their direction, position, intensity and field size that ensure the target coverage with the radiotherapeutist prescribed dose while sparing the organs at risk. The treatment plan is performed with a treatment planning system (TPS) using algorithms and experimental dosimetric data to calculate and optimize the patient dose distribution.

The dose distributions calculated by the TPS are subject to two major sources of errors. On one hand, the determination of dosimetric data for small beams is challenging given their small size compared to the detectors size, the high dose gradient and the lack of lateral electronic equilibrium (Verhaegen et al., 1998; Das et al., 2000; Cheng et al., 2007; Das et al., 2008). On the other hand, most algorithms implemented in the TPS are not able to accurately model the physics involved in small beams, in particular the transport of charged particles in heterogeneous media (Wilcox and Daskalov, 2008; Ma et al., 2008). It is therefore necessary to evaluate the accuracy of TPS algorithms using reliable bi-dimensional (2D) or tri-dimensional dose measurements in heterogeneous phantoms.

One of the available SRT facilities on the market is the CyberKnife® from Accuray Inc. (Sunnyvale, CA, USA). The system utilizes its own dedicated treatment planning system called MultiPlan. It has currently two dose calculation algorithms: a pencil beam-based algorithm, named RayTracing, which assumes the condition of charged particle equilibrium throughout the volume of calculation (Sharma et al., 2010; Chan et al., 2013), and a simplified Monte Carlo (MC) algorithm based on EGS4 code (Ma et al., 2008). This paper does not focus on the evaluation of MultiPlan algorithms, but aims to:

- firstly develop an experimental method based on EBT3 radiochromic films to accurately measure 2D dose distributions of small beams especially in heterogeneous media;
- secondly validate the protocol by comparing measured 2D dose distributions with a full MC simulation calculated with the PENELOPE code (Salvat et al., 2008). This simulation code accurately takes into account the secondary charged particles transport, which is crucial in small beams due to the lack of lateral charged particles equilibrium.

2. Materials and methods

2.1. Study overview

The study is divided in two parts. The first part is dedicated to the development of a protocol for 2D dose distribution measurements in small beams using EBT3 radiochromic films (Ashland ISP Advanced Materials) and the estimation of measurement uncertainties associated to this protocol. EBT3 radiochromic films are expected to be a good candidate for 2D small beam dose verification (Dieterich et al., 2011; Borca et al., 2013). It has been previously shown that radiochromic films provide good agreement with Output Factors and Off-Axis Ratios calculated in water by MC simulation, because of their high water-equivalence and spatial resolution (Wilcox and Daskalov, 2007; Wilcox and Daskalov, 2008; Moignier et al., 2014). Each element of the measurement chain, including the EBT3 film dosimeter itself and the EPSON Dual Lens Perfection V700 flatbed scanner (denoted by V700) used for their digitalization, was characterized to optimize the protocol and minimize the measurement uncertainties.

The second part is dedicated to the validation of the protocol for 2D small beam dose distribution measurements. The approach follows different steps that are summarized hereafter:

- First, three simple plans were modeled on the MultiPlan TPS. One plan was performed with a homogeneous phantom (RW3 material) and two plans were performed with a heterogeneous phantom (RW3, bone and lung materials).
- These plans were modeled with the PENELOPE MC code (full MC simulation). This code is used as a reference in our work because of its ability to accurately simulate the charged particles transport in heterogeneous media.
- The phantoms equipped with EBT3 films were irradiated according to the three simple plans.
- The protocol was validated by comparing the measured dose distributions and the PENELOPE MC calculated dose distributions.

2.2. Protocol for bi-dimensional dose distribution measurements with EBT3 radiochromic films

2.2.1. Corrected optical density

EBT3 radiochromic film is composed of one sensitive layer (thickness of approximately 30 μm) sandwiched between two symmetrical polyester layers (thickness of approximately 125 μm for each layer). After the film irradiation, a polymerization takes place in the active layer, changing the optical properties: this layer becomes darker as the dose deposition increases. The absorbance is maximal in the red area of the light spectrum (Butson et al., 2005) and can be physically quantified by the optical density (OD) with a transmission densitometer as:

$$\mathrm{OD} = -\log\left(\frac{\Phi}{\Phi_0}\right) \tag{1}$$

where Φ_0 and Φ are the light intensity before and after crossing the media, respectively. The EBT3 film OD after exposure can be measured using the image of the digitized film in two spatial dimensions (Z,X) with the V700 scanner as:

$$\mathrm{OD}\ (Z,X) = -\log\left(\frac{\mathrm{PV}\ (Z,X)}{2^{16}-1}\right) \tag{2}$$

where PV(Z,X) is the pixel value in the red channel of the TIFF image from the film after exposure. Similarly, the 2D background optical density of the film before exposure is given by:

$$\mathrm{OD}_{\mathrm{bkg}}\ (Z,X) = -\log\left(\frac{\mathrm{PV}_{\mathrm{bkg}}\ (Z,X)}{2^{16}-1}\right) \tag{3}$$

In order to convert the OD in dose, a calibration curve is performed by exposing radiochromic films to known radiation doses. The calibration of the radiochromic films was done between 0.0 and 4.5 Gy by step of 0.5 Gy, and the points (OD, dose) were fitted with a 3rd degree polynomial curve.

The uniformity of the radiochromic film active layer as well as the uniformity of the scan field are not perfect, which can lead to errors in the 2D optical density determination. Two correction methods of this non-uniformity are commonly used: the background subtraction (BS) correction (Devic et al., 2005) and the multichannel correction (Micke et al., 2011). Only the BS method was used since the multichannel method was equally or less performing in our protocol (Huet et al., 2014).

The 2D “net” optical density corrected with BS method ($net\mathrm{OD}_{\mathrm{corr}}$) is defined as: