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Two-dimensional thermoluminescence dosimetry system for proton beam quality assurance

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HIGHLIGHTS

- Three proton energies were considered: 80, 150 and 225 MeV.
- Characteristic dose of 227 Gy, 209 Gy and 203 Gy was calculated.
- The linear dose response was found up to 20 Gy.
- Spot sizes of pencil beam were measured with 2D TL dosimetry system.
- The results were compared with Gafchromic EBT3 calculation.

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ABSTRACT

The response of a large-area two-dimensional (2D) thermoluminescence (TL) dosimetry system with 20×20 cm^2 TL LiF:Mg,Cu,P foils, developed at the Institute of Nuclear Physics PAN was studied for doses of therapeutic proton beams with energies of 80 MeV, 150 MeV and 225 MeV. The one-hit detector model fitted to measured dose response yielded characteristic doses of 227 Gy, 209 Gy and 203 Gy respectively. The system was applied to investigate geometrical parameters of spots produced by proton pencil beams at the Bronowice Cyclotron Centre IFJ PAN. Mean spot sizes measured with TL foils were compared with mean spot sizes calculated for Gafchromic® films. It was shown that the 2D TL system was capable to measure the spot size up to peak doses of 20 Gy without additional correction for dose response. For measurements of the spot size using Gafchromic® EBT3 films an additional calibration must be applied to correct for the non-linear response for doses exceeding 1 Gy.

1. Introduction

Modern cancer radiotherapy using energetic proton beams achieves good uniformity and conformity of the delivered dose with the treatment volume. Advanced techniques employ narrow pencil beams of different energies and scanning system to scan the volume of interest point by point. In order to achieve good uniformity and steep dose gradients the exact position of single spots are calculated by a Treatment Planning System (TPS) based on a beam model prepared for each treatment unit individually during commissioning process (Doolan et al., 2015). Therefore precise measurements of the pencil beam shape are necessary to assure the quality of the beam model (Farr et al., 2013; Gillin et al., 2010). A pencil beam can be characterized by its cross-section called a spot. It is generally assumed that energy of protons in the spot are approximately the same and fluence distribution within the spot is described by the two-dimensional Gaussian function (Schwaab et al., 2011), expressed in polar coordinates as:

$$f(r,\theta) = A \cdot e^{-\frac{r^2}{2\sigma^2}}, \qquad (1)$$

with parameters σ as the spot size and A as the spot height. Indeed, real spots are asymmetric and can be described by two-dimensional Gaussian function with σ_x and σ_y parameters.

Active devices based on scintillators with a CCD camera (e.g. Lynx, IBA Dosimetry) or ionisation chamber matrixes (e.g. MatriXX PT, IBA Dosimetry) are difficult to use in phantoms. Moreover, the chamber matrixes demonstrate relatively low spatial resolution to determine the spot parameters in radiotherapy with very narrow pencil beams. Therefore, radiographic (e.g. Kodak films) and radiochromic (e.g. Gafchromic foils) systems are routinely used in many

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medical facilities worldwide (Sorriaux et al., 2013). They are easy to handle and can be used in solid or water phantoms, and feature with enough spatial resolution to measure single pencil beam precisely (Hara et al., 2014). A disadvantage of these foils is a non-linear dose response above 1 Gy (Martišíková and Jäkel, 2010b). Measured images need to be corrected using additional calibration, which is frequently unique for a particular lot of detectors. It causes additional uncertainties not only in dosimetric measurements but also for geometrical investigations.

The two-dimensional (2D) thermoluminescence (TL) dosimetry system developed at Institute of Nuclear Physics PAN (IFJ PAN) consists of TL detectors in the shape of foils (Olko et al., 2006), a dedicated TL reader equipped with suitable heating system and a CCD camera (Olko et al., 2008) and dedicated software for image acquisition and post-processing (Gajewski et al., 2013). The detector foils based on LiF TL material demonstrate wide linear dose response (Gajewski et al., 2013; Kisielewicz et al., 2010). They are flexible and water resistant and can be easily used in water or solid phantoms.

The objective of the work was to apply the 2D TL dosimetry system to determine the geometrical parameters of proton beam spots and to compare properties of the system with the commercially available Gafchromic® EBT3 dosimetry system. The hypothesis was that due to the wider linear dose response, the shape of a spot measured with 2D TL dosimetry system would not be deformed and it could be applied to higher doses. The system has been employed in measurements of an active pencil scanning beam, PBS, at the therapeutic gantry unit equipped with the dedicated scanning nozzle at the Bronowice Cyclotron Centre, IFJ PAN, Kraków.

2. Material and methods

2.1. 2D Thermoluminescence dosimetry system

The system consists of TL detectors in the shape of foils, TL reader and dedicated software. TL foils were produced from a mixture of LiF:Mg,Cu,P (MCP-N) TL phosphor and poly-EthyleneTetraFluoroEthylene (ETFE) polymer pressed at high temperature (Olko et al., 2006). Foils of size 20×20 cm^2 are flexible and mechanically stable, water-resistant and reusable. The TL reader is equipped with a CCD camera and large area heating plate (Olko et al., 2008). The reading process is controlled by a home-made software FlatView. The software is used also for readouts correction and analysis (Gajewski et al., 2013).

2.2. Irradiation

Irradiations took place in the gantry-1 therapeutic room at the Bronowice Cyclotron Centre, IFJ PAN, using scanning proton beam. Foils were positioned in the isocentre of gantry room, perpendicular to the beam axis. Irradiations with single pencil beams were performed in air using different monitor units (MU) per spot. The experiment was repeated for three proton energies: 80 MeV, 150 MeV and 225 MeV with spot sigma 6.1 mm, 3.9 mm and 2.5 mm respectively. Linear Energy Transfer (LET) in water for this energies are 8.63, 5.45 and 4.17 MeV cm^2/g respectively (Berger et al., 2005).

Calibration of the dose for different MU per spot for these three energies was performed using cylindrical Markus chamber type 23343 (PTW Freiburg, Germany) of sensitive volume 0.055 cm^3 and diameter 5.3 mm.

2.3. Analyse methods

2.3.1. 2D TL measurements

TL detectors were read out using standard procedure described in (Gajewski et al., 2013). In order to remove low temperature TL peaks after irradiation, detectors were pre-annealed in 100 °C for 20 min. Afterwards they were read out using the large-area TL reader by heating them up to 240°C with the heating rate of 0.64 °C/s and collecting the emitted TL light with a CCD camera. The image of each detector was corrected for non-uniformity using Individual Reference Images.

Spot images were analysed individually by fitting Gaussian curves to X and Y profiles going through the spot centre of mass. The spot size, σ, is then defined as the mean value of σ_x and σ_y parameters and the mean value of amplitudes is the spot height.

2.3.2. Gafchromic EBT3 response simulations

The response of radiochromic films is usually expressed in net Optical Density (netOD) units (Niroomand-Rad et al., 1998; Devic et al., 2005) according to the equation:

$$netOD = -\log_{10}\left(\frac{PVR_{irr}}{PVR_{unirr}}\right) \quad , \tag{2}$$

where PVR_{irr} and PVR_{unirr} are raw pixel values from the red colour channel of readouts of irradiated and not irradiated film. The response of Gafchromic® EBT3 detectors for dose of 203 MeV protons was reported by Reinhardt et al. (2012), where the response equation $D = A_0 netOD + A_1 netOD^{A_2}$ was presented with fit coefficients $A_0 = 9.93(0.52)$ Gy and $A_1 = 42.47(4.25)$ Gy and fixed parameter $A_2 = 2.6$. Since no significant LET dependence is observed for protons of energies exceeding 20 MeV (Reinhardt et al., 2012; Martišíková and Jäkel, 2010a), the same dose response was assumed for each proton energy considered in this study.

Simulations of spot shapes were performed in Matlab environment. The TL low dose spots, not exceeding 5 Gy in peak, were recalculated assuming the Gafchromic® dose response pixel by pixel for doses ranging from 1 Gy to 200 Gy. The simulations were repeated for each considered proton energy.

2.3.3. Dosimetry

For the reference dosimetry the Markus chamber with 5.3 mm diameter of sensitive are awas applied. The chamber covers only the central part of a spot measuring dose D_M. The fluence distribution within the spot is described by two-dimensional Gaussian function. The number of particles, N_M, crossing the Markus chamber was calculated by integration over the part of the spot:

$$N_M = A \cdot \int_0^{2\pi}\int_0^{r_M} r e^{-\frac{r^2}{2\sigma^2}} \mathrm{d}r\mathrm{d}\theta = 2\pi\sigma^2 \cdot A \cdot \left(1 - e^{-\frac{r_M^2}{2\sigma^2}}\right), \tag{3}$$

where $r_M = \frac{5.3}{2}$ mm is the radius of the chamber sensitive area, σ is the mean size of spot and A is the maximal fluence. The dose at the spot peak, D_{max}, can be then calculated as:

$$D_{max} = D_M \cdot \frac{r_M^2}{2\sigma^2 \cdot \left(1 - e^{-\frac{r_M^2}{2\sigma^2}}\right)} \quad . \tag{4}$$