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Monte-Carlo based prediction of radiochromic film response for hadrontherapy dosimetry

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ABSTRACT

A model has been developed to calculate MD-55-V2 radiochromic film response to ion irradiation. This model is based on photon film response and film saturation by high local energy deposition computed by Monte-Carlo simulation. We have studied the response of the film to photon irradiation and we proposed a calculation method for hadron beams.

1. Introduction

For many years, films have been used in radiotherapy to determine dose distribution. The film response is well known for such classical applications. Hadrontherapy uses different beam types, which makes the film response more complex.

Radiochromic films seem to be useful detectors for dosimetry with hadron beams because of their high spatial resolution which allows to measure dose distributions in regions of high-dose gradient. The film resolution is better than 1 μm per pixel [1]. The MD-55-V2 radiochromic films studied in this work are 310 μm thick, with two 16 μm sensitive layers of diacetylene monomeric microcrystals on a clear polyester base. The sensitive layers undergo partial polymerization by the ionizing radiation [2]. The irradiated films have two absorption peaks in the red region of the spectrum centered at 614 and 674 nm [3] hence the film color is blue. These peaks increase as the absorbed dose increase and the films darken.

With the photon beam of a typical radiotherapy accelerator, film response is simply a function of the dose (see Section 2.1). However, with hadron beams, film response also depends on the hadron track structure i.e. hadron charge and energy, especially near the Bragg peak. For the same total dose to the film, local ionization and dose are much higher around ion tracks when using hadron beams, whereas they are more uniformly distributed over the whole film when using photons. Film response could become more complex with the fragmentation of the hadrons in the material which produces new particles of different atomic numbers and energies. Formation of a spread-out Bragg peak (superposition of several beams with different energies) also contributes to modifying film response when using hadron beams.

In this study, we propose a model to predict response as a function of the local behavior of the film irradiated using hadron beams. Film response to photon beams is used as a reference to calculate response to ion irradiation. We will first study the response of the film to photons, then propose a calculation method for ion beams.

2. Optical density

The MD-55-V2 film dose response can be calculated using the absorption spectrum of the film and the light spectrum of the scanner [4]. The present study aimed to establish the global behavior of the film as a function of the dose absorbed and of incident particle features. In particular, we studied the energy

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deposition close to the track. Indeed, the density of deposited energy around an ion track is very high and may influence film response. We defined the local linear energy transfer (local LET) as the energy deposited along a track segment in a cylinder of radius r centered on the track segment divided by the length of the track segment. We considered r to be smaller than the size of polymer microcrystals, i.e. in the order of the micrometer.

2.1. Low local LET particles

For particles with low local LET, the light transmittance through an infinitesimal surface area dS of a film irradiated to a dose D_{dS} is

$$T_{dS}(\lambda, D_{dS}) = \frac{I(\lambda, D_{dS})}{I_0(\lambda)} \tag{1}$$

where $I_0(\lambda)$ is the intensity of the light for the wavelength λ passing through the film and $I(\lambda, D_{dS})$ the intensity after the film. $I_0(\lambda)$ and $I(\lambda, D_S)$ are dependent on the light source of the scanner used to read the film. The optical density is defined as

$$OD_{dS}(D_{dS}) = -\log\left(\frac{\int_0^\infty I(\lambda, D_{dS})\, d\lambda}{\int_0^\infty I_0(\lambda)\, d\lambda}\right). \tag{2}$$

We consider that the optical density can be expressed with parameters a and b:

$$OD_{dS}(D_{dS}) = -\log\left(\frac{1}{I_0^{tot}(a \cdot D_{dS} + b)}\right) = \log(I_0^{tot}(a \cdot D_{dS} + b)) \tag{3}$$

where $T(0) = 1/(I_0^{tot} \cdot b)$ is the transmittance value of an unirradiated film and $I_0^{tot} = \int_0^\infty I_0(\lambda)\, d\lambda$ is the total intensity of the light. The net optical density is defined as

$$OD_{dS}^{net}(D_{dS}) = OD_{dS}(D_{dS}) - OD_{dS}(0) \tag{4}$$

$$OD_{dS}^{net}(D_{dS}) = \log(I_0^{tot}(a \cdot D_{dS} + b)) + \log(T(0)) \tag{5}$$

$$OD_{dS}^{net}(D_{dS}) = \log(a' \cdot D_{dS} + 1). \tag{6}$$

We consider that the light spectrum is stable over the whole scan area. For a surface S of the film irradiated to a dose D, the transmittance is

$$T(D) = \frac{1}{S}\int_S T_{dS}(D_{dS})\, dS = \frac{1}{S}\int_S \frac{1}{(I_0^{tot}(a \cdot D_{dS} + b))}\, dS. \tag{7}$$

The optical density is

$$OD(D) = -\log(T(D)) = -\log\left(\frac{1}{S}\int_S \frac{1}{(I_0^{tot}(a \cdot D_{dS} + b))}\, dS\right) \tag{8}$$

$$OD^{net}(D) = -\log\left(\frac{1}{S}\int_S \frac{1}{(a' \cdot D_{dS} + 1)}\, dS\right). \tag{9}$$

And for a homogeneous dose D over the whole surface S of the film:

$$OD^{net}(D) = OD_{dS}^{net}(D) = \log(a' \cdot D + 1). \tag{10}$$

2.2. High local LET particles

The track structure of heavy charged particles is characterized by high energy deposition along trajectories. The energy deposited may be locally higher than the film capabilities. This can be seen as a saturation of the film and the excess energy deposited is lost, i.e. does not contribute to darkening the film. The coloration of the film around the track is lower than the coloration of films irradiated homogenously at the same dose with low local LET particles. Accordingly, the coloration likely corresponds to an irradiation with low local LET particles delivered at a lower dose named effective dose, or D_{eff}. To model this behavior, we have looked for a function to express the effective local linear energy transfer LET_{eff} as the function of the local LET of the particle. At low local LET, the equation yields $LET_{eff} = LET$ and in the high local LET region, the function shows a saturation without horizontal asymptote. In the case of a homogeneous irradiation, the effective local linear energy transfer LET_{eff} is expressed as the function of the local LET of the particle:

$$LET_{eff} = \tau \ln\left(\frac{LET}{\tau} + 1\right) \tag{11}$$

where τ is the limit of the linear region of the film effective local LET. The effective dose deposited by a particle along a track segment L is

$$D_{eff} = \frac{LET_{eff} \cdot L}{M} \tag{12}$$

where M is the mass of the film volume considered. And the optical density is

$$OD^{net}(D_{eff}) = \log(a' \cdot D_{eff} + 1) \tag{13}$$

where a' is the film response parameters defined in the previous section. In cases where LET/τ tends toward zero:

$$LET_{eff} = \tau \ln\left(\frac{LET}{\tau} + 1\right) \to LET. \tag{14}$$

And, we retrieve Eq. (10)

$$OD^{net}(D_{eff}) \to OD^{net}(D). \tag{15}$$

3. Experimental setup and simulation

3.1. Experimental setup

In this study, we used Gafchromic® MD-55-V2 radiochromic films (International Specialty products, Wayne, NJ, batch # P0234MDV2). The films were read four days after irradiation using a Vidar VXR-16 DosimetryPRO Film Digitizer (Vidar Corporation, Herndon, Virginia) at the Centre Léon Berard (Lyon, France). This scanner has a fluorescent white light source with a spectral emission range between 250 and 750 nm. It is coupled to a linear CCD digitizing system. The resolution used was 89 μm per pixel. Films were taped onto transparency paper and scanned using the Omnipro IMRT software (Scanditronix Wellhofer). Optical density was measured with about 5% accuracy [1].

Photon irradiations were carried out at the Centre Léon Berard (Lyon, France) using an Elekta 6 MV beam linear accelerator with the films placed perpendicularly to the radiation beam. Ten centimeters of solid water was present before the film position. Films were irradiated at several doses between 0 and 150 Gy. To read the films, we chose a region of interest in the center of the film ($\simeq 1\,cm^2$) and we measured the dose at the film position with a thimble ionization chamber. The precision of dose measurements was 2% and the error on the dose delivered was less than 1%.

Ion irradiations were done at GANIL (Caen, France). A PMMA triangle (2 cm × 4 cm × 5 cm) was installed in front of a film and irradiated with a 75 MeV/u ^{13}C beam at 20 Gy and with a 95 MeV/u ^{12}C beam at 60 Gy (see Fig. 1). Using this experimental setup, we obtained the deposition of the whole Bragg curve in one film by measuring the optical density along the x axis. Note that the angle of the triangle allows to spread ($\alpha < 45^\circ$) or to shrink ($\alpha > 45^\circ$) the Bragg curve, whereas an angle of 45° conserves lengths. Experiments at the GANIL were performed using an α angle of 35°, so we had to apply a correction to the position. The correction