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EBT2 FILMS RESPONSE TO ALPHA RADIATION AT 48.3 MEV

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To advance the development of a radiobiological experimental set-up for alpha particle irradiations at the Arronax cyclotron, experiments were performed to get the dose response of Gafchomic EBT2 films for alpha particles at 48.3 MeV. A system has been developed using a thin monitor copper foil and an X-ray spectrometer to measure the beam intensity and to calculate the delivered dose. On the other hand, the authors have irradiated EBT2 films, with 6-MV X rays, to get the dose response of EBT2 films for photons. The dose response curve for alpha particles shows an effect of polymerisation saturation compared with the dose response curve for photons.

INTRODUCTION

The ARRONAX (Accélérateur pour la Recherche en Radiochimie et Oncologie à Nantes Atlantique) cyclotron in Saint-Herblain, France, is a facility delivering accelerated protons and alpha particles up to 68 MeV[1]. At Arronax, radiobiological studies evolve around two axes: the low-energy range (alpha emitters energy range <10 MeV) in order to optimise radioimmunotherapy treatments, and the high-energy range (30–68 MeV)—which is exclusive to Arronax—in order to understand the fundamental mechanisms generated by cells in response to ionising radiations.

For beam shape measurements or relative dosimetry at low doses (1–30 Gray), Gafchromic film in general and especially EBT2 models appeared to be the best 2D living tissue-equivalent dosemeter[2]. The EBT2 model self-develops blue colour after irradiation, which is based on induced polymerisation inside the active layer.

For EBT2 film, the absorbed-dose energy dependence was found very weak with photon energy of >100 keV[3, 4]. However, at photon energy of <100 keV, the absorbed-dose energy dependence varies by 50 or 10 % depending on the manufacturing lot due to changes in the ratio of mass energy absorption coefficients of the active layers to water[5, 6]. Protons with high energy (>50 MeV) have similar response as photons[5], but irradiation with low-energy proton (in the vicinity of the Bragg peak) and carbon ions, which have a high linear energy transfer (LET), led to a lower darkening compared with photons for the same delivered dose[7–9]. Since those films are relative dosemeters, they need a calibration that depends on the beam characteristics (energy, LET).

A literature review on Gafchromic films showed that there is no data about the response of the films to an irradiation with alpha particles. It is therefore definitely necessary to develop dosimetric tools for alpha particles with energies of <68 MeV.

An experiment has been made to get the dose response of Gafchromic EBT2 film for alpha particles. During these experiments, a system has been developed to monitor the beam intensity using an X-ray spectrometer[10]. In parallel, the authors have irradiated EBT2 films, with 6-MV X rays, to compare with the dose response of EBT2 films for alpha particles. First, the authors present the experimental setup with the details and the methods used to perform the study. In a second part, the results of the experiments with alpha particles and photons are presented.

MATERIALS AND METHODS

Gafchromic EBT2 film calibrations

Gafchromic EBT2, radiochromic film (Lot No. A11051002A) has been utilised for the measurement of optical density change per unit radiation energy response measurements with 6-MV photons and high-energy alpha particles. After irradiation, exposed as well as unexposed film pieces for background correction were stored together in a light-tight envelope at room temperature. Films were scanned 48 ± 1 h after irradiation with an Epson V700 scanner in professional mode and after four preview scans to stabilise the scanner temperature[11–13]. The resolution was of 150 dpi. The images produced were 48-bit RGB colour images. These images were analysed using the red channel. The films were positioned in the centre of the scanning area, oriented in landscape mode and the irradiated side in opposite face of the scan bed. The region of interest (ROI) was defined as 80 % of the irradiated area on films and centred on the beam spot. The net optical density (net OD) of the exposed spot [Equation (1)] is then calculated over the same ROI.

The net OD is calculated from the mean pixel values:

$$\text{net OD} = \log_{10} \frac{PV_0 - PV_{bckg}}{PV - PV_{bckg}} \tag{1}$$

where PV_0, PV and PV_{bckg} are, respectively, the mean pixel values of an unexposed, exposed film and black opaque cardboard[13].

The corresponding uncertainty is expressed by[13]:

$$\sigma_{\text{net OD}} = \frac{1}{\ln 10} \sqrt{\frac{\sigma_{PV_0}^2 + \sigma_{bckg}^2}{(PV_0 - PV_{bckg})^2} + \frac{\sigma_{PV}^2 + \sigma_{bckg}^2}{(PV - PV_{bckg})^2}} \tag{2}$$

where σ_{PV}, σ_{PV_0} and σ_{bckg} are the standard deviations associated with the mean pixel values. The inhomogeneity is defined by $\sigma_{\text{net OD}}$/net OD over the ROI. All analyses were performed with the free image processing software ImageJ (rsbweb.nih.gov/ij/).

Irradiation with 6-MV photons

For photon irradiations, the authors used the 6-MV photons at the isocenter of a clinical linear accelerator (NOVALIS, BrainLab) at the Institut de Cancérologie de l'Ouest (ICO) (Saint-Herblain, France). Films were irradiated at a depth of 15 mm in an RW3 slab phantom (300 × 300 × 300 mm^3). The reference dosimetry in the photon beams was done according to the TRS 398 (IAEA, Vienne, 2000) and corrections for temperature, pressure and beam quality were taking into account, such that the accuracy in dose determination is assumed to be better than ±3 %. The films were cut into 50 × 50 mm^2. A field size of 98 × 98 mm^2 was used at 100-cm source-axis distance. Dose ranged from 1.5 to 15 Gy.

Experimental set-up for irradiation with alpha particles

For alpha particle studies, a monoenergetic $^4He^{2+}$ beam of 68 MeV was provided by Arronax cyclotron (Saint-Herblain, France). To optimise the transverse size and to centre the beam at the needed location, the beam spot size is firstly observed from the fluorescence on an aluminium oxide (Al_2O_3) foil[14]. The alumina is removed before EBT2 film irradiation. The beam intensity was between 1 and 10 pA. Figure 1 shows a schematic view of the experimental set-up dedicated to Gafchromic EBT2 studies. After crossing the vacuum window (75-µm Kapton), the beam passes through a 1-cm-diameter collimator, and then a second collimator of 5-mm diameter located at 1 m after the Kapton window. The spatial straggling due to the 1-m gap of air improves the beam homogeneity

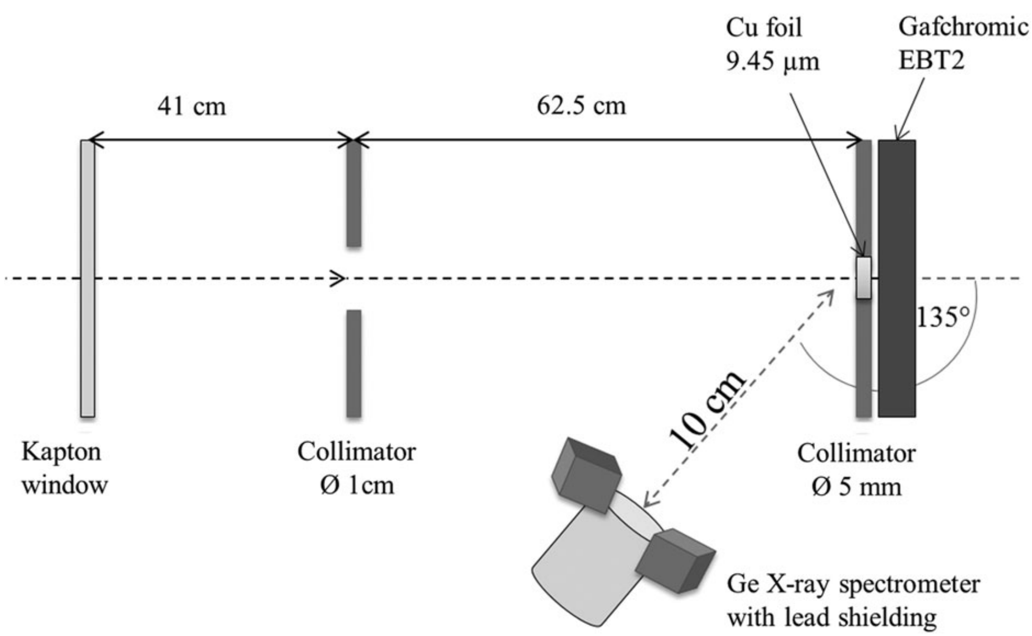

Figure 1. Schematic drawing of experimental set-up for EBT2 film irradiation with alpha particles coupled to the Ge X-ray spectrometer.

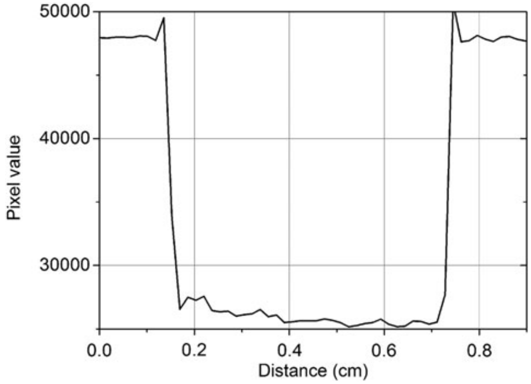

Figure 2. Spot profile of an irradiated film with alpha particles (unit pixel value).

on 5-mm diameter at the EBT2 film surface entrance (see Figure 2).

In front of the second collimator, the beam passes a thin Cu foil (purity >99 %, GoodFellow, Inc.) of 9.45 μm in thickness and 5 mm in diameter. Then, it traverses through Gafchromic film held by a frame. The incident beam hits perpendicularly the thinnest polyester layer of the EBT2 film. The energy of alpha particles given by the cyclotron is 68 MeV before the exit kapton window. After that, the energy losses suffered by the alpha particle beam through the various medium listed below were calculated using the SRIM/TRIM 2012 program[15]. The composition of the EBT2 film [Polyester layer (50 μm) and adhesive layer (25 μm)][16] was considered in the calculation SRIM to find out the energy at the film's active layer. The impact of variability of film EBT2 composition on the energy loss of alpha particles was checked. For 20 % variation of the polyester layer thickness and the adhesive layer thickness with respect to the values mentioned below, the energy of alpha particles at the entrance of active layer changes less than 1 % and the variation of the corresponding stopping power is <0.6 %. So the authors can consider that the error in the determination of the energy loss of alpha particles, due to the uncertainties of EBT2 film composition, is negligible. This is explained by the fact that the low values of the thicknesses, densities and average atomic numbers of the EBT2 layers in the case of high-energy range of alpha particles lead to a negligible energy loss of the particles crossing the first three layers of EBT2 film.

With the experimental configuration described earlier, films of 6.5 × 6.5 cm^2 were irradiated to doses ranging from 1.8 to 15 Gy. The doses are determined using X-ray spectrum measurements as detailed later. The authors calculated the net OD in the film exposed ROI to obtain the film dose response calibration curve expressed as the net OD against the dose.

Dose calculation from X-ray intensities

The interaction of the beam with the copper foil induces the emission of copper X ray of energy of 8 keV. These photons are registered by a germanium (Ge) X-ray spectrometer located at 135°. The counts collected by the spectrometer N X rays are proportional to the number of alpha particles traversing the copper foil $N\alpha$.

$$N_{\text{X rays}} = K \times N\alpha \tag{3}$$

with K being related to the amount of X rays emitted by Cu foil[17]:

$$\mathrm{K} = \frac{\rho N_{\mathrm{A}}}{M_{\mathrm{mol}}}\sigma\varepsilon\int_0^L \mathrm{e}^{-\frac{\mu x}{\cos\theta}}\mathrm{d}x \tag{4}$$

where N_A is the Avogadro number, ρ and M_{mol} are the density and the molar mass of the Cu foil target, σ is the X-ray production cross section for Cu irradiated with an alpha beam of 52 MeV (alpha energy at the copper entrance) given by ISICS code[18] based on the ECPSSR theory[19]. The theoretical cross section utilised is in a good agreement with the experimental one[20, 21]. μ is the mass attenuation coefficient of the X ray[22], $\int_0^L \mathrm{e}^{-\frac{\mu x}{\cos\theta}}\mathrm{d}x$ is the amount of X rays that cross the foil of thickness L without being re-absorbed, θ is the X-ray detection angle with respect to the target surface normal and ε is the detection efficiency for the 8-keV X ray. Efficiency was determined using a semi-empirical model for Ge detector[23]. This model was tested with standard radioactive calibrated sources (CERCA LEA). The difference between theoretical and experimental efficiencies is ~2 %.

The uncertainty on $N\alpha$ is mainly due to the error on the detection efficiency and on the statistical uncertainty of measured X-ray number.

This measurement method was verified by comparing the number of particles obtained using a monitor reaction $^{27}\mathrm{Al}(p, x)^{24}\mathrm{Na}$[24].

Then, dose (Gray) to water applied to the films by alpha particles of energy E at fluence F was determined by[8]:

$$D = F\frac{\mathrm{d}E/\mathrm{d}x}{\rho} \times 1.6 \times 10^{-10} \tag{5}$$

where $(\mathrm{d}E/\mathrm{d}x)/\rho$ (MeV cm^{-2} g^{-1}) is the mass stopping power of water.

RESULTS

The pixel value profile of an irradiated film is shown in Figure 2. The inhomogeneity is <5 % over the ROI. It regroups the non-uniformity of the beam, the

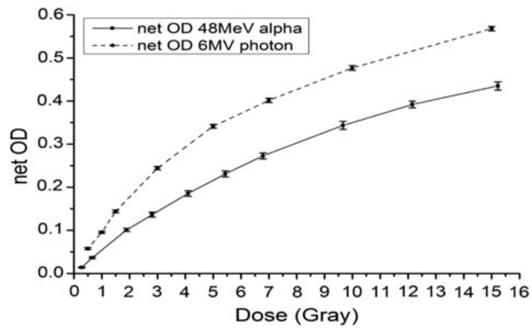

Figure 3. Calibration curves of EBT2 films irradiated with alpha particles at 48.3-MeV and 6-MV photons.

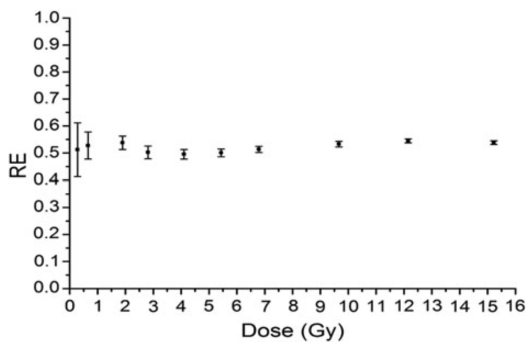

Figure 4. The measured RE of EBT2 films as a function of the applied dose for alpha particles at 48.3 MeV.

film inhomogeneity and the uncertainty of scanning. The energy at the film's active layer and the corresponding mass stopping power of water calculated with SRIM are, respectively, 48.3 MeV and 156 MeV cm^{-2} g^{-1}. The uncertainty on the dose determination is due to the uncertainty on the number of particles $N\alpha$ and is <5 % except for doses of <1 Gy. Figure 3 presents the measured net OD in terms of the delivered dose for alpha, and for photons with 6 MV. The authors clearly see that the film response to alpha beam irradiation has a lower net OD than to photon irradiation for a given dose (quenching effect).

To quantify the quenching effect, the authors use the relative efficiency (RE) defined as the ratio between the dose delivered by photons and the dose delivered by the alpha particles for the same optical density[8]. Figure 4 shows the measured RE of EBT2 films as a function of the applied dose for alpha particles at 48.3 MeV.

DISCUSSION

The X-ray spectrometer system coupled with radiochromic film, to the authors' knowledge, is not already used for monitoring the dose on facilities delivering alpha particle beam. For the same dose, the response of the films to alpha particles is ~50 % of the response to photon beams. A similar effect was observed for EBT film with carbon ions[8] and with low-energy protons[9]. This quenching effect could be explained by the saturation of polymerisation, which gives a lower net OD than the reference one for a given dose. This effect is exclusive to ions because they have a non-uniform energy deposition[25–28]. Precisely, the energy deposition decreases from the centre of the particle track, which leads to high ionisation density close to the track centre. The enormous amount of energy released in a small area around the path can cause the saturation effect[26–28].

CONCLUSION

An experiment took place at Arronax to improve the dose monitoring of alpha particle irradiations for radiobiology experiments. A system using a copper foil and an X-ray spectrometer was used in order to measure online beam intensity by means of X-ray spectrum. This special set-up allowed the authors to assess the deposited dose and the Gafchromic EBT2 films response after irradiation by alpha particles at energy 48.3 MeV. A quenching effect or net OD saturation (50 %) has been observed compared with the photon reference response curve. As regard to this result, further investigations are needed. So, the authors plan to run an equivalent experiment using different beams available at Arronax, in order to characterise the response of the radiochromic films as a function of LET and ionisation density.

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