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INVESTIGATION OF ENERGY DEPENDANCE FOR EBT3 RESPONSE TO IRRADIATION WITH ALPHA BEAMS

A. Basset[1], C. Koumeir[1,3]*, S. Chiavassa[2,4], G. Delpon[2,4], C. Le Deroff[1,5], A-M. Frelin[5], A. Guertin[3], F. Haddad[1,3], V. Métivier[3], N. Servagent[3], N. Varmenot[1,2]
[1]GIP ARRONAX, Saint Herblain
[2]Institut de Cancérologie de l'Ouest, Saint Herblain
[3]SUBATECH, IMT Atlantique, CNRS/IN2P3, Université de Nantes, Nantes
[4]INSERM U1232, CRCINA, Nantes
[5]GANIL (CEA/DSM-CNRS/IN2P3), Bd Henri Becquerel, 14076 Caen, France

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The response of EBT3 radiochromic film to ionizing radiation has been investigated for alpha beams. An experiment has been performed at the ARRONAX cyclotron to measure the net optical density (net OD) of EBT3 films as a function of the deposited doses of an alpha beam at different energies. A stack of 4 films was irradiated, therefore the beam energy is changed as a function of the film position between 45 MeV and 22 MeV. No differences in the film responses were observed in function of the alpha beam energy. The same calibration (Dose vs net OD) can be used for EBT3 film in this range of alpha beam energy. It is necessary to extend this study at lower energy down to the Bragg peak region.

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 aim to understand the fundamental mechanisms generated by cells in response to ionizing radiations in order to optimize the light ion radiation therapy. To conduct experiments of radiobiology in good conditions, the setting up of dosimetric detectors such as radiochromic films is necessary.

Radiochromic films, and especially the Gafchromic EBT film family, are largely used for beam shape verification or relative dosimetry at low doses (1 – 30 Gy) ([2, 3, 4, 5, 6]). They offer a sub-millimeter spatial resolution and the possibility to make depth dose measurements in regions where beam quality degradation does not affect the film response. As claimed by the manufacturer (Ashland Inc, NJ, USA), the composition of the active layer of EBT3, the third generation, remains unchanged ([7]), and it has similar dosimetric performance as its precursor EBT2 ([8]). In addition, EBT3 presents a symmetric structure, an active layer sandwiched between two polyester substrates equipped with an anti-Newton artifact coating.

The dose responses of EBT3 films for photon beams have a weak energy dependence in the MV and kV X-rays beams ([9,10,11]). Irradiations with clinical proton beams (> 60 MeV) have shown a similar response as photons ([8, 9]). Other works have investigated the response of EBT films for low energy proton beams (< 10 MeV) ([12,13,14, 15]). They found an under-response (or a lower darkening) compared to high energy protons (or photons) for the same delivered dose. Our previous work on EBT2 film response to 48 MeV alpha particles showed an under-response identified as a quenching effect, compared to the dose response to 6 MV X-rays ([16]). In this work, we will extend our investigation on the energy dependence for the response of the EBT3 films, to irradiation with incident alpha energies between 22 and 45 MeV.

The experimental settings allowed irradiating either a single film or a stack of 4 films. In this second mode, each film played the role of an energy degrader. Therefore, each film was irradiated at a different energy.

First, the experimental setup and the methods used to perform the study are described. In the second part, the response of EBT3 films irradiated with different energies according to the two modes (introduced above) are presented and discussed.

MATERIALS AND METHODS

Experimental setup for irradiation with alpha particles

A monoenergetic $^{4}He^{2+}$ beam of 67.4 MeV was provided by ARRONAX cyclotron (Saint-Herblain, France). The beam intensity was about 1 pA. Fig.1 shows a schematic view of the experimental set up dedicated to the Gafchromic EBT3 irradiation. After crossing the vacuum window (75 µm Kapton), the beam passes through a 5 mm diameter collimator, then a second collimator of 6 mm diameter located at 117 cm downstream the Kapton window. This gap of air improved the beam homogeneity, due to the spatial straggling of the beam.

*Corresponding author: charbel.koumeir@subatech.in2p3.fr

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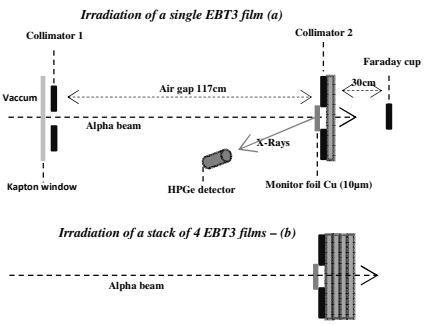

Figure 1: schematic drawing of the experimental setup for EBT3 film irradiation with *alpha* particles in two modes: single film (a) and stacked films (b)

In front of the second collimator, the beam passes a thin Cu foil (GoodFellow Inc) of 10 µm in thickness and 8 mm in diameter. Then it traverses through the film held by a frame. The beam interaction with the copper foil induces the emission of copper X-ray. These photons are registered by a germanium (Ge) X-ray spectrometer for beam intensity monitoring. As indicated earlier, the irradiations were performed with a single film (case a) and a stack of four films (case b). In this latter case, the first film is located at the same position as the single film of the case a. The beam energy decreases progressively with films position to reach its lower value in the 4th film, while the stopping power increases and reaches its highest value in this latter position (see table 1).

Gafchromic EBT3 films calibrations

EBT3 film pieces of 6 cm * 6 cm size were used for the irradiations with alpha particles. After irradiation, exposed films, as well as unexposed films for background correction, were stored together in a light-tight envelope at room temperature. Films were scanned 48 ± 1 hour after irradiation with an Epson V700 scanner, in transmission mode and landscape orientation after five preview scans to stabilize the scanner temperature ([17-19]). All image correction methods were turned off. The images produced were 48 bit RGB color images with a spatial resolution of 150 dpi. These images were analyzed using the green channel because the films were irradiated with doses between 4 and 20 Gy (see dose calculation section) and the green channel is suited for high dose range [4-50Gy][20, 21] . A region of interest (ROI) was defined as 80% of the irradiated area on films and centered on the beam spot. The net optical density (*net OD*) of the exposed spot (Eq. (1)) was then calculated over the same ROI.

$$netOD = log_{10}\frac{PV_0 - PV_{bckg}}{PV - PV_{bckg}} \quad (1)$$

where PV_0, PV and PV_{bckg} are respectively the mean pixel values of an unexposed, exposed film and black opaque cardboard ([16]).

The corresponding uncertainty was expressed by ([19]):

$$\sigma_{netOD} = \frac{1}{ln10}\sqrt{\frac{\sigma_{PV_0}^2+\sigma_{bckg}^2+\sigma_{scan}^2}{(PV_0-PV_{bckg})^2}+\frac{\sigma_{PV}^2+\sigma_{bckg}^2+\sigma_{scan}^2}{(PV-PV_{bckg})^2}} \quad (2)$$

Where σ_{PV}, σ_{PV0} and σ_{bckg} are the standard deviations of the mean pixel values. $\sigma_{scan}$is the uncertainty of the scanner response reproducibility. σ_{scan} was evaluated by using a grayscale target.

The inhomogeneity, defined by $\frac{\sigma_{netOD}}{netOD}$ over the ROI, was below 10 % for all irradiated films. It includes the beam non-uniformity, the film inhomogeneity and the scanning uncertainty. All analyses were performed with the free image processing software ImageJ ([22]).

Dose calculation

As EBT3 films are considered water equivalent, absorbed dose in films for an alpha particles beam of energy *E* at fluence *F* was determined by the following relation ([23]):

$$D[Gy]=F[cm\text{-}2]\times LET[MeV.cm2.g\text{-}1]\times 1.6\times 10^{-10} \quad (3)$$

Where F is the fluence of the ions crossing the sample and LET is the linear energy transfer (1.6×10^{-10} is a conversion factor to have the dose in Gy).

Fluences are determined using the X-ray spectrum of the Cu foil recorded during the same irradiation as described in reference ([16]). Before the film irradiations, the intensity of the X-ray emissions from the monitor foil has been calibrated by a Faraday cup placed behind the collimator 2 (Fig. 1). The measurement of the beam intensity given by the Faraday cup was verified by comparing the number of particles obtained using a monitor reaction 27Al(p, x)24Na and by the measurement of the K X-ray ionization cross section of gold with 66 MeV proton beam. The accuracy of the Faraday cup obtained is better than 3%. Overall uncertainty on dose is less than 4 %, mainly attributable to the beam fluence uncertainty.

The alpha particle energy given by the cyclotron was 67.4 MeV before the exit Kapton window. After that, the energy losses suffered by the alpha particle beam, through the various media listed above, were calculated using the SRIM/TRIM 2012 program ([24]).

The alpha beam energy in air, at the film sample entrance, was characterized using a silicon semi-conductor detector (80µm thick) positioned in place of the sample. The detector was calibrated in energy with a ^{241}Am alpha source. The comparison between the simulated spectrum of the beam energy loss, obtained with the SRIM/TRIM program, and the experimental one was in good agreement.

The composition of the EBT3 film (the PET layer and the active layer ([5])), was considered in the calculation SRIM to find out the mean energy in each active layer and the corresponding linear energy transfer (LET) in water (table 1). The energy spread of the incident beam within the active film layers was below 3%. This implies a sharper stopping power distribution.

Active layer position	Alpha energy [MeV]	LET [MeV.g^{-1}.cm^2]
1	44.8	170
2	38.4	193
3	31.2	230
4	22.0	304

Table 1 the average beam energy in each film active layer and the corresponding linear energy transfer (LET) in water

Fig. 2 presents the simulated depth-dose curve (SRIM) of the alpha beam in a water layer of 2 mm thickness placed at the entrance of the film sample. The position of each active layer (vertical dashed lines) was determined by calculating the equivalent water thickness of the EBT3 film.

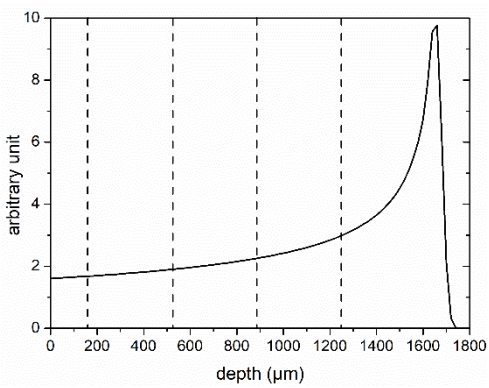

Figure 2: the depth-dose curve of the alpha beam in function of the equivalent water thickness of the stack of 4 EBT3 films. The dashed lines indicate the position of each active layer.

With the experimental configuration described above, films were irradiated to doses ranging from 4 to 20 Gy. No irradiation with doses smaller than 4 Gy was performed due to high uncertainties on the number of detected X-ray and therefore on the absorbed dose.
These doses are within the range of the dynamic dose of EBT3 according to the manufacturer ([25]).
We calculated the *net OD* in the film exposed ROI to obtain the film dose response expressed as the dose versus the net OD.

RESULTS

Fig. 3 presents the response of EBT3 films to alpha beam irradiation at 44.8 MeV. Empty circles (see Fig 1) correspond to the irradiation of the case (a). The Dose uncertainty (1 sigma) is either smaller or of the same size as the plot symbols. The netOD uncertainty (1 sigma) was calculated with equation (2). Solid circle points correspond to second irradiation under the same conditions. The variation between the two sets of points remains well smaller than the error bars. This comparison shows that the measurements were repeatable. Therefore, we consider the points with an empty circle as the reference points. The solid line represents a fitting dose-response for the reference irradiation according to the analytical function given by the equation (4)[9]:

$$\text{Dose} = a \times \text{netOD} + b \times \text{netOD}^n \quad (4)$$

The parameter n was fixed at 3.1.

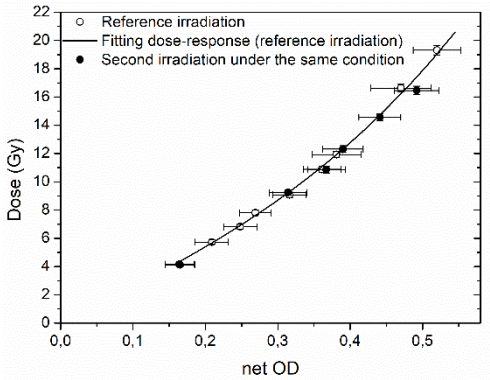

Figure 3: variation of the dose vs netOD of EBT3 films irradiated with alpha particles at 44.8 MeV

Fig. 4 presents the response of EBT3 films to alpha beam at different incident energies (see table 1) obtained with the irradiations of stacked films presented in the schematic (b) of Fig. 1. The irradiation time was adapted to obtain dose depositions in the same range as the reference points. The four graphs correspond respectively to the irradiated films in positions 1, 2, 3 and 4. On each graph, the points with an empty circle correspond to the film response of the irradiated films at a given position, and the solid lines correspond to the fitting dose-response, presented above.
The points shift toward the highest doses as the film position changes from 1 to 4. In the first graph (top left of Fig. 4) corresponding to the first film, the points have the lowest doses values compared to the other graphs because the alpha beam has the highest energy and the lowest LET.

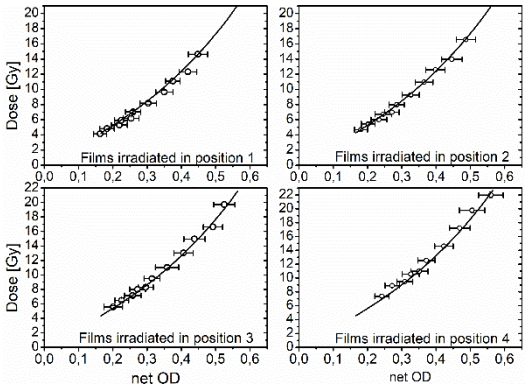

Figure 4: the response of EBT3 films to alpha beam irradiation at different positions in the stack of films

To compare the response of each stacked film with the reference film (the relative response), the ratio between the delivered dose to the film and the reference film for the same optical density was calculated. The fitting curves of Fig. 4 were used to calculate the relative responses. Fig. 5 presents the relative response in function of the alpha beam energy. Each point is determined with the mean relative response over the dose range of the corresponding film position.

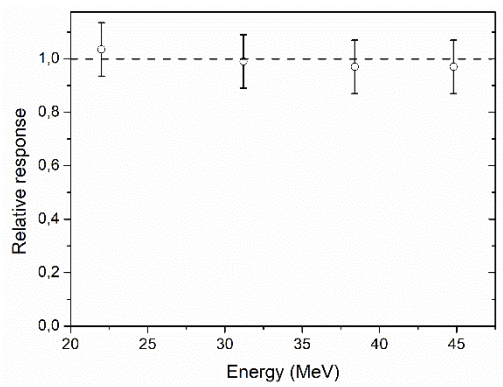

Figure 5 the response of the stacked films relatively to the reference response

The points values are close to 1, and the differences between them remain in the error bars.

DISCUSSION

The calculated dose for irradiated films according to formula (3) contains only the primary dose from the incident beam. The authors have neglected the doses from the secondary particles produced by the interaction of the beam with the irradiated area. In fact, the incident alpha energy used in this work (12 MeV/u) is much lower than those used in clinical carbon and proton beams ([23, 26]) for which the contribution of the secondary particles is not negligible. Another proton beam study ([13]) with the same range of energy than the beam used in this work, shows that the dose produced by the secondary particles has a minor effect in that deposited by the primary beam.

The response of the film in position 1 is the same as the response from the reference irradiation. Indeed, the alpha beam passes through the film at position 1 with the same energy than in the configuration (a). Moreover, the deposited dose by the primary beam is preponderant relative to the doses of the secondary particles generated by the other films of the stack. This shows that the two configurations, single film and stacked films, are equivalent to the irradiation of EBT3 films in this energy range of alpha beams.

For the other positions, the responses of the films are also the same as the response of the reference irradiation, although the beam energies and the associated LETs were different. The energy range of the alpha beam, between 44.8 and 22 MeV, is located in the plateau region (Fig. 2). The LET varies between these two energies by a large factor, around 2. Therefore, the results show no effect of the LET in this region. The same behavior was observed with the proton beams at the plateau region ([7, 13, 27]) with initial incident energy of a few tens of MeV. In these latter studies, the EBT3 film response changed only in the region of the Bragg peak. Since we had no change in response of EBT3 film between 44 and 22 MeV, we can expect that the EBT3 films have the same response to irradiation with alpha beams from the initial energy at 68 MeV down to 22 MeV.

CONCLUSION

An experiment using an initial alpha beam of 68 MeV has been realized at the cyclotron ARRONAX to characterize the response of EBT3 films. Four stacked films were irradiated to be able to vary the energy of the incident beam at the same time. The energy of the alpha particle beam, at the entrance of each active layer, was located in the plateau region between 44.8 (first layer) and 22 MeV (fourth layer). The value of the corresponding LET varies by about a factor of 2 in the whole of this incident energy range. The EBT3 films were irradiated to doses between 4 and 20 Gy and their net optical densities were measured. The responses of the films in each position of the stack were compared with those of the films irradiated individually under the same conditions (reference irradiation). The variations of the films responses between each position in the stack remain in the errors bars. This shows no effect of the LET variation on the responses of the EBT3 films to alpha beam irradiation in this range of incident energy. From a dosimetry point of view, the same calibration response of the EBT3 film to the alpha beams can be used in a large

range of incident energy. It is interesting to extend the experiment with the alpha beam towards the Bragg peak region and to compare the results with existing data on proton beams.

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References

1. F. Haddad et al., ARRONAX, a high energy and high intensity cyclotron for nuclear medicine, Eur. J. Med. Mol. Imaging 35, 1377-1387 (2008).
2. S. Devic, Radiochromic film dosimetry: Past, present, and future, Physica Medica 27, 122-134 (2011)
3. S. Devic et al, Reference radiochromic film dosimetry: Review of technical aspects, Physica Medica 32, 541-556 (2016).
4. S. A. Park et al., Dose verification of proton beam therapy using the Gafchromic EBT film, Radiations Measurements 46, 717-721 (2011).
5. F. Borgognoni et al, X-ray sterilization of insects and microorganisms for cultural heritage applications, Nucl. Intrum. Meth. Phys. Res. B, 406, 309-313 (2017).
6. S. Agosteo et al, The LILIA (laser induced light ions acceleration) experiment at LNF, Nucl. Intrum. Meth. Phys. Res. B, 331, 15-19 (2014).
7. F. Fiorini et al., Under-response correction for EBT3 films in the presence of proton spread out Bragg peaks, Physica Medica 30, 454-461 (2014).
8. S. Reinhardt et al., Comparaison of Gafchromic EBT2 and EBT3 films for clinical photon and proton beams, Med. Phys. 39, 5257 (2012).
9. J. Sorriaux et al., Evaluation of Gafchromic EBT3 films characteristics in therapy, photon, electron and proton beams, Physica Medica 29, 599-606 (2013).
10. JL. M. Guerda et al, Energy dependence of the new GAfchromic EBT3 film: Dose response Curves for 50 kV, 6 and 15 MV X-Ray Beams, International Journal of Medical Physics, Clinical Engineering and Radiation Oncology, 2012, 1, 60-65.
11. T. A. D. Brown et al. Dose-response curve of EBT, EBT2 and EBT3 radiochromics films to synchrotron-produced monochromatic x-ray beams, Med. Phys. 39, 7412 (2012).
12. D. Kirby et al., LET dependence of GafChromic films and an ion chamber in low-energy proton dosimetry, Phys. Med. Biol. 55, 417-433 (2010).
13. S. Reinhardt et al Investigations of EBT2 and EBT3 films for protons dosimetry in the 4-20 MeV energy range, Radiat Environ Biophys 54, 71-79 (2015).
14. M. Vadrucci et al. Calibration of GafChromic EBT3 for absorbed dose measurements in 5 MeV proton beam and (60)Co γ-rays, Med. Phys. 42, 4678 (2015).
15. M.C. Battaglia et al, EBT3 film calibration in the Bragg peak region for proton beams below 5MeV, Nucl. Intrum. Meth. Phys. Res. B, 444, 117-124 (2019).
16. Le Deroff et al., EBT2 films response to alpha radiation at 48.3 MeV, Radiation Protection Dosimetry, 161, 428-432 (2014).
17. L. Paelinck et al., Precautions and strategies in using a commercial flatbed scanner for radiochromic film dosimetry, Phys. Med. Biol. 52, 231-242 (2007).
18. M. Martisikova et al., Analysis of uncertainties in Gafchromic EBT film dosimetry of photon beams , Phys. Med. Biol. 5., 7013-7027 (2008).
19. S. Devic et al., Precise radiochromic film dosimetry using a flatbed document scanner, Med.Phys. 7, 32 (2005)
20. S. Devic et al, "Optimizing the Dynamic Range Extension of a Radiochromic Film Dosimetry System," Medical Physics 36, 429-437 (2009).
21. S. Aldelaijan et al, "Radiochromic film dosimetry of HDR 192Ir source radiation fields," Med. Phys. 38, 6074-6083 (2011).
22. Image J, rsbweb.nih.gov/ij/.
23. M. Martisikova et al., Dosimetric properties of Gafchromic EBT films in monoenergetic medical ion beams, Phys. Med. Biol. 55, 3741-3751 (2010).
24. J.F. Ziegler, J.P. Biersack, The stopping and range of ions in matter, IBM Res. (2000).
25. EBT3 specification and user guide. Available on http://www.gafchromic.com/documents/EBT3_Specifications.pdf.
26. C. Grassberger et al. Elevated LET components in clinical proton beams. Phys. Med. Biol. 56, 6677–6691 (2011).
27. A. carnicer et al., Development and validation of radiochromic film dosimetry and Monte Carlo simulation tools for acquisition of absolute, high-spatial resolution longitudinal dose distributions in ocular proton therapy, Radiations Measurements 59, 225-232 (2013).