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Gel dosimeters as useful dose and thermal-fluence detectors in boron neutron capture therapy

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The dosimetry method based on Fricke–Xylenol-Orange-infused gels in form of layers has shown noticeable potentiality for in-phantom or in-free-beam dose and thermal flux profiling and imaging in the high fluxes of thermal or epithermal neutrons utilised for boron neutron capture therapy (BNCT).

Gel-dosimeters in form of layers give the possibility not only of obtaining spatial dose distributions but also of achieving measurements of each dose contribution in neutron fields. The discrimination of the various dose components is achieved by means of pixel-to-pixel manipulations of pairs of images obtained with gel-dosimeters having different isotopic composition. It is possible to place large dosimeters, detecting in such a way large dose images, because the layer geometry of dosimeters avoids sensitive variation of neutron transport due to the gel isotopic composition. Some results obtained after the last improvements of the method are reported.

Keywords: Gel dosimetry; Neutron dosimetry; BNCT; Dose imaging

1. Introduction

Gel dosimetry applications for detecting absorbed dose or thermal neutron fluence images in neutron fields suitable for Boron neutron capture therapy (BNCT) have been widely investigated.

BNCT is a form of radiotherapy that takes advantage of the possibility of selectively accumulating the isotope ^{10}B in tumour cells and of the high-cross-section ($\sigma = 3837$ b) of the reaction with thermal neutrons $^{10}\mathrm{B}(\mathrm{n},\alpha)^{7}\mathrm{Li}$. Owing to the short range in tissue of the emitted

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α and ^{7}Li particles (<10 μm), all their energy is locally released and absorbed in the cell itself, thus saving the surrounding healthy cells. BNCT is similar to conformal radiotherapy, in which the target is each single cell. As such, BNCT is of particular interest for diffused tumours, such as liver tumours. Moreover, owing to the high linear energy transfer (LET) and relative biological effectiveness (RBE) of α and ^{7}Li particles, BNCT is potentially effective for some radio-resistant tumours, such as glioblastoma multiforme and some types of melanoma.

Neutrons are not directly ionising particles and the modalities of their energy release in a medium are very complex. The various kinds of secondary radiation have different LET and RBE and so it is necessary to separate the different dose components. The relative contributions of such secondary components to the total absorbed dose depend on neutron energy spectrum, on beam geometry and on material, size and dimension of the irradiated volume. Therefore, it is necessary to obtain spatial information of the absorbed doses by imaging, or at least mapping, the various dose contributions both in tumour and in healthy tissue. This goal is attained by the dosimetry method described here.

Besides the reactions with ^{10}B, the main dose contributor for radiotherapy purpose, the reactions mainly responsible for the released energy in tissue are those with hydrogen and nitrogen, that is $^1\mathrm{H}(\mathrm{n},\gamma)^2\mathrm{H}$ ($\sigma = 0.33$ b), whose γ-rays of 2.2 MeV can travel many centimetres through tissue, and $^{14}\mathrm{N}(\mathrm{n},\mathrm{p})^{14}\mathrm{C}$ ($\sigma = 1.81$ b), whose emitted protons of about 0.6 MeV have short range in tissue giving local dose deposition. In epithermal neutron fields, the fast neutrons give a small contribution to the absorbed dose mainly due to elastic scattering with hydrogen nuclei.

2. Gel dosimeters

Many studies and experiments have been carried out for improving the gel dosimetry method, particularly with respect to BNCT.

Gel dosimeters consist of water solutions in a state of gel, containing suitable chemical compounds that have the role of making measurable the effect of ionising radiation. The best results have been obtained with Fricke–Xylenol-Orange-infused gel dosimeters, containing a ferrous sulphate solution and in which ionising radiation causes oxidation of ferrous ions to ferric ions. Measurable effects are the variation of transversal and longitudinal relaxation rates of hydrogen nuclei [1], due to the different magnetic moments of the paramagnetic ions Fe^{++} and Fe^{+++}, or the variation of visible light absorbance at a wavelength of about 585 nm, produced by the complex of Xylenol-Orange with ferric ions [2]. Among the difficulties encountered in the utilisation of such dosimeters, is the effect of diffusion of ferric ions that requires a quick analysis of the dosimeters after irradiation. As an alternative, to avoid such a difficulty, some studies are presently carried out concerning polymer-gel dosimeters, in which ionising radiation produces a polymerisation effect with consequent increase of the opacity of the medium. Also in this material, the absorbed dose results into a linear correlation with the variation of both relaxation rates and optical absorbance. The monomer solution incorporated in the gelatine consists of acrylamide and N,N'-methylene-bysacrylamide. These monomers can be chemically polymerised and cross-linked to form a so-called polyacrylamide gel (PAG). Polymer-gel dosimeters are still in a first phase of experimentation and need noticeable improvement. In fact, good consistency of images after irradiation has been found (up to months) but poor stability of the unirradiated gel matrix, resulting in a strong dependence of the dosimeter response on the time between preparation and irradiation. Moreover, the profiles extracted from dose images and compared to those obtained with Fricke–Xylenol-Orange-gel or also with Monte-Carlo simulations do not yet show satisfactory consistency [3, 4].

Only the results obtained with Fricke–Xylenol-Orange-gel are here reported. In the high-thermal/epithermal neutron fluxes utilised for BNCT, such dosimeters have shown to be very advantageous for performing beam control and in-phantom dose verification, as they are able to get information that cannot be obtained with other methods. In fact, the usual imaging techniques, such as using gafchromic films, cannot be utilised in such neutron fields owing to the resulting material activation. Moreover, the important goal of separating the contributions of the various dose components was successfully achieved with gel dosimeters, despite their low sensitivity to high LET radiation. An advantage of gel dosimeters is also the fact that they have good tissue-equivalence for neutrons and for the secondary radiation.

Extensive work to optimise the protocols for dosimeter preparation, light transmittance detection and image manipulation has been carried out, with the aim to detect large dose images with satisfactory reliability.

To show the potentiality of the Fricke–Xylenol-Orange-gel dosimeters to measure the spatial distribution of the absorbed dose for photons and electrons, some results are reported in the following sections.

2.1 *Dose imaging method*

Dosimeters consist of layers of gel, 3 mm thick, placed between two transparent polystyrene sheets and contained in a thin frame having suitable shape and dimensions, which depend on the specific requirements of the measurements. Dosimeter analysis is based on visible light transmittance imaging. To this purpose, dosimeters are placed on a plane light source and transmitted light in the wavelength interval around 585 nm is imaged, before and after irradiation, by means of a CCD camera provided with an optical filter [5, 6]. The absorbed dose is a linear function of the difference of optical density Δ(OD) of the images detected before and after irradiation. Dedicated Matlab® software has been developed that, after proper manipulation of the Grey Level (GL) images in order to amend artefacts, performs pixel-to-pixel elaborations of the GL images to obtain Δ(OD) images. For each gel preparation, a group of dosimeters is utilised to achieve calibration. The obtained calibration coefficient is then utilised to convert Δ(OD) images into dose images.

2.2 *Gel dosimeters in photon and electron fields*

Fricke–Xylenol-Orange-gel dosimeters in form of layers have given trustworthy results in fields of low-LET radiation. Some results are reported here, in order to show the reliability of dosimeters in such radiation fields. Dose images have been measured by means of gel dosimeters exposed to two different beams of commercial medical linear accelerators. In both cases, 19 rectangular dosimeters (11 cm $\times$ 5 cm with thickness of 0.3 cm) have been piled up and surrounded by polystyrene to form a cubic phantom with 20 cm of side. In the first irradiation set-up, the beam characteristics were: 18 MV Photon beam, source-surface distance (SSD) = 100 cm, field size (FS) = 10 cm $\times$ 10 cm, total delivered dose = 20 Gy. In the second irradiation, the set-up was: 16 MeV electron beam, SSD = 100 cm, FS = 10 cm $\times$ 10 cm, total delivered dose = 20 Gy.

In figure 1, the percentage depth dose (PDD) distribution on the central axis of the beam for a 18 MV photon beam is shown. The corresponding dose distribution calculated with Monte-Carlo (PENELOPE [7]) simulation is reported in the same figure. In figure 2, PDD distribution on the central axis of the beam for a 16 MeV electron beam measured with both gel dosimeter and ionisation chamber is shown. The agreement between the dose profiles measured with gel

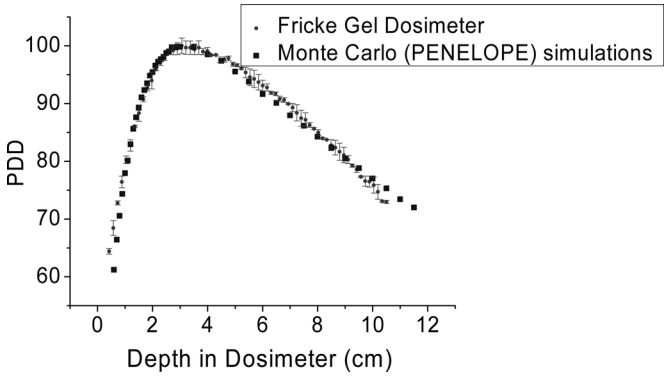

Figure 1. PDD distribution on central axis beam for a 18 MeV photon beam, measured with gel dosimeter and calculated with Monte-Carlo (PENELOPE).

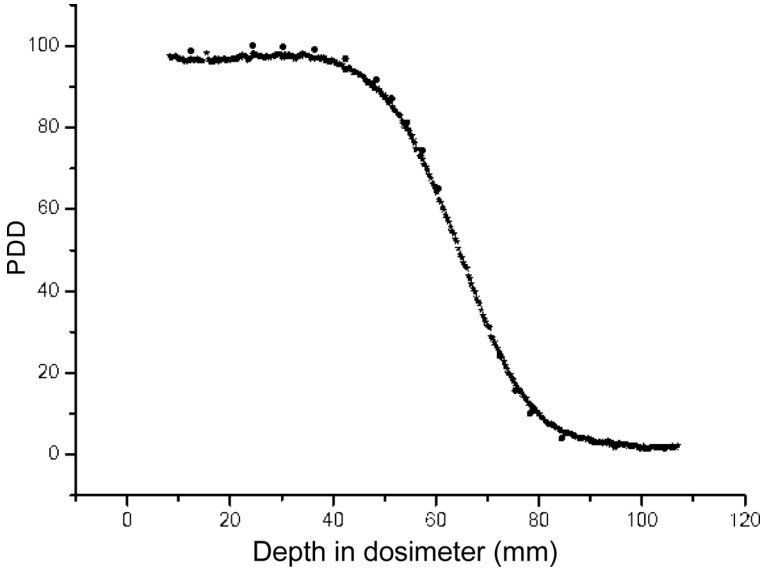

Figure 2. PDD distribution on central axis beam for a 16 MeV electron beam, measured by gel dosimeter (line) and ionisation chamber (points).

dosimeters and those measured with ionisation chambers or calculated confirm the reliability of the method.

3. Results in a BNCT neutron field

In order to test the potential of Fricke-gel dosimeters for both checking an epithermal neutron field and imaging the in-phantom thermal neutron flux, some irradiations have been carried out with the epithermal neutron beam at the High-Flux Reactor (HFR) in Petten. The exploited epithermal beam is that usually used in the BNCT clinical trials. Unfortunately during this experiment, the secondary shutter of the beam (usually well collimated) had not

been completely opened, and a circular-shaped region on the top of the circular collimator was covered by the shutter.

In order to test the capability of gel dosimeters to give a simple method of checking the radiation field, without particular complexity, a couple of rectangular gel dosimeters 11 cm × 5 cm with thickness of 0.3 cm (external dimension 12 cm × 6 cm with thickness of 0.5 cm) have been placed in front of collimator, adjoining one to the other and in crossed directions as shown in figure 3. The GL images of the two dosimeters are reported in figure 4. In the figure the GL standard strip, always imaged with dosimeters and utilised for correcting the light intensity instability, is visible. From the two images, the dosimeter shape has been cut and the real geometrical configuration has been reconstructed. The result of such operation is shown in figure 5, where the field anisotropy is evident due to the shutter mis-match. The 3D representations of the doses measured by the two dosimeters are reported in figure 6.

A measurement of thermal flux distribution in the vertical plane of a spheroidal phantom consisting of non-dosimetric gel, contained in a PMMA holder (with diameter ∼ 16 cm) was

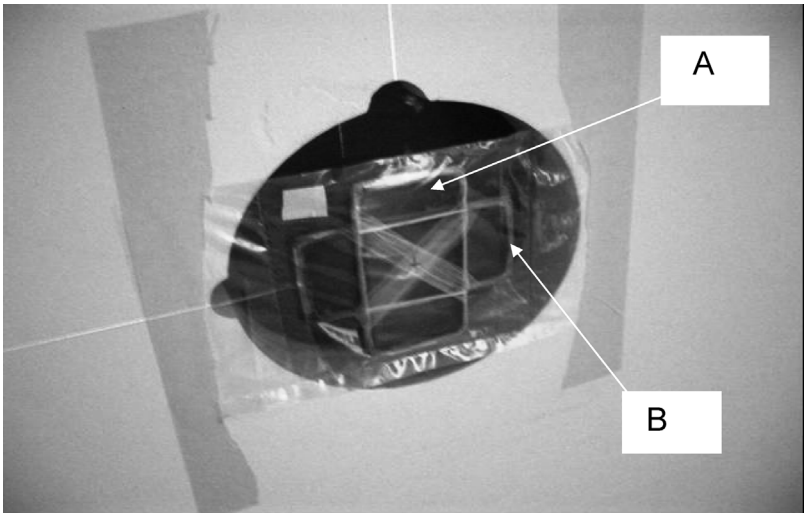

Figure 3. Configuration of dosimeters irradiated in free beam, placed in front of the reactor collimator.

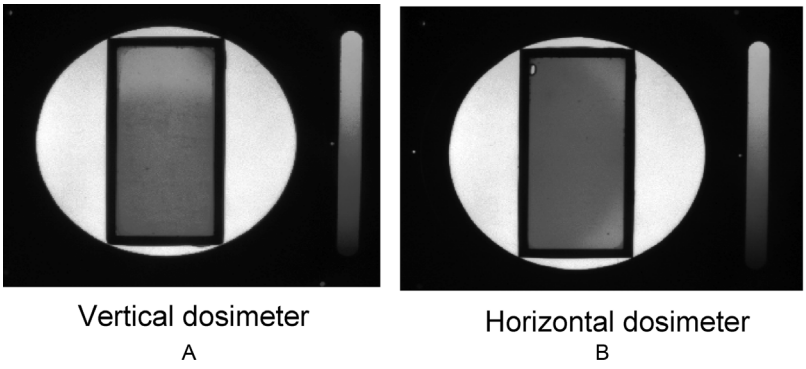

Figure 4. Images, detected with the CCD camera, of the two dosimeters after irradiation.

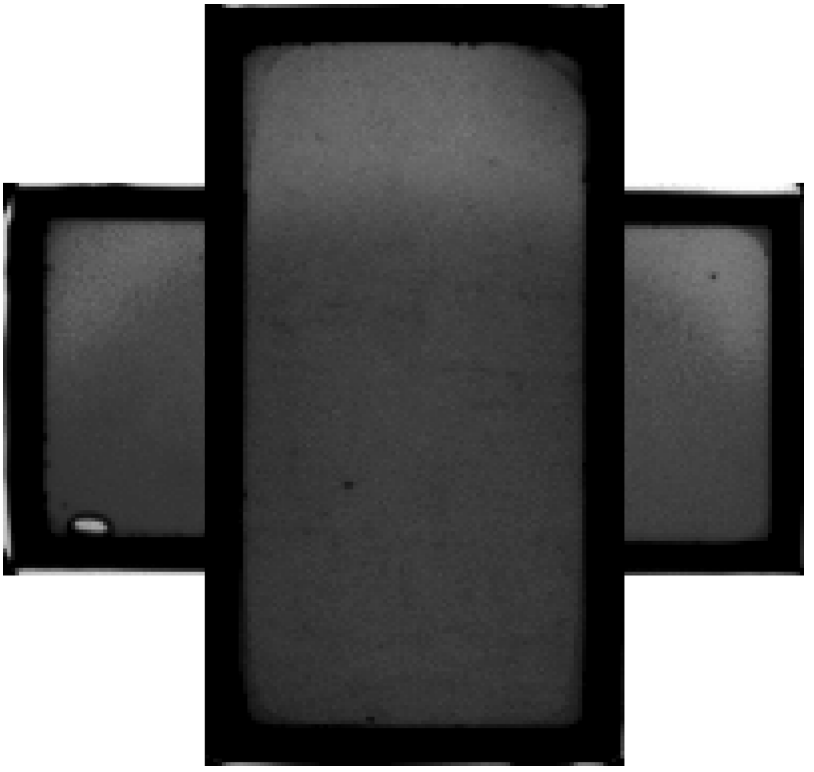

Figure 5. From the images of figure 4 the two dosimeters have been cut and then settled in the position of irradiation. The result of this operation is reported in the figure.

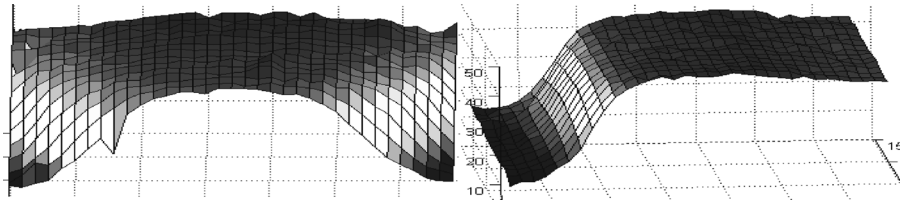

Figure 6. 3D representations of the doses measured by the two dosimeters.

also performed. To this aim, two gel dosimeters having circular shape (∼16 cm of diameter) with thickness of 3 mm have been placed one close to the other with vertical orientation in the central plane of the phantom. Both gel dosimeters are tissue-equivalent but one is infused with 40 μg/g of ^{10}B. Gamma and boron doses have been separated with the method described in ref. [8]. The dose measured by the first dosimeter is due to gamma rays and eventually to fast neutrons, if not negligible. In the dosimeter containing ^{10}B, an additional contribution comes from the charged particles emitted in the boron reactions, whose dose is detected with a reduced sensitivity (41%). The boron dose has been evaluated by pixel-to-pixel manipulation of the images detected with the two dosimeters and, utilising kerma factors, the thermal neutron flux image has been obtained (figure 7).

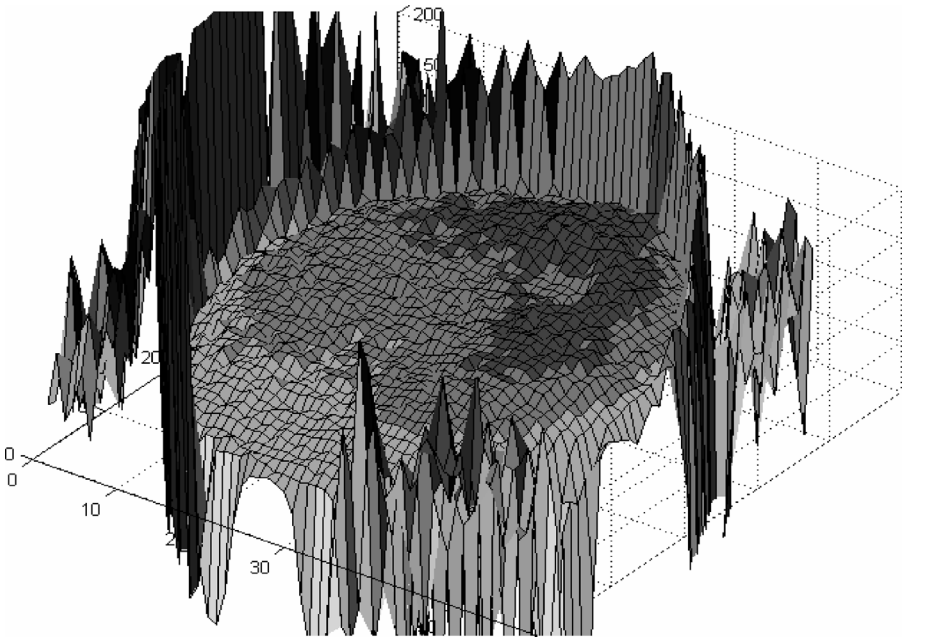

Figure 7. 3D representation of thermal neutron flux.

4. Conclusions

The results reported here show that gel dosimeters in layer-form are a very useful tool for beam control and in-phantom dose imaging in the neutron fields for BNCT.

Acknowledgements

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