Methods for dose measurements in small phantoms irradiated at BNCT epithermal column

G. Gambarini [a,b,*], A. Negri [b], V. Regazzoni [a,b], D. Magni [a], R. Nolli [c,b], F. Campi [c], J. Burian [d], M. Marek [d], V. Klupak [d], L. Viererbl [d]

[a] Physics Department, Università degli Studi di Milano, Milan, Italy
[b] INFN – Section of Milan, Italy
[c] Energy Department, Politecnico di Milano, Milan, Italy
[d] Department of Neutron Physics, Research Centre Rez, Ltd., Czech Republic

1. Introduction

It is well known that the dosimetry for BNCT requires achieving the determination of the spatial distribution of the different dose contributions due to the various secondary radiations generated by neutron reactions with tissue, owing to the different relative biological effectiveness (RBE) of all such dose components (International Atomic Energy Agency, 2001).

In tissue exposed to an epithermal neutron beam, the absorbed dose results from different contributions: the gamma dose coming from the 2.2 MeV photons generated by the reaction $^{1}H(n,\gamma)^{2}H$ of thermal neutrons with hydrogen and from reactor background, the dose from protons due to the reaction of thermal neutrons with nitrogen $^{14}N(n,p)^{14}C$, the fast neutron dose mainly due to recoil protons from elastic scattering with hydrogen nuclei and, in tissue in which ^{10}B is selectively accumulated, the dose due to alpha and lithium particles released in the reaction of thermal neutrons $^{10}B(n,\alpha)^{7}Li$. The contribution coming from the nitrogen reactions is low and depends on the real percentage of nitrogen in the biological tissue, which is different in the various tissues and changes with age. However, it can be evaluated from the thermal neutron fluence by means of the kerma factor. For the other dose components, it is necessary to perform measurements or calculations of the spatial distribution of each of them because the relative contributions have different trend in space and depend on both the shape and the size of the irradiated volume.

BNCT beams are usually characterised by means of measurements and calculations in a standard water phantom having dimensions $50 \times 50 \times 25\ cm^3$. Such determinations are very important in order to verify the beam quality. When smaller volumes are irradiated, all the absorbed dose distributions are different with respect to those measured in the water phantom with the same neutron beam characteristics. Therefore, in order to have reliable information of the absorbed doses, it is convenient to perform specific measurements for each configuration, designing suitable phantoms similar to the target volumes. Moreover, to carry out reliable dose measurements, it is necessary to utilise appropriate dosimeters, capable of measuring the different dose contributions, with good spatial resolution and without affecting

* Corresponding author at: Department of Physics, Università degli Studi di Milano and INFNvia Celoria 16-20133 Milano, Italy. Tel.: +39 02 50317243.
E-mail address: grazia.gambarini@mi.infn.it (G. Gambarini).

the radiation field. The method based on Fricke-gel dosimeter in form of layers, developed for previous experiments, was found to be very effective for achieving images of the various dose components in phantoms exposed to thermal or epithermal neutron beams suitable for NCT. This dosimeter geometry, however, is not appropriate for dose measurements in very small phantoms. A proper gel dosimetry method has been recently studied and developed to perform dose measurements in small phantoms, such as those simulating little mice. The method allows to obtain gamma and boron dose profiles. From boron dose, by means of kerma factors, thermal neutron fluence profiles can be attained.

Also thermoluminescence detectors (TLDs) can be profitably utilised in small phantoms, because of their small dimensions. With TLDs it is possible to measure, in various positions, the gamma dose and the thermal neutron fluence, useful for calculating boron dose and also nitrogen dose, if convenient.

Finally, it is profitable to perform intercomparison of the results obtained with the two methods in order to control their consistency.

Fig. 1. Epithermal column mouth with a gel dosimeter layer for free beam characterisation.

2. Materials and methods

Two dosimetry methods have been improved for dose measurements in small phantoms: a method is based on Fricke gel dosimeters and the other on TLDs.

Concerning Fricke gel dosimeters, the convenient geometries, the modalities of preparation and analysis and the response variation in time have been studied by means of exposures to photons.

TLDs were calibrated with photon irradiations too.

2.1. Irradiation facilities

The study of the dosimeter response was performed utilising a ^{137}Cs source, usually exploited for biological sample irradiation. The dosimeters were surrounded by tissue-equivalent (TE) plastic in order to achieve charge particle equilibrium.

The exposures at uniform and known dose for calibration with photons were achieved by placing each dosimeter in a water equivalent phantom (Plastic Waters Nuclear Associates, Carle Place, New York, USA) that was then irradiated with a radiotherapy facility. Phantom geometry and exposure parameters were suitably settled in order to obtain an uniform radiation field in the dosimeter region, with the wished dose.

Neutron measurements were performed with the epithermal neutron beam of the LVR-15 reactor, dedicated to BNCT experiments, at the Research Centre Řež (Czech Republic). The collimator of the epithermal column has a circular shape, with 12 cm diameter. In free beam, with reactor operating at approximately 9 MW, the epithermal neutron flux is $6.5 \cdot 10^8\ cm^{-2}\ s^{-1}$, the fast neutron flux is $5.5 \cdot 10^7\ cm^{-2}\ s^{-1}$, the thermal neutron flux is $3.8 \cdot 10^7\ cm^{-2}\ s^{-1}$, the photon absorbed dose measured in the beam axis by ionisation chamber was 1.98 Gy/h and fast neutron kerma in tissue was 3.5 Gy/h (Burian et al., 2009). In Fig. 1, the mouth of the epithermal beam collimator is shown.

With the aim of irradiating small biological samples, the epithermal beam was moderated by a polyethylene disk 2 cm thick, with a diameter of 13 cm. Some samples were fixed to this disk that was placed against the collimator mouth, other were settled in the polyethylene cylindrical box with 13 cm of external diameter and 8 cm of height, having two identical polyethylene disks 2 cm thick as base and cover. The box is shown in Fig. 2.

2.2. Fricke gel dosimeters

The Fricke gel dosimeters utilised for the here described measurements are laboratory-made radiochromic gels in which the gelling agent is porcine skin, in the amount of 3% of the final

Fig. 2. Polyethylene box for small mice exposures, closed (left) and without the cover disk (right).

weight. The chemical composition of the dosimeters is: ferrous sulphate solution [1 mM $Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$], sulphuric acid [25 mM H_2SO_4] and xylenol-orange [0.165 mM $C_{31}H_{27}N_2Na_5O_{13}S$]. It is meaningful (important) to note that such dosimeters are diluted solutions and have a very good water-equivalence for neutrons and for whichever secondary radiation (gamma, charged particles). In fact, the solutes are in millimolar concentrations and only have the role to make detectable the effect of radiation, without giving any measurable contribution to the absorbed dose. In Fricke-xylenol-orange-infused gel dosimeters, the radiation induces oxidation of ferrous ions and xylenol-orange forms a complex with ferric ions that absorbs visible light around 585 nm. The optical analysis of light absorbance at this wavelength is then an effective method for achieving absorbed dose values. In fact, the optical absorbance that is the difference of optical density D(OD) is proportional to the absorbed dose, up to saturation. For achieving light absorbance, in the developed methods the dosimeters are placed on a flat and uniform light source and transmittance images are acquired, before and after irradiation, by means of a CCD chamber equipped with optical filter around 580 nm. The images are then processed by means of suitably developed software which allows to obtain dose images or profiles. Fricke gel dosimeters in form of layers, typically 3 mm thick, were developed in the laboratory for dose measurements in phantoms of large dimensions (Gambarini et al., 2004, 2006). For BNCT dosimetry, methods for separating the various dose contributions have been proposed and improved (Bartesaghi et al., 2009; Gambarini et al., 2010a). The chemical composition of the dosimeters is suitably changed, in order to attain dose separation. A couple of standard and boron-added (usually with 40 ppm of ^{10}B) dosimeters, irradiated in the same position inside a phantom, allow determining the boron dose distributions. The method for gamma and fast neutron dose separation is based on the absorbance images obtained with a couple of standard- and heavy-water-made dosimeters, exploiting the different energy that is released by recoil protons and deuterons.

In TE phantoms of small dimensions, Fricke gel dosimeters in layer geometry should jut out the phantom and then cannot be used for dose measurements because the absorbed dose in a given position is significantly dependent on the amount of surrounding material. In fact, such a material contributes to both thermal neutron flux and gamma dose. Also inside the phantom, it is important to avoid modifications of the radiation field by dosimeters themselves.

To assemble gel dosimeters of small dimensions, capable of giving dose profiles in small phantoms, Fricke-xylenol-orange-infused gel was inserted into thin tubes consisting in rigid and transparent plastic cylinders with an external diameter of 2.8 mm and an internal diameter of about 2.2 mm (from IMV Technologies Italia s.r.l.). Their length is of 13 cm, but the thin tubes can be cut to have the convenient length, depending on each specific necessity. Such dosimeters are shown in Fig. 3.

A method has been optimised to fill such thin tubes with Fricke gel, avoiding bubble formation: the dosimetric solution, before its hardening, is not injected, as for gel layer preparation, but carefully drawn in with a syringe. Then, the tube ends are sealed with mastic and Teflon tape. A dedicated MATLAB code has been written, to analyse optical images in the case of tubular dosimeters. Because of their circular section, the value of light transmittance has to be taken along the axis of the acquired strip. Owing to light scattering effects, in the detected images the transmitted light is maximum at the strip centre. The developed programme converts dosimeter images into numerical matrices, thus finds the strip centre along each dosimeter image and finally achieves the profile of optical density difference along the dosimeter.

Some dosimeters were also obtained by inserting Fricke gel in standard cuvettes usually utilised for optical spectroscopy. Such containers have square section with external side of 12 mm and internal side of 10 mm. The height is of 45 mm, partially occupied by the plug. For the optical analysis, the method utilised for layer gel dosimeters can be exploited.

The CCD camera parameters must be suitably chosen for transmittance image acquisition with dosimeters in thin cylinders or in cuvettes. For thin cylinders, it is opportune to have high pixel to millimetre ratio, in order to get lower statistical error. For dosimeter gel in cuvettes, with 10 mm of optical path, the higher light absorption requires particular attention to avoid grey level saturation in the detected images.

Some dosimeters were prepared in the laboratory of Milan, other at the Research Centre Řež. No calibration was possible at this centre and then all dosimeters were calibrated at the Milan laboratory, the first group some days before exposure to the epithermal beam, the second one some day after neutron exposure. A variation in time of the dosimeter sensibility is common, mainly due to progressive oxidation of the Fricke gel through time. This change depends on the dosimeter configuration and on the permeability to oxygen of the container material. In order to evaluate the sensitivity trend in time for the dosimeters in thin tubes and cuvettes, a 5 days journey simulation experiment was performed. Gel dosimeters were produced, packed and maintained in the same conditions of the dosimeters that travelled to or from Řež. Then, they were irradiated in the following days to a given dose. A slight variation in sensitivity was found, and the results were utilised for normalising the obtained doses of the measurements with neutrons.

2.3. Thermoluminescence dosimeters

Thermoluminescence dosimeters are suitable for measurements in small phantoms because of their little dimension. In BNCT dosimetry, the radiation field is a mixed neutron-photon field. The choice of TLDs that can give reliable results is highly dependent on the specific field characteristics. If the background is negligible and the gamma dose is due only to the 2.2 MeV photons produced by the reactions of thermal neutrons with hydrogen, the more convenient choice for measures of the gamma component of the field would be CaF_2:Tm (TLD-300) dosimeters owing to their negligible sensitivity to neutrons. If a background whose spectrum contains low energies is not negligible, proper corrections are necessary to compensate the higher sensitivity of such dosimeters to low energy photons (Becker et al., 2008; Gambarini et al., 2008). ^{7}LiF:Mg,Ti detectors (TLD-700) are mostly utilised for gamma dose measurements in BNCT dosimetry, but their response is usually sensibly affected by the thermal neutron contribution and suitable subtraction of such a contribution is necessary (Aschan et al., 1999). For thermal neutron fluence measurements, and consequent boron dose evaluation, ^{6}LiF:Mg,Ti detectors (TLD-600) can be profitably used only if the reactor power can be suitably lowered, because they undergoes radiation damage at high epithermal fluences. A method was proposed (Gambarini et al., 2010b) for achieving the evaluation of the photon dose from the shape of the measured glow curve (GC) of a TLD-700, without measurements or calculations of the thermal neutron fluences in the positions of dosimeters, but with the unique knowledge of the shape of the GC of a TLD-600 exposed in the mixed neutron/photon field of BNCT, not calibrated.

The last method was exploited in this work. Some TLD-600 chips were inserted in the polyethylene box above described that was exposed to the epithermal beam for few seconds, with the aim of obtaining the ratio between the heights of the two dosimetric peak in the GC of a LiF:Mg,Ti detector exposed to thermal

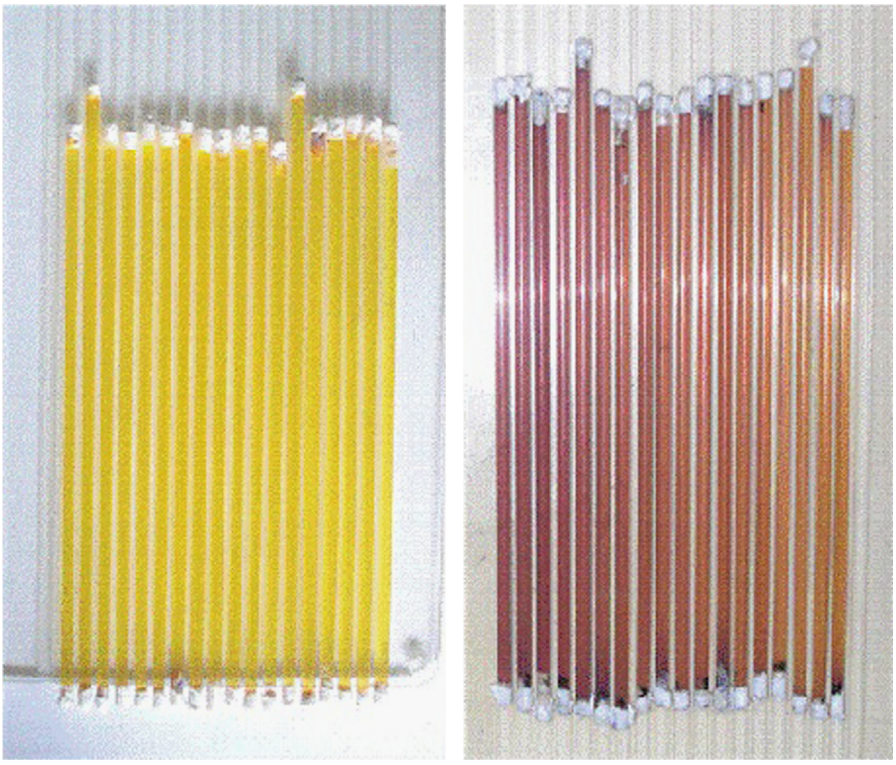

Fig. 3. Small tubes of Fricke gel before exposure and irradiated at various doses.

neutrons. In fact, gamma dose is negligible in TLD-600 exposed to so high thermal neutron fluxes. Then, in-phantom measurements were performed with TLD-700 chips. In such dosimeters, thermal neutron contribution can be low or high, depending on the ratio of gamma dose to thermal fluence and then on the dosimeter position in the phantom. So, the gamma doses were calculated with the formula reported in the last cited paper and the measurement error has resulted to go from 5% to 15%.

The dosimeters where analysed with a Harshaw 3500 TLD reader, always one week after irradiation. The maximum temperature was 350 °C and the heating rate 7 °C s^{-1}. Before each irradiation, the TLDs were annealed in an oven at 400 °C for 1 h, then in another oven at 100 °C for 2 h, and left to cool at room temperature until the next day.

2.4. Phantoms

All phantoms were made with TE gel obtained by suitably melting the gelling agent Agar in distilled water, in the amount of 2% of the final weight.

Phantoms simulating little mice had cylindrical shape, with a diameter of 25 mm and a height of 50 mm. Four dosimeters in thin tubes were inserted near the cylinder axis, two with standard Fricke gel and two added with 40 μg/g of ^{10}B. In the case of cuvettes, only one dosimeter was settled inside the mice phantom, and phantoms containing dosimeters with or without ^{10}B were placed in symmetrical position, in order to have the same gamma dose and the same neutron fluence in the couples of dosimeters utilised for separating dose contributions. TLDs chips were embedded into Teflon tape, in order to avoid dosimeter injure, and fixed to a thin polyethylene strip on order to inert them along the phantom axis saving information about the exact position. In Fig. 4-a, mice phantoms containing thin dosimetric tubes are shown. In Fig. 4b, two Fricke gel cuvettes, one without and the other with ^{10}B, are visible.

For cell culture experiments, cells stick to a wall of cell culture flasks or of 6 × 1 ml microscopy slide chambers and such containers are filled with a suitable physiological liquid. To measure the dose absorbed at the cell position during irradiation, some flask, after cutting the plug, was filled with gel. Microscopy slide chambers were substituted by cuvettes, whose dimensions are very near, field with gel. In such phantoms, dose measurement were performed with thin tubes of Fricke gel or with TLD-700 chips, positioned adjacent to the wall that was placed against the polyethylene moderator 2 cm thick. Culture flasks were partially shielded by a boronated cover. In Fig. 5, a flask containing Fricke gel tubes and two flasks positioned for irradiation are shown. The thin Fricke gel tubes were alternatively put with ^{10}B or without.

3. Results

Before performing in-phantom measurements, the moderated beam that impacted on samples was inspected. To this aim, a Fricke gel dosimeter layer, 3 mm thick, was placed internally to the irradiation box, leaning against the first layer of polyethylene. Then the box was placed against the mouth of the collimator and irradiated. The same thing was done with another identical gel dosimeter, containing 40 μg/g of ^{10}B. By means of pixel-to-pixel manipulation of transmittance images, the D(DO) images have been obtained and, from such images, the gamma plus fast neutron dose image and the ^{10}B dose image were achieved. In Fig. 6, the obtained spatial distribution of gamma plus fast neutron dose rate is shown. From the ^{10}B dose, by means of the kerma factor, the thermal neutron flux was finally attained. In Fig. 7, the spatial distribution of the thermal neutron flux is shown. The fast neutron dose has not been measured in this geometry, but it is not much dependent on the amount of surrounding materials, as happens for thermal neutron flux and gamma dose. So, it has been subtracted from the results obtained in measurements in small phantom, on the

Fig. 4. (a) Thin tubes of Fricke gel in mice phantoms. (b) Fricke gel without ^{10}B and with ^{10}B in cuvettes, after exposure in mice phantoms partially shields with a cadmium screen.

Fig. 5. Flask containing Fricke gel tubes and two flasks positioned for exposure.

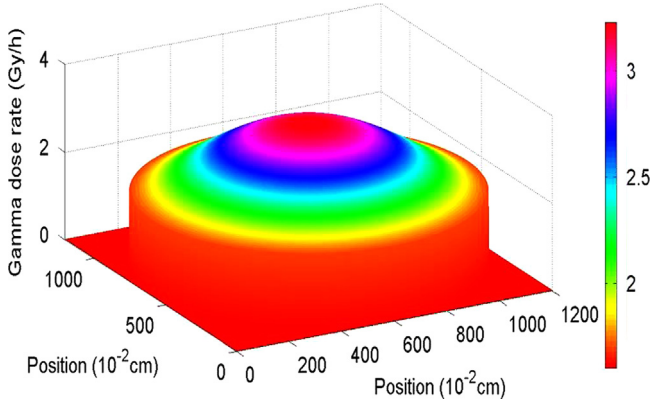

Fig. 6. Spatial distribution of gamma plus fast neutron dose rate after polyethylene moderator.

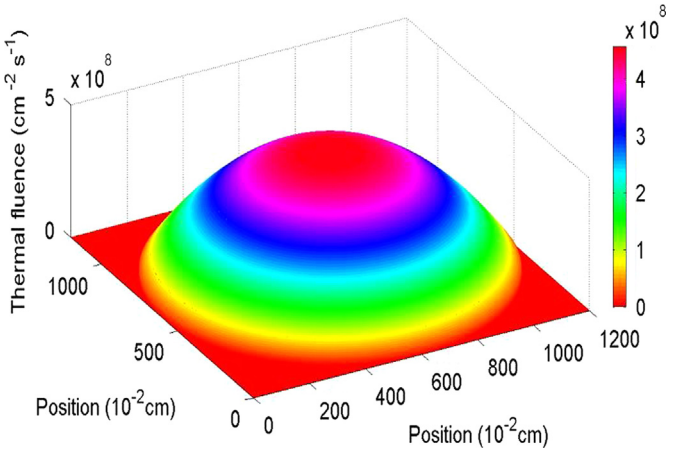

Fig. 7. Spatial distribution of the thermal neutron flux after polyethylene moderator.

basis of its spatial distribution in the standard water phantom (Gambarini et al., 2010a).

Measurements with mice phantoms were carried out, putting four phantoms at a time in the irradiation box, in the same geometrical configuration used in biological experiments. Mice phantoms were or bare or partially shielded by cylindrical shells of material containing ^{10}B, as shown and also schematically illustrated in Fig. 8. The results obtained in bare phantoms are shown in Fig. 9, where dose profiles obtained with gel dosimeters in thin tubes and in cuvettes and dose values measured with TLDs are reported. The

Fig. 8. Phantoms with dosimeters, in the irradiation box.

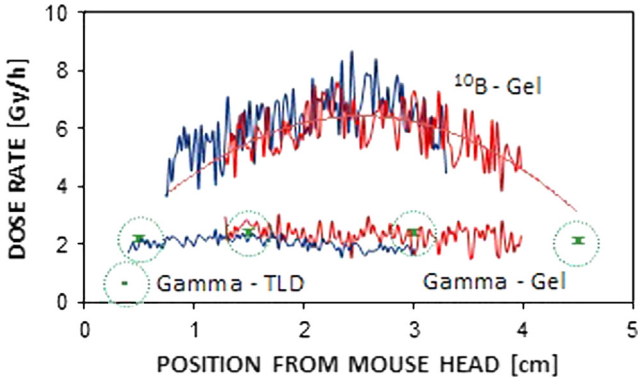

Fig. 9. Dose profiles in mice phantoms.

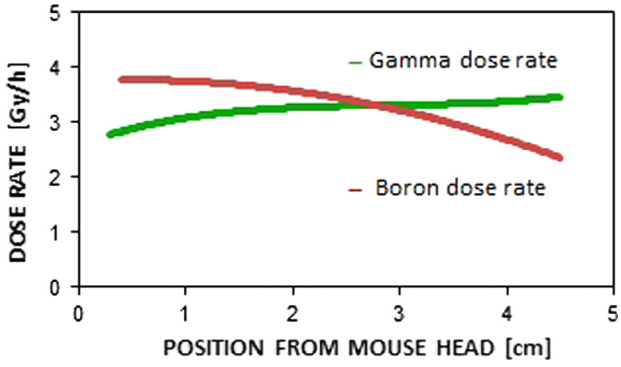

Fig. 10. Dose profiles in mice phantoms partially shielded with a borate screen.

shape of the profiles of the boron dose is due to the fact that in the central region the flow of thermal neutrons was higher, because of their position in the phantoms. The high gradient of thermal flux in the region occupied by the phantoms caused differences in the dose profiles obtained, when the puppets were not oriented precisely or if the dosimeters were not exactly centred. For phantoms partially shielded, we report in Fig. 10 the dose profiles as deduced by the various results obtained with gel dosimeters and TLDs.

Phantoms simulating cell culture irradiation were placed on the moderating polyethylene disk, in central position. Flasks were partially shielded with a borated screen. The results are reported in Fig. 11 and 12.

4. Conclusions

The obtained dose profiles and the intercomparison of results obtained with the two different kinds of dosimeters show good

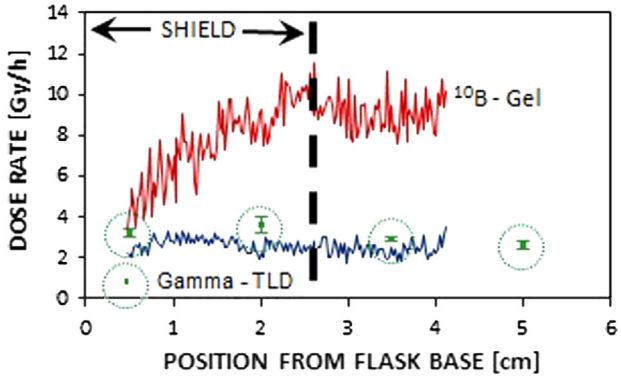

Fig. 11. Dose profiles in flasks for cell culture irradiation, partially shielded with a borate screen.

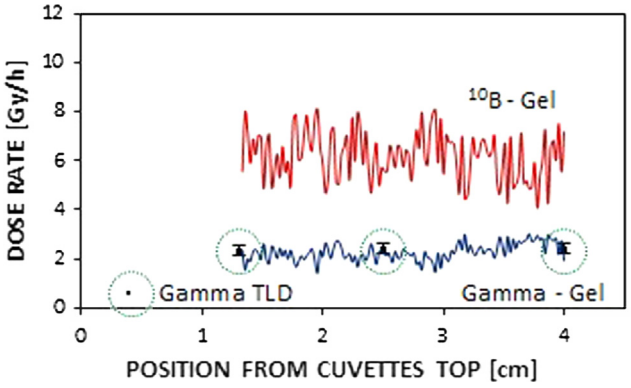

Fig. 12. Dose profiles in cuvettes simulating microscopic-slide-chambers for cell culture.

consistency and confirm that the proposed methods efficiently provide determination of the spatial distribution of the gamma and boron doses in small phantoms exposed to a BNCT neutron beam.

The dispersion of the results obtained by means of gel dosimeters is a consequence of the dispersion of the CCD camera acquisitions and could be amended with a smoothing operation performed by the developed software, not utilised for obtaining the data here reported.

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