Fricke gel layer dosimeters in BNCT: recent applications

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Abstract. Radiochromic gel dosimeters in form of layers based on Fricke solution have shown to be a valuable method for in-phantom dose measurements in a mixed BNCT radiation field. Using dosimeters with different isotopic composition it is possible to determine bidimensional distribution of the different dose components. In the last years, the method has been continuously improved, permitting to achieve reliable dose images with areas until 14x16cm^2, also in epithermal columns with a relevant spectral component of fast neutrons.

1. Dosimetry in BNCT

Boron neutron capture therapy (BNCT) is an experimental technique whose aim is to selectively release heavy charged particles in the cancer cells exploiting the high capture cross section of ^10^B. A BNCT treatment is composed by two steps: at first, a boron carrier capable to concentrate itself mainly in the tumour cells is administered to the patient; then, at a proper time after the drug administration, the patient (or the organ) to be treated is exposed to a thermal or epithermal neutron field. ^10^B nuclides capture neutrons with high probability (63837b for 25meV neutrons), leading to one of the following reactions:

^10^B + n -> ^4^He + ^7^Li + ~ (0,48 MeV) + 2,31 MeV (94%)
^10^B + n -> ^4^He + ^7^Li + 2,79 MeV (6%)

The ^4^He and ^7^Li particles release almost all their kinetic energy in the malignant cells, since they have a combined average range of 12-13µm, comparable to the linear dimensions of a mammalian cell; moreover, being heavy charged particles with a total average energy of 2.34MeV, they have an elevated linear energy transfer (LET) resulting in a high radiobiological effectiveness (RBE), providing an effective tumour–seeking boron carrier.

BNCT is a complex technique that in the last years has obtained encouraging results, however without passing completely the toxicity and efficacy trials; it needs multidisciplinary efforts in order to become competitive with the traditional radiotherapy based on electrons and photons. The crucial point is the normal tissue sparing, achievable developing highly selective boron carriers and studying suitable neutron sources.

Different kinds of neutron sources for BNCT are under study, but until now only nuclear reactors can provide a neutron field with acceptable characteristics of energy spectrum, flux and background gamma radiation. In particular, epithermal neutron beams, that is with a relevant component of neutrons with energy between 0.5eV and 10keV, are convenient for BNCT trials of deep tumour
treatments. However, this kind of sources have unavoidable components of background photons and fast neutrons (>10keV) damaging indistinctly all the tissues.

Differently from the conventional radiotherapies, the tissues exposed to a BNCT radiation field are traversed by four distinct radiation components, each one with a different LET and causing the absorption of dose with different RBE. The so-called therapeutic dose is due to boron neutron capture. Fast neutrons, interacting with nuclei, release their kinetic energy mainly to the hydrogen nuclei in tissues, causing recoil protons. Hydrogen can capture thermal neutrons, generating 2.2MeV photons; other gamma rays come from the column structure. Finally, also nitrogen can capture neutrons, emitting a proton with the $^{14}$N(n,p)$^{14}$C reaction.

As far as dosimetry is concerned, it is important to determine beside the therapeutic dose also the dose due to the undesired radiation components. In fact, the neutron fluence has to be sufficiently high in order to achieve the tumor control; but, on the other hand, the maximum admitted fluence is established on the basis of the dose in healthy tissues, which has to be within tolerance limits [1].

Usually, when the effect on a patient of a BNCT treatment has to be foreseen, the boron and the nitrogen doses are estimated by means of the kerma approach considering the in-tissue thermal fluence; the last is mainly evaluated performing in-phantom activation foils measurements [2].

Dose measurements in BNCT are challenging. The most common detectors for gamma and fast neutron dose evaluation are paired ionization chambers and thermoluminescence detectors (TLD) but, because of a number of unpredictable factors, such dosimeters can hardly reach an accuracy below 8-10% (one standard deviation). It is therefore recommended to perform both the gamma and fast neutron dose measurements exploiting more than one type of experimental technique.

Fricke gel dosimeters in form of layers have proved to give a valuable method to determine in-phantom absorbed dose spatial distributions. Differently from ionization chambers and TLDs that perform point measurements, these gel dosimeters can provide bidimensional images of the different absorbed dose components. The measurement shown in this paper have been carried out at the epithermal column of the LVR-15 reactor at Rež (CZ) [3]. Utilizing Fricke gel dosimeters with different isotopic composition, it was possible to obtain distinctly images of boron, photon and fast dose components.

2. Fricke gel dosimeters for BNCT

Fricke gel dosimeters in form of layer are laboratory-made radiochromic gels with the following standard composition: ferrous sulphate [1mM Fe(NH$_4$)$_2$(SO$_4$)$_2$·6H$_2$O]]; sulphuric acid [25mM H$_2$SO$_4$]; porcine skin [3% of the final weight] as gelling agent and Xylenol Orange [0.165mM C$_3$H$_7$N$_2$Na$_5$O$_{13}$S] as metal ion indicator. The dosimeters can be framed in different shape and size, usually with a thickness of 3mm, and are inserted in a phantom having a good tissue equivalence for neutrons. As far as the neutron transport in phantom is concerned, the non-perturbative effect due to dosimeters of such thickness has been demonstrated by means of Monte Carlo (MC) simulations.

The dosimeters are imaged before and after the irradiation with a charged coupled device (CCD) camera. The optical transmittance at 585nm is acquired by detecting grey levels (GL) matrix. A proper software has been developed in order to perform a pixel-to-pixel elaboration and obtain the difference of optical density [OD]. By means of calibration with a reference photon source, the OD images are converted into dose images.

Exploiting the GL images of dosimeters with different compositions irradiated in the same position of the phantom, elaboration algorithms have been developed in order to provide dose images due to the different radiation components [4,5].

A couple of standard and boron added (usually with 40ppm of $^{10}$B) dosimeters is used to determine both gamma and boron dose distributions; while the method to separate the gamma and fast neutron doses is based on a couple of standard and heavy-water-made dosimeters.
In the last years, the Fricke-gel-layer experimental technique has been continuously improved. A particular care has been devoted to the improvement of the method reliability; in particular, in one of the experimental configurations it has been estimated that an uncertainty of 6-7% in the total dose evaluation resulted in an error of around 30% of the determined boron dose. Moreover, since in BNCT the amount of absorbed dose in tissues far away from the target volume is not negligible, larger dosimeters have been assembled (with areas until 16x14cm$^2$). Dosimeters with such areas show problems of thickness homogeneity which have been solved by performing transmittance images before the irradiation also at 430nm and utilizing properly developed algorithms [6].

The data shown in this paper have been obtained utilizing rectangular dosimeters with areas of 12x6cm$^2$ and 16x14cm$^2$ (the sensitive areas are about 11x5cm$^2$ and 15x13cm$^2$, respectively). The layers were inserted either in a BNCT standard (50x50x25cm$^3$) water phantom or in a cylindrical (d = 16cm, h = 14cm) water equivalent phantom, having dimensions comparable to a human head. Fig. 1 shows, as an example, a couple of standard and 40ppm boron 12x6cm$^2$ dosimeters placed on the planar light source; these dosimeters have been irradiated for 90’ in the cylindrical phantom.

![Image](image1.png)

**Figure 1** Gel dosimeters (12x6cm$^2$) placed on the planar light source for transmittance imaging detection after a 90’ irradiation. In the boron added dosimeter (above) the nuance due to dose absorption is more apparent that in the standard one (below).

### 3. Measurements with Fricke gel layers

In order to determine boron dose distributions, it is necessary to irradiate a standard Fricke dosimeters and a boron added one in the same position in the phantom. Fig. 2 shows the $\Delta$(OD) images of a couple of 16x14cm$^2$ dosimeters exposed in the cylindrical phantom; the two dosimeters have been irradiated for 2 hours at the nominal power of the reactor. The obtained $\Delta$(OD) images are proportional to the absorbed dose, and are shown with some percentage isodose curves pointed out with colors.

Applying to these data a coefficient obtained by means of a calibration performed with a photon source, it is possible to convert them into the so-called “gamma-equivalent dose” distributions. The total absorbed dose is clearly due to the different components of the radiation field, and applying to the $\Delta$(OD) images a coefficient obtained with a gamma calibration, the different sensitivity of Fricke gel to radiation having different LET is neglected. The gamma-equivalent dose distributions are presented as 3d plots in Fig. 3.
Figure 2 [a(OD)] images of a couple of 16x14cm² gel layers, exposed for 2h in the water phantom; a standard (on the left) and a 40ppm boron added (on the right) dosimeter are shown. The neutron beam collimator was positioned on the left side of the images. Some percentage isodose curves are highlighted.

Since a standard Fricke gel exposed in an epithermal column radiation field is sensitive only to the gamma and the fast neutron components, while a boron added dosimeter absorbs also the dose due to the boron captures, it is possible to obtain the boron dose distribution by subtraction, taking into account the relative sensitivity of the dosimeters to photons and to the heavy charged particles produced by the boron capture. The boron dose distribution achieved from data shown in Fig. 3 is depicted in Fig. 4. The trend of the boron dose distribution is related to the thermal neutron fluence in the phantom; for example, the presence of a dose maximum on the central beam axis at around 2 cm of depth is due to the thermalization of the epithermal neutron beam traversing the phantom material.

Figure 3 Gamma-equivalent absorbed dose distributions in a standard (a) and a 40ppm boron added dosimeter (b) obtained by images shown in Fig. 2. Note the different scales on z-axis.
The separation of the photon and the fast neutron doses was carried out applying a suitable procedure, which includes the use of a standard and a heavy-water-made dosimeter and proper MC simulations in order to calculate the ratio between the delivered energy of recoil protons and deuterons [7]. As far as the treatment planning is concerned, it is crucial to evaluate accurately the absorbed dose due to fast neutrons, since this radiation component deposits its energy non-selectively in tissue and has a high radiobiological effectiveness.

A couple of 12x6cm$^2$ dosimeters was inserted in the cylindrical phantom and exposed for 2 hours. Fig. 5 shows the on-axis profiles; the photon dose was measured also with thermoluminescence dosimeters (TLD), while MC simulations have been carried out in order to calculate the relative fast neutron absorbed dose. Both TLD and MC data are plotted together with the gel dosimeter data for comparison (MC data are normalized at the point at 2.25cm of depth), showing a satisfying agreement.

![Figure 4](image1.png) **Figure 4** Boron dose distribution imaged in the water phantom.

![Figure 5](image2.png) **Figure 5** Photon (a) and fast neutron (b) dose on-axis profiles. The dosimeters have been exposed for 2 hours in the cylindrical phantom. Fricke gel data are compared with TLD measurements and MC calculations.
4. Conclusions and acknowledgements

Fricke gel dosimeters in form of layers have proved to perform valid measurements of the different
dose components in tissue or tissue-equivalent material exposed to a reactor BNCT epithermal beam.
Recent improvements allow to acquire dose images of areas until 13x15 cm$^2$ and to provide a
reliable separation not only of boron and photon doses but of fast neutron absorbed dose too.
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