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GEL DOSIMETRY FOR CONFORMAL RADIOTHETRAPY

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Abstract

With the continuum development of conformal radiotherapies, aimed at delivering high dose to tumor tissue and low dose to the healthy tissue around, the necessities has appeared of suitable improvement of dosimetry techniques giving the possibility of obtaining dose images to be compared with diagnostic images. Also if wide software has been developed for calculating dose distributions in the fields of various radiotherapy units, experimental verifications are necessary, in particular in the case of complex geometries in conformal radiotherapy. Gel dosimetry is a promising method for imaging the absorbed dose in tissue-equivalent phantoms, with the possibility of 3D reconstruction of the spatial dose distribution, with millimetric resolution. Optical imaging of gel dosimeters, based on visible light absorbance analysis, has shown to be a reliable technique for achieving dose distributions.

1. Introduction

The present advancement of radiotherapy techniques is aimed at achieving local energy release in tumours saving the surrounding healthy tissue. Moreover, radiobiology research has lead to take into consideration radiation quality and relative biological effectiveness (RBE). Therefore, conformal therapies have been widely developed, able to deliver the proper dose to well defined volumes of tissue, utilising γ-rays, electrons or other radiation having higher linear energy transfer (LET), such as protons or other charge particles emitted in neutron reactions.

This progression in radiotherapy has caused the sprouting of new dosimetry methods aimed at achieving absorbed dose imaging with the best possible precision and the best spatial resolution, in the various radiation fields, such as the techniques employing radiochromic or radiographic films and gel dosimeters. In fact, notwithstanding the considerable accuracy and improvement of computerised modelling, the calculated doses are not completely reliable for complex 3D treatments planning, so that experimental validation is recommendable.

Gel dosimetry is a technique in great development, based on tissue-equivalent gels in which a chemical dosimeter is infused. The phantoms made with such gels are continuous dosimeters, where the absorbed dose can be imaged and 3D distribution reconstructed. Various kinds of gel dosimeters have been proposed and different kinds of imaging techniques have been developed. The two main families of gel dosimeters are Fricke-infused-gels and polymer-acrylamide-gelatin (PAG).

In 1984 Gore et al.[1] have suggested to perform 3D dosimetry by means of nuclear magnetic resonance imaging (NMRI), in phantoms made with agarose or gelatine gel infused with Fricke dosimeter, which is mainly composed of a ferrous sulphate solution. The imaging method take advantage of the fact that ionising radiation causes oxidation of ferrous ions (Fe^{2+}) to ferric ions (Fe^{3+}) and that the last ones produce a stronger paramagnetic enhancement of the proton NMR relaxation rates. After this suggestion, many papers have appeared, concerning studies aimed at improving the method [2-6] or applications to various radiotherapy modalities[7,9].

The low sensitivity of the NMRI method for Fricke-infused-gel analysis, often jointed with the difficulty of having access to such an analyser, has pushed to develop imaging techniques based on optical measurements. Following the suggestion of Appleby[10], the metal ion indicator xylenol orange, which forms coloured complexes with ferric ions, has been added in the dosimeter-gel composition. When analysed with a spectrophotometer, a ferrous/agarose/xylenol orange (FAX) gel shows visible-light absorption around 440 nm; after exposure to ionising radiation, there is a decrease in the absorption at this wavelength and absorption around 585 nm appears[11], whose yield increases with dose. The gel colour, initially light yellow or ochre, changes toward red-brown or blue, depending on the amount of xylenol orange in the dosimeter composition. So, some optical technique for gel analysis has been proposed [12,13] and developed in addition to NMRI.

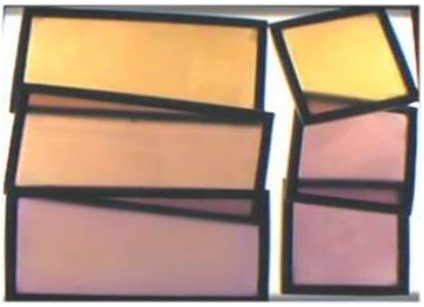
The action of gel molecular structure is that of hindering the diffusion of ferrous and ferric ions, keeping dose images stable for some time. Nevertheless, diffusion effect is not negligible, and it may cause deformation and, after longer times, also destruction of dose images. Therefore, prompt analysis after irradiation is required in order to warrant the correct spatial information. This is the main problem of NMRI analysis of gel dosimeters. Xylenol orange has resulted to slow ion diffusion, and now it is often included in gel dosimeter components also when NMRI is performed. To avoid diffusion trouble, dosimeters not involving metal ions have been searched and developed, taking advantage from radiation-induced polymerization[14,15].

All kinds of gel dosimeters, independently of the chemical dosimetric process involved and of the analysis technique, have the fundamental characteristic of being diluted water solutions, where the action of ionizing radiation starts, like in human tissue, with the radiolysis of water molecules. In fact, the energy directly absorbed by the solute is negligible; the role of solute is that of evincing the absorbed energy with a measurable effect. Therefore, phantoms can be prepared, of the required shape, showing very good tissue–equivalence for whichever directly ionizing radiation, and the phantoms itself is a continuum dosimeter. In the case of directly ionizing radiation, in fact, the absorbed dose spatial distribution is properly obtained, after manipulation of the detected gel images. In the case of neutrons, the requirements of tissue-equivalence are more complex, because of the various secondary radiation components. But it is just in this situation that gel dosimeters reveal to be particularly convenient, because it is possible to design gel matrix with suitable isotopic composition and to achieve spatial distribution of the various radiation components[16].

2. Gel dosimeters and imaging technique

The here presented gel dosimeters are radiochromic Fricke gels (Fricke-Xylenol-Orange-Infused gels). The standard composition of dosimeters is: Agarose [$C_{12}H_{14}O_5(OH)_4$] in the amount of 1% of the final weight, 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 $C_{31}H_{27}N_2Na_5O_{13}S$]. The tissue equivalence of this dosimeter is very good. In fact, the effective atomic number for a photoelectric effect is equal to 7.70 (in the muscle it is 7.71). As said before, the effect of ionising radiation is the conversion of ferrous ions in ferric ions, and the conversion yield is proportional to the absorbed dose (at least until saturation arises). Therefore, after ionising radiation, from the variation of some detectable physical property depending on the ferrous and ferric

ion amounts, the absorbed dose can be indirectly determined. The ferrous ion oxidation yield has resulted to be considerably higher than that of the standard Fricke dosimeter. The main drawback Fricke gel dosimeters consists in the not negligible effect of ion diffusion that causes a continuum loss of spatial resolution, during the time between irradiation and analysis. The image spread is of the order of a square millimetre per hour. Therefore, a prompt phantom imaging after irradiation is necessary to achieve good spatial resolution, but it is difficult if the imaging instrumentation is not near the irradiation facility. Therefore, we have studied a method for gel dosimeter imaging based on light transmittance measurements performed by means of a transportable instrument that can be quickly assembled near the irradiation facility[13]. In the proposed method, gel dosimeters are in form of layers of convenient shape and thickness (1-3 mm). The layers can be piled up to compose a phantom. For the analysis, gel layers are placed on a plane light source near a strip of grey-level (GL) standards; optical transmittance images are detected using a CCD camera provided with a suitable optical filter around 585nm. The grey-level strip allows to control, and eventually amend, the instability in time of the light source intensity. In order to avoid spurious effects and ferric ion diffusion, gel dosimeters are imaged just before and after irradiation, within 30-40 minutes. This time has been shown to be necessary in order to reach the chemical equilibrium after irradiation.



(a)

(b)

Fig. 1 – Gel dosimeters after irradiation. (a) Dosimeters irradiated in known gamma fields, for calibration. (b) Dosimeter exposed in phantom, for depth dose imaging and profiling.

The absorbed dose can be correlated to the Gray Levels (ΔGL) of the transmittance images detected before and after irradiation. In fact, ΔGL values can be easily converted in absorbance values (or optical density, ΔOD) with simple mathematics:

$$\Delta OD = \log_{10}\left(\frac{\Delta GL_{before}}{\Delta GL_{after}}\right)$$

and the ΔOD values are proportional to the absorbed dose.

Because of the strong dependence of the chemical yield on dosimeter composition, the response is affected by the precision of the quantities of chemical compounds. In order to minimize the error, a few samples of each gel preparation are

always utilized for calibration. Both the sensitivity and the linearity interval depend on the dosimeter composition and can be suitably adjusted according to the radiation field; the most immediate mean is to change the amount of Xylenol Orange in the dosimeter composition. In Fig. 2, an example of calibration curve is shown.

For the evaluation of the 2D and 3D dose distributions and for graphical visualisation, a suitable software was implemented using MATLAB®. Starting from two transmittance images, one acquired before and the other after irradiation, the software performs pixel-to-pixel manipulations and, through the suitable algorithms, evaluates the difference in the optical density in each position of the image. Utilizing the calibration curve, the program converts the matrix of ΔOD in a dose matrix and, moreover, gives the possibility to reduce the noise level, if necessary.

The modalities for gel dosimeter preparation and analysis have been studied and optimized, with the aim of achieving good reliability of results.

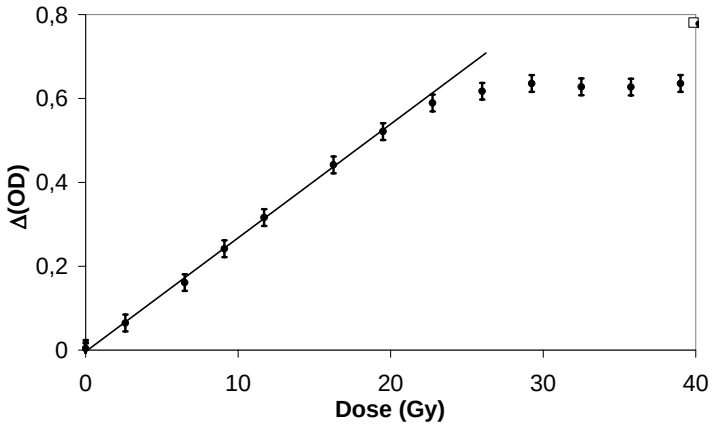
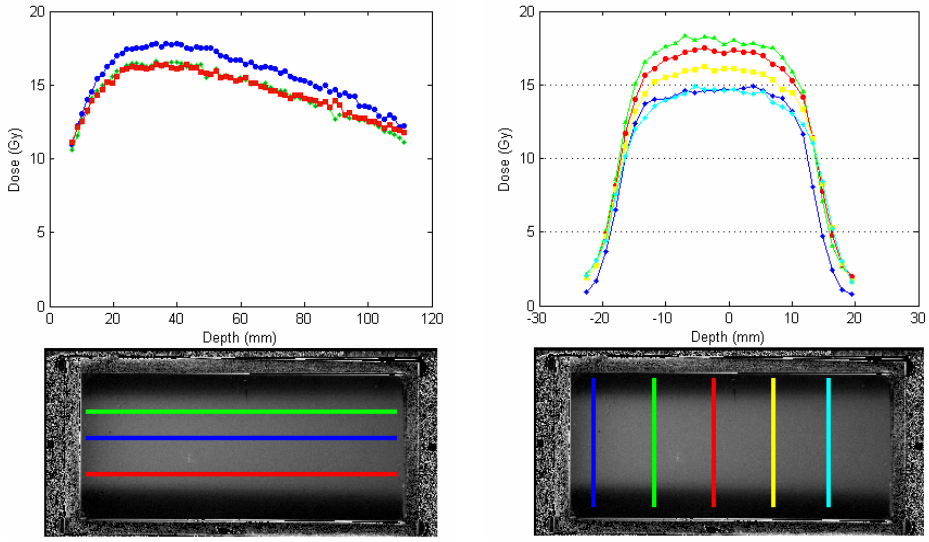


Fig. 2 - Calibration curve of a gel dosimeter, performed with a ^{137}Cs γ-ray source.

3. In-phantom measurements

In-phantom images and depth-dose profiles have been obtained with gel dosimeters analysed as explained above. The results have been compared with those measured with ionisation chamber or diode and with results of Monte Carlo simulations. Moreover, percentage isodose curves were extracted with the radiation treatment planning system Prowess 3D (Prowess Inc, Chico, Ca, USA) and such curves were qualitatively compared with those extracted from the dose images obtained with gel dosimeters.

Some results are here reported, obtained with gel dosimeters exposed to photons in a radiotherapy unit (18 MV), with a beam of 2 cm × 3 cm. The dosimeters were placed, close one to other, in a phantom of polystyrene having cubic shape with 20 cm of side. In Fig.3, the dose image obtained by means a gel dosimeter is shown, together with some dose profiles extracted from the image in directions (a) parallel and (b) orthogonal to the beam axis.



(a) (b)

Fig. 3 – Dose image obtained with a gel dosimeter, and dose profiles extracted from the image in directions (a) parallel and (b) orthogonal to the beam axis.

In Fig. 4a, the isodose curves are reported on the dose image and, to test the consistency of the method, in Fig. 4b the same isodose curves calculated with the radiation treatment planning system Prowess 3D (Prowess Inc, Chico, Ca, USA) are shown too.

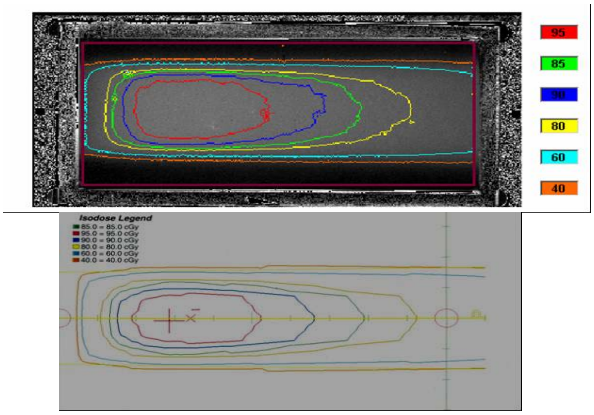


Fig.4 – (a) Isodose curves reported on a dose image. (b) isodose curves obtained with Prowess 3D.

The developed software reconstructs also a volume distribution of the absorbed dose. In Fig. 5, three isodose surfaces extracted from such a volume dose distribution are shown.

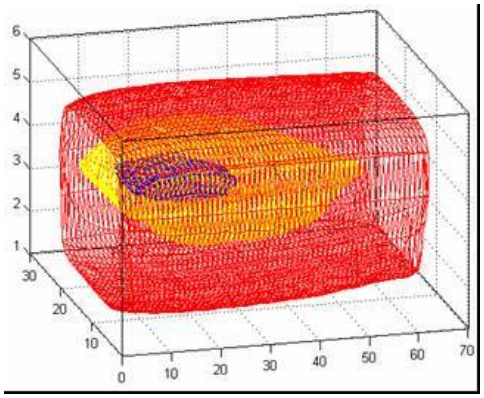


Fig. 5 – Isodose surfaces extracted from the 3D dose rendered by the dedicated software.

4. Conclusions

The here reported results show that good profiles, images and 3d reconstructions of in-phantom absorbed dose can be obtained through Fricke gel dosimeters in form of layers, analyzed by means of optical image.

5. References

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