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Dose Imaging in radiotherapy photon fields with Fricke and Normoxic-polymer Gels

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Abstract. Gel dosimeters are integrating dosimeters, that enable dose verification in three dimensions. Optical analysis of gel dosimeters has demonstrated to be an available technique for imaging the absorbed in-phantom dose exposed to radiotherapy beams. The goal is to demonstrate the ability of gel dosimeters to achieve accurately and spatial resolution in dose mapping, also when high dose regions are produced by a complex three dimensional treatment planning. Two types of dosimeters are investigated, a Fricke gel (Fricke-Xylenol-orange-infused gel) and a normoxic-polymer gel (polyacrylamide gel). Dosimeter gel samples of different shapes were exposed to photon fields, at various energies. Transmittance images were taken by means of a CCD camera and a spectrophotometer. In phantom 3-D images were realised with both dosimeter gels. An irradiation, using a linear accelerator, was realised in order to validate the method and techniques. Central axis depth dose profiles of the phantom were extracted and compared with ionization chamber measurements. Tissue-equivalence and other properties for both gels were studied using Monte Carlo techniques. Off-axis profiles and three dimensional dose distribution were obtained by simulations and compared with experimental dose distributions.

1. Introduction

In the last decades the radiation therapy techniques have gone through a significant development. We have today treatment techniques with an improved capability for tumour control while sparing normal tissue surrounding the tumour target. These techniques are, for example, conformal radiotherapy, dynamic treatments, stereotactic multiple beams, intensity modulated radiotherapy (IMRT) and multileaf collimation. Such modalities can be used to minimise patient complications. These achievements are possible owing to the technological improvements that make possible to apply complex irradiation methods. One of the main peculiarities for achieving the optimised treatment is the need to ensure that the treatment really fulfils the dose calculation of the treatment planning system (TPS). When conformal radiotherapy techniques are used, spatial location of dose gradients should be

determined in order to completely verify the planned absorbed dose distribution. The last developments in radiotherapy treatment are so complex, that they need computer supported three-dimensional treatment planning system, then the dose calculation algorithms must be able to handle scattering and density corrections in three dimensions. This can not be achieved with sufficient accuracy by means of standard dosimetric techniques. Then, there is an evident requirement of experimental methods for three dimensional dose verification.

The absorbed dose distribution within the patient is calculated using just a limited amount of initial measurements. For simplicity, idealised beam measurements in water are generalised to all treatment regimes by the TPS. Then, there is a great need for three dimensional absorbed dose measurements, in order to verify the complete treatment planned dose distribution. Gel dosimetry has the potentiality to be used for these measurements [1]. The peculiarity of gel dosimetry compared to conventional dosimeters, particularly for three dimensional dose distribution, has been well reviewed in previous papers [2]. Over the last years there have been continuous developments in gel dosimetry, starting with the proposed method of Gore [3] when Fricke-gel dosimeter was proposed. That is a dosimetric solution added with a gelling agent in order to achieve true three dimensional dose distribution. Another gel dosimeter was subsequently proposed, which is based on a radiation induced polymerisation process.

For the first kind of gel dosimeter, containing a ferrous solution (Fe2+), the absorbed dose is proportional to the concentration of ferric ions (Fe3+). While, for the second kind of dosimeters, the polymer dosimeters, and a polymerisation process induced by radiation is verified in the gel matrix. When the absorbed dose in a solution of monomers exceeds a certain value, the solution suffers a polymerisation process. When a gelling agent is mixed with a monomer solution, it has be shown that there is the possibility of determining the spatial distribution of absorbed dose from the measurement of the effect, linearly correlated to the absorbed dose, as relaxation rates in resonance magnetic analysis [4] or light absorbance [1]. The monomer solution incorporated in the gelatine consists of acrylamide and N,N'-methylene-bysacrylamide, and these monomers can be chemically polymerised and cross-linked to form a so-called polyacrylamide gel (PAG).

2. Methods and Materials

2.1 Dosimeter's optical analysis technique

The optical analysis method used in this work has been already widely described in previous papers [1]. Then, here is given just a briefly description of the method. The method is based on the imaging of visible light transmittance through the dosimeters, detected before and after irradiation. In order to perform optical transmittance analysis, gel dosimeters are in form of layers and they are placed on a plane and homogeneous illuminator. The dosimetric gel is inserted in properly designed containers composed of two transparent Perspex sheets, holt by a frame, as visible in Figure 1. The dosimeters have various shapes depending on the convenience. The images are detected by means of a CCD camera, eventually supplied with a suitable optical filter.

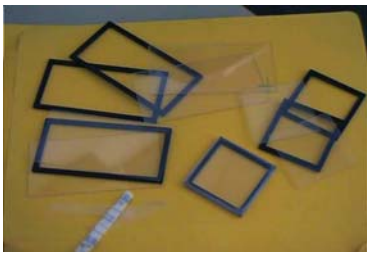

Figure 1: Gel dosimeter containers

After acquisition, the Gray Level (GL) images are converted into optical density images.

The optical density difference between images detected before and after irradiation is linearly related to the absorbed dose, as established by the Lambert-Beer law, assuming that the conditions of validity of this law are fulfilled. Therefore, the optical density images are converted into dose images by means a suitably determined calibration coefficient. A dedicated software (Matlab®) was conveniently developed for this technique and then used for image analysis. Using calibration data, the software allows to convert the optical density difference matrix in a dose matrix. This software reads and elaborates automatically the GL-images and gets the optical density difference matrix (proportional to the dose matrix). Then, using calibration data, the dedicated software converts the optical density difference matrix into a dose matrix, from which it is possible to extract the desired dose profiles.

The software gives also the dose surfaces in the gel dosimeter. In addition, using several piled up dosimeters layers, it's possible to realize a true three dimensional dose reconstruction of the absorbed dose.

2.2 Fricke gel preparation

The preparation of Fricke gel dosimeters has been performed as described in previous papers [1]. The composition of the gel is shown in Table 1.

Table 1: Fricke gel composition

Constituents	FeSO4	Agarose	H_2SO_4	X-O	Ultra pure water
Amount	1mM	1% final weight	25mM	0.165mM	Residual

2.3 PAG preparation

A detailed description of the PAG's preparation technique is found in literature [5]. Since, oxygen is a known inhibitor of polymerization in PAGs, the gels used in these experiments were manufactured in a purged gas glove box. The quantity of gelatine was varied from 4% to 6 % of final weight. PAG's composition is summarised in Table 2.

Table 2: PAG composition

Constituents	Acrylamide	N,N'-methylene-bisacrylamide	Gelatine	Ultra pure water
Amount (% of weight)	3	3	4, 5, 6	residual

2.4 Phantom Construction

A cubic phantom of 22cm of size was used. The phantom consists of a set of Perspex plastic layers 5mm thick, the central layers having a special rectangular cut in order to allow the rectangular gel dosimeter insertion. These cuts in the central layers ensure a good setting of the gel dosimeters for irradiation. Perspex plastic was chosen to design the phantom, according to the dosimetric tissue-equivalence of this material. A photograph of the phantom with the dosimeters is shown in Figure 2.

Figure 2: Phantom with dosimeters

2.5 Radiation exposure

As a first step, Fricke and PAG dosimeters were exposed to a photon beam from a Cs^{137}-source in order to study the dosimeter responses to the absorbed dose and also to establish the dosimeter calibrations. Successively, knowing the calibration factor for a set of dosimeter of gel dosimeters obtained from the same preparation process, dosimeters of this group were accommodated in the Perspex plastic phantom and irradiated with a high energy photon beam from a linear accelerator (Varian Clinac 2100C, Varian Inc.) operating at 18 MV. A photograph of the phantom, containing the gel dosimeters, ready to be exposed to the photon beam of the linear accelerator is shown in Figure 3.

Figure 3: Phantom with dosimeters exposed to Linac beam

Photographs of dosimeter samples after irradiation are reported in Figures 4a and 4b for Fricke and polymer gel, respectively.

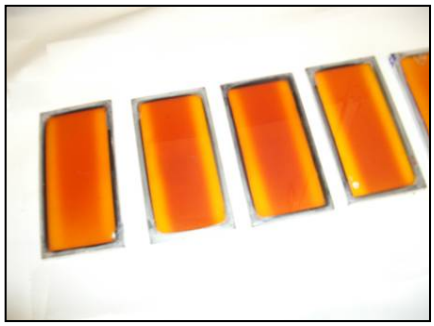

Figure 4a: Irradiated Fricke gel dosimeters

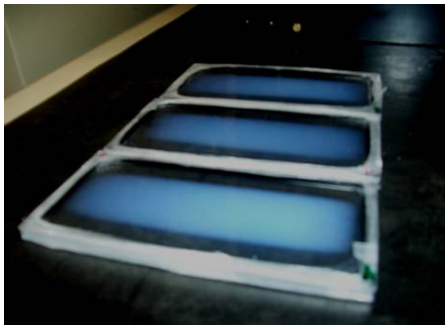

Figure 4b: Irradiated PAG dosimeters

2.5 Monte Carlo Simulations

Monte Carlo calculations were performed using the PENELOPE® code [6]. This code system performs Monte Carlo simulations of coupled electron-photon transport in arbitrary materials. The adopted scattering model allows the simulation of electron, positron and photon as primary particles. Photon transport can be simulated with high accuracy in the energy range from 100 eV to 1 GeV.

PENELOPE generates random electron-photon showers in complex material structures consisting of any number of distinct homogeneous regions (bodies) of different compositions. The code allows the user to write own simulation program, with arbitrary geometry and scoring.

The main program, which is provided by the user, has to control the evolution of the simulated tracks and keep score of the relevant quantities. The simulation of photon transport follows the usual detailed procedure, i.e. all the interaction events in a photon history are simulated in chronological succession. The simulation of electron and positron tracks is performed by means of a mixed (class II) algorithm. Individual hard elastic collisions, hard inelastic interactions and hard bremsstrahlung emission are simulated in a detailed way, by means of a random sampling from the corresponding restricted differential cross sections. This procedure ensures reliable simulation results, while sparing simulation CPU time.

3. Results and Discussion

3.1 Gel dosimeters calibration

A Cs^{137} photon source was used to calibrate the dosimeters. Samples of both types of dosimeters, prepared and elaborated together with those used for the in-phantom exposure to the Linac beam, were used to obtain the calibration. The optical density difference was studied, by means of the CCD camera GL images, as a function of the absorbed dose. Resulting calibration curves are shown in Figures 5a and 5b, for Fricke and normoxic-polymer gels, respectively.

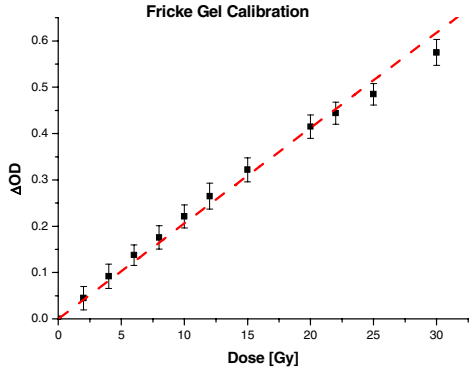

Figure 5a: Calibration for Fricke gel

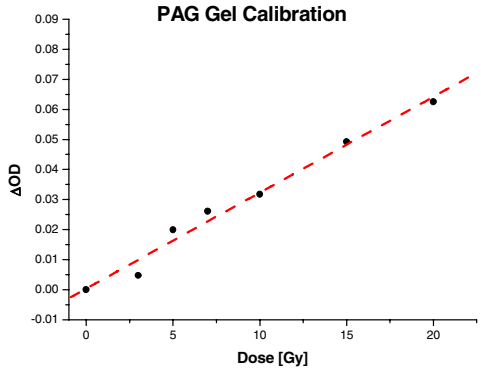

Figure 5b: Calibration for PAG

3.2 Preliminars for Monte Carlo simulations

In order to ensure acceptable Monte Carlo simulations, it's necessary to know some characteristics and properties, like the dosimeter and phantom materials and their geometric disposition during the irradiation procedure. Also the beam characteristics are necessary as input for an accurate simulation.

Generally, it's not easy to know the Linac photon fluence, then a common way to approach the photon beam parameters is to calculate, making use of Monte Carlo simulation data, the photon

fluence corresponding to the actual accelerator. Incorporating the so determined photon fluence, a first measurement of the depth dose distribution is done and compared with the ionisation chamber reference data, in order to evaluate the accuracy of the selected photon fluence. The obtained result, (using a CPU cluster facility) and simulating a large enough quantity of shower's histories, is shown in Figure 6.

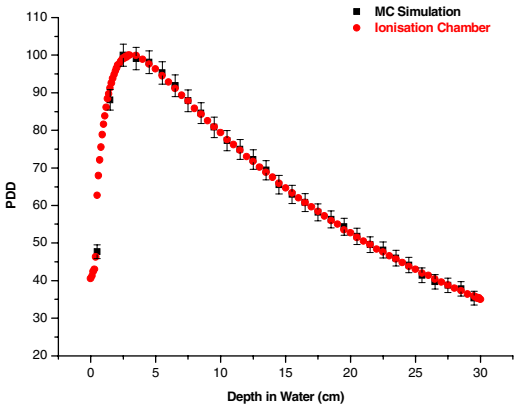

Figure 6: Monte Carlo PDD comparison with ionisation chamber data

3.3 Stability of the PAG dosimeters after irradiation

Polymer gel was studied with the aim of getting a gel dosimeter without diffusion effect. Therefore, this is the most important characteristic of this type of gel. In order to investigate the relatively stability of the here considered PAG dosimeter, measurements of the gel response as a function of the absorbed dose at several times after irradiation exposure were realised.

The dose response after irradiation was monitored, starting from 1 hour, and up to 2 months to verify the stability. The results are shown in Figure 7, from which it's possible to conclude that there is an acceptable stability for the PAG dosimeter.

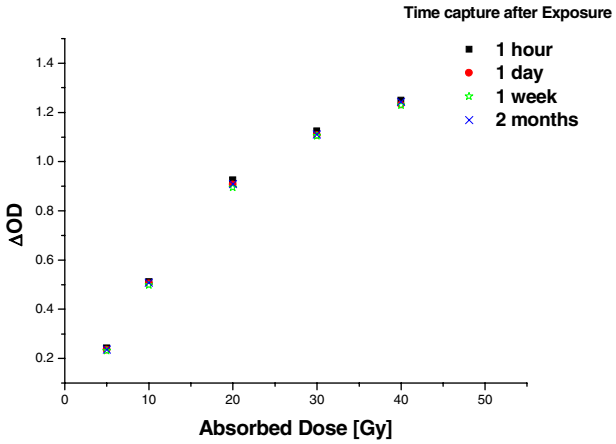

Figure 7: Optical Density Difference for several times after irradiation for PAG

3.4 Results of in-phantom irradiations

Depth dose profiles were extracted from the dose images obtained with gel dosimeters irradiated in the Perspex phantom. Such profiles were then compared with reference measurements, got with ionisation chamber. In order to establish how much time one has to wait after irradiation before capturing the dosimeter images, it was performed a set of image detections. It was found an acceptable performance when taking the images 1 hour after exposure, in complete accord with previous studies. An on-axis depth dose profile, normalised at maximum, compared with that of a standard dosimeter and Monte Carlo simulations is shown in Figure 8.

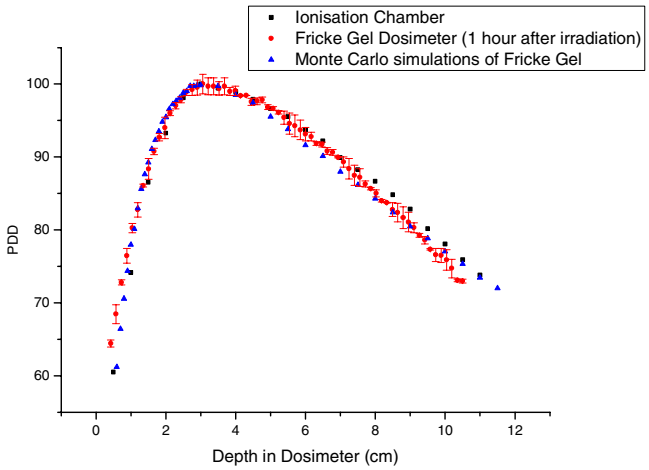

Figure 8: Comparison of Fricke gel and reference dosimetric depth dose profiles

The on-axis percentage depth dose profiles obtained for normoxic-polymer gel were compared with those corresponding to the Monte Carlo simulations and Treatment Planning System, as shown in Figure 9.

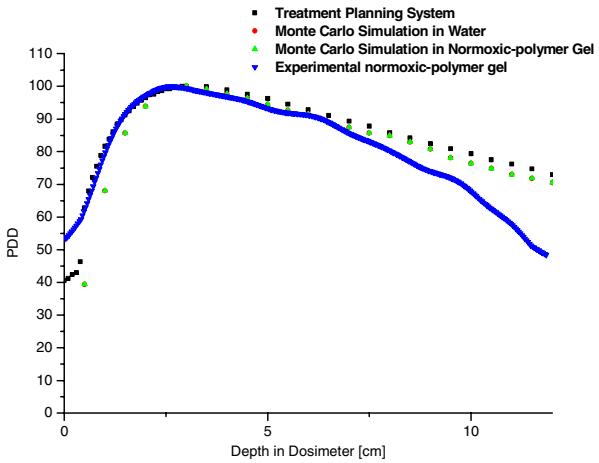

Figure 9: PDD on-axis for PAG

The isodose curves obtained with Fricke gel dosimeters were compared with those calculated by means of the Monte Carlo simulations, as well. A good agreement has resulted, as it is shown in Figures 10a and 10b.

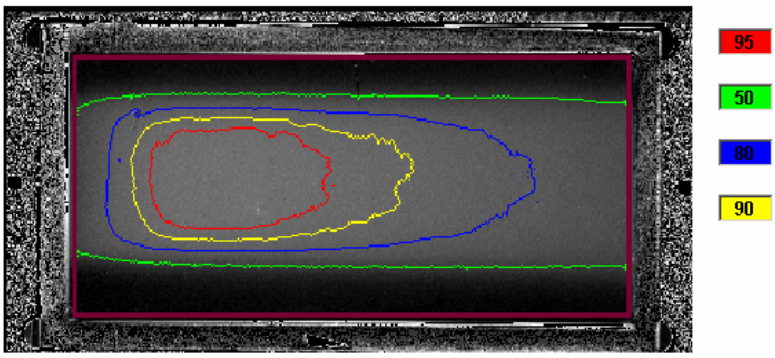

Figure10a: Experimental Fricke isodose curves

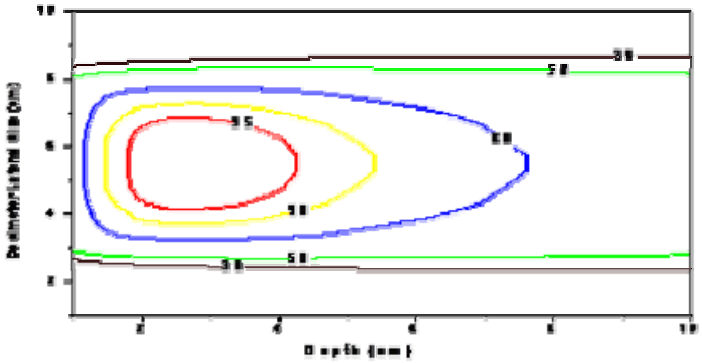

Figure 10b: Fricke Monte Carlo calculated isodose curves

In conclusion, the obtained on-axis dose profiles, off-axis dose profiles and isodoses curves obtained with Fricke gel dosimeters show a general good agreement with the standard dosimetric techniques used as reference.

The dose response of the here considered PAG should be still studied. Some considerations about the gel dosimeters filling process and subsequently incorporated modifications could suggest a better response, when determining the dose profiles.

Acknowledgements

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