3D dose imaging for arc therapy techniques by means of Fricke gel dosimetry and Monte Carlo simulations

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Abstract. Radiotherapy is one of the most effective techniques for tumour treatment and control. During the last years, significant developments were performed regarding both irradiation technology and techniques. However, accurate 3D dosimetric techniques are nowadays not commercially available. Due to their intrinsic characteristics, traditional dosimetric techniques like ionisation chambers, film dosimetry or TLDs do not offer proper continuous 3D dose mapping. The possibility of using ferrous sulphate (Fricke) dosimeters suitably fixed to a gel matrix, along with dedicated optical analysis methods, based on light transmission measurements for 3D absorbed dose imaging in tissue-equivalent materials, has become of great interest in radiotherapy. Since Gore et al. showed in 1984 that the oxidation of ferrous ions to ferric ions still happen even when fixing the ferrous sulphate solution to a gelatine matrix, important efforts have been dedicated to developing and improving real continuous 3D dosimetric systems based on Fricke solution. The purpose of this work is to investigate the capability and suitability of Fricke gel dosimetry for arc therapy irradiations, which may constitute a first step to attempt dedicated dosimetry for Intensity Modulated Arc Therapy. The dosimetric system is mainly composed by Fricke gel dosimeters, suitably shaped in form of thin layers and optically analysed by means of visible light transmission measurements, acquiring sample images just before and after irradiation by means of a commercial flatbed-like scanner. Image acquisition, conversion to matrices and further analysis are accomplished by means of dedicated software, which has been developed in order to include suitable algorithms for optical density difference calculation and corresponding absorbed dose conversion. Also, dedicated Monte Carlo (PENELOPE) subroutines have been adapted in order to achieve accurate simulation of arc therapy irradiation techniques. Applications to 90° arc irradiation by means of a cobalt 60 machine show qualitatively good overall agreement between Fricke gel dosimeters and Monte Carlo simulations. In addition, high quality dose imaging has been achieved by means of computer tomography-like 3D reconstruction algorithms. However, the proposed methods are still being developed and require significant further improvements.

KEYWORDS: External radiotherapy; Fricke gel dosimetry; Monte Carlo simulation; Arc therapy techniques.

1. Introduction

Recent advances in radiation treatment technologies, such as IMRT and stereotactic radiosurgeries, have provided novel and alternative ways for patient treatment, even considering situations that could not be effectively treated via conventional radiation therapy procedures. However, as the treatment technique becomes more complex and irradiation dose increases, the demand for accurate three-dimensional dose distribution mapping also increases.

Conventional methods available for determining the absorbed dose within the irradiated target include ionisation chambers, thermoluminescent dosimeters (TLD), radiochromic films and diode devices. However, they do not possess good tissue equivalence and are lacking the true three-dimensional nature for the measurement. For instance, radiochromic films can satisfactorily measure the dose distribution in the film plane but three-dimensionality is hard to achieve. Furthermore, film dosimeters have shown not negligible dependence on incident energy and orientation. Also, it is possible to employ computer calculations and Monte Carlo simulations for absorbed dose distribution assessment. However, experimental dosimetric techniques require nowadays novel methods in order to achieve accurate dosimetry for treatment planning verification, particularly regarding modern complex irradiation techniques.

Gel dosimetry has generated great interest since its first appearance as a unique technique capable of performing 3D dose mapping for quality assurance of treatment plans in radiotherapy. Nowadays, two main gel systems, polymer gels and Fricke gels, are being investigated worldwide for their possible use.
as 3D dosimeters [1]. Both gel dosimetric systems may be analysed by means of magnetic resonance imaging (MRI) techniques [2]. In a Fricke gel, radiation causes oxidation of ferrous ($\text{Fe}^{2+}$) ions into ferric ($\text{Fe}^{3+}$) ions. The ferric ions are paramagnetic and their presence alters both the spin–spin relaxation rate and the spin–lattice relaxation rate, MRI therefore becoming a useful analysis method. However, the difficulties found regarding the MRI scanner access for routine dosimetry have encouraged the investigation of simpler analysis methods. Actually, strong efforts are being devoted presently to the development and improvement of novel optical analysis techniques, mainly due to their relative low cost and easy use.

Fricke gel dosimetry offers significant advantages regarding elaboration simplicity and non-toxicity, as well as being soft-tissue equivalent over a very large photon energy range including the radiotherapy energies [3]. Since the invention of Fricke gel dosimetry, the method has constantly been improved. Particularly, at present Fricke gel dosimeters suitably shaped in form of thin layers and optically analysed have proved to be a promising tool [4-6] for accurate 3D dosimetry. Therefore, the knowledge of the scanned Fricke gel dosimeter layer performance for conventional arc therapy may contribute significantly to the final goal, namely to investigate the feasibility of the method for Intensity Modulated Arc Therapy (IMAT).

With the rapid development of computer technology, the Monte Carlo technique, currently one of the most accurate methods for dose calculation [7], is becoming more practical for use in radiation therapy treatment planning systems. It may be expected that the outcome of radiation therapy treatment could be improved by using Monte Carlo dose calculation, particularly for modern complex radiotherapy techniques; for this reason Monte Carlo methods are being developed worldwide for treatment planning dose calculations. At present, there are several general-purpose Monte Carlo codes in widespread use for radiation transport simulation, e.g. EGS4, ETRAN/ITS, MCNP, GEANT4 and more recently PENELOPE [8], which has been employed here for the development of dedicated routines.

This study investigates the feasibility and performance of Fricke gel dosimeter layers optically analysed by means of a commercially available flatbed-like scanner for arc therapy techniques, which allow homogeneous irradiation of a target volume lying concavely around an organ at risk with a relatively large inner radius, and being characterized by the gantry rotation during irradiation. Elaborated treatment techniques, like arc therapy, require accurate dosimeters capable of dose accumulation during the whole irradiation.

Due to the fact that the gantry is constantly moving during treatment, tracking single source position during delivery becomes less important and it is difficult to assess in practice [9]. Therefore, it becomes necessary to measure the integrated planned dose in order to obtain an estimate of the final dosimetric accuracy of the treatment. Scanned Fricke gel dosimeter layers appear to be particularly suitable for this application, which may be complemented by means of appropriate dedicated Monte Carlo simulations.

2. Materials and Methods

2.1 Dosimetric system

2.1.1 Elaboration of Fricke gel dosimeter layers

Fricke gel dosimeter layers have been manufactured in chemical laboratory facilities. The exact chemical composition was: 1mM ferrous ammonium sulphate ($\text{Fe(NH}_4\text{)}_2\text{(SO}_4\text{)}_2$), 25mM sulphuric acid ($\text{H}_2\text{SO}_4$), 0.165mM xylene orange (C$_{31}$H$_{27}$N$_2$Na$_5$O$_{13}$S), 3% of final weight gelatine (porcine skin) powder and ultra pure water up to the final weight.

The gelatine powder has been mixed to half of the total water at 45°C, heating during 20 minutes with constant stirring. Separately, the ferrous sulphate, xylene orange, acid and the rest of the water have been mixed (xylene orange infused Fricke solution) and left apart from light exposure. After 20 minutes heating, when the gelatine powder was completely melted, the heating process was stopped monitoring the temperature continuously. When gelatine solution was at 42°C, it has been carefully mixed with the Fricke solution, avoiding excessive bubble formation. Once the Fricke solution was completely melt with the matrix gelatine, it has been injected into properly designed polystyrene containers (Fig. 1).
After injection, the Fricke gel dosimeter layers have been left at room temperature for half an hour and after that they have been kept at low temperature (4-6°C) for at least 12 hours before irradiation.

2.1.2 Characterization of the optical properties of Fricke gel dosimeters and read-out systems

The selected analysis methods consisted on optical techniques. The Fricke gel dosimeter absorbance characterization has been assessed by means of spectrophotometry (Agilent m. 8453); whereas the spatial dose distribution measurements have been carried out with a commercial flatbed-like scanner (Epson Stylus CX3700).

Absorbance measurements have been compared to a non-irradiated sample. For the spectrophotometric analysis, Fricke gel solution has been inserted into standard spectrophotometric vials (40×10×10mm³ cuvettes).

The Fricke gel dosimeter layers have been imaged just before and 30 minutes after irradiation by means of the scanner. A gray level scale has been included in the scanned image in order to perform suitable corrections for eventual voltage changes during scanning.

Due to the not negligible intrinsic fluctuations in the scanner performance, it was necessary to acquire three images (before and after exposure) for each sample.

Dedicated “in-house” software (MatLab supported) has been developed for image detection, analysis, processing and visualization.

Essentially, this suitable program computes pixel-to-pixel optical density differences ($\Delta O D$) between before and after irradiation according to:

$$\Delta O D(k,l) = \log_{10}\left[\frac{GL_{\text{Before}}(k,l)}{GL_{\text{After}}(k,l)}\right]$$

where $GL_{\text{Before}}(k,l)$ and $GL_{\text{After}}(k,l)$ are the corresponding gray level intensities acquired before and after irradiation, respectively, at the $(k,l)$ pixel.

It is well known that absorbed dose is linearly related to the optical density difference, whose proportionality defines the dosimeter dose-response or calibration factor, therefore becoming straightforward to compute the dose distribution from the corresponding $\Delta O D$ after dose-response assessment [5, 6, 10].

2.2 Phantom design and characterization

Due to specific requirements for arc therapy irradiation techniques and aiming to achieve accurate reproducible measurements, a dedicated phantom has been designed, developed and employed to this purpose. Tissue-equivalence is an important condition in dosimetry for phantom design; therefore suitably anatomically shaped certified solid or virtual water would be the best choice. However, due to its significantly low cost and relatively good enough tissue-equivalence, PMMA has been studied and characterized in order to establish accurately its properties. Computed tomography (CT) has been employed for PMMA material mean electronic density ($\rho_e$) assessment. CT scanning enables to determine the Hounsfield index (HI), which is known to be linearly related to sample’s $\rho_e$.
In order to assess the phantom electronic density relative to water, samples of different materials (considered for construction of the designed phantom) have been scanned. Fig. 2 reports a CT slice image, whereas the obtained HI and corresponding electronic densities are summarized in Table 1.

**Figure 2:** CT image of different materials considered for designing the phantom along with the selected regions (dashed lines) for which the HI calculations were performed.

<table>
<thead>
<tr>
<th>Material</th>
<th>Hounsfield Index mean value</th>
<th>Electronic density relative to water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Water</td>
<td>1039.5±0.3</td>
<td>1.00</td>
</tr>
<tr>
<td>PMMA type I</td>
<td>1257±3</td>
<td>1.21±0.03</td>
</tr>
<tr>
<td>PMMA type II</td>
<td>1206±1</td>
<td>1.16±0.01</td>
</tr>
<tr>
<td>Plastic type I</td>
<td>1080±1</td>
<td>1.04±0.01</td>
</tr>
<tr>
<td>Plastic type II</td>
<td>1111±4</td>
<td>1.07±0.04</td>
</tr>
</tbody>
</table>

In view of the obtained results from the CT study, PMMA type II has been selected for the construction of the main phantom layers, whereas PMMA type II has been used for phantom platform, which avoids eventual phantom movement and ensures reproducible positioning. Thin layer shaped dosimeters have been manufactured using plastic type II for the frames and plastic type I for the covering transparent layers.

**Table 1:** Hounsfield Index mean value and corresponding standard deviation for different materials of the designed phantom by means of CT scan.

The designed phantom should be capable to accommodate the Fricke gel dosimeter layers within its volume constituting a tissue-equivalent target. Also, it should be valuable if phantom shape and dimensions could approximate reasonably some part of patient anatomy. In addition, due to the specific irradiation technique involved, rotation symmetry would be convenient.

**Figure 3:** Dedicated designed PMMA phantom for arc therapy containing the Fricke gel dosimeter layers.
Therefore the selection was a cylinder (200mm height and 194mm diameter) constituted by concentric superposition of cylindrical layers of different thickness (20mm, 10mm and 6mm). The 20mm and 10mm thick cylindrical layers are solid, whereas the 6mm thick have suitable cuts in order to allow the dosimeter accommodation, as shown in Fig. 3.

2.3 Monte Carlo subroutines

Monte Carlo subroutines for Fricke gel dosimetry simulation have been developed using the PENELOPE package. Suitable modifications to the sample main program have been introduced with the aim of simulating divergent rectangular collimated and dynamic beams. Simulations should reproduce the $^{60}$Co bomb arc irradiation, therefore incident monoenergetic (1.25MV) $10.0\times10.0\text{cm}^2$ at isocentre field size have been simulated during a “step&shoot” dynamic irradiation, with the source coplanar positioning describing the required arc by means of 1 degree steps. Initially, shorter steps have been also considered, but it can be easily shown that simulation accuracy does not improve significantly, while calculation time increases considerably. Monte Carlo dedicated subroutines allowed introducing the exact geometrical and material properties of the designed phantom, even for the Fricke dosimeter layers inside the phantom, whose chemical composition has been suitably defined in a dedicated material file. Measurement set up has been carefully reproduced during simulation, as sketched in Fig. 4.

Figure 4: Irradiation set up: during arc irradiation measurement (a) and corresponding sketch for MC simulations (b).

2.4 Proposed method for 3D dose imaging

Fricke gel dosimeter layers optically analysed have proved to be suitable for 3D dose imaging [11,12]. Essentially, the proposed method consists on a 3D tomographic-like reconstruction from single layer information. Dedicated algorithms have been developed in order to assess the 3D absorbed dose from the bidimensional distributions corresponding to the single dosimeter layers, whose location inside the designed phantom and relative to the incident beam need to be well known. The method is based on a voxel technique, whose dimensions are determined by the bidimensional pixel discretization along with a third value corresponding to the perpendicular axis. Clearly, the third voxel dimension is limited by the dosimeter layer thickness. Therefore, the 3D dose at the $k,l,m$ voxel ($D(k,l,m)$) assessment can be expressed by:

$$D(k,l,m) = D_m(k,l)$$ (2)

Where $D_m(k,l)$ is the bidimensional dose distribution corresponding to the Fricke gel dosimeter layer placed at the position $m$ respect to the perpendicular axis evaluated at the $k,l$ pixel.
Once the 3D absorbed dose distribution is achieved, the dedicated software allows to perform suitable analysis and visualization, including unwanted fluctuation filtering, two types of smoothing process (“box” or “Gaussian” method), voltage change correction by means of the reference gray level scale, region of interest (ROI) selection and several algorithms for 3D visualization, like isodose surface, projections onto principal planes and suitable intersection with user defined surfaces.

3. Results

3.1 Preliminary characterization of Fricke gel dosimeter optical absorbance

The change in chemical composition is used as an indirect measure of the absorbed dose. The radiation chemical yield \( G \) is defined by:

\[
G(X) = \frac{n(X)}{\varepsilon}
\]

where \( n(X) \) is the mean amount of substance of specific entity \( X \) produced, destroyed or changed by the mean energy imparted \( (\varepsilon) \) to a mass unit of matter. In SI units, \( G \) values have dimensions of mole per kilogram and gray \( (\text{mol kg}^{-1}\text{Gy}^{-1}) \). But it is also common to express \( G \) values in terms of ions/100eV, which is obtained by multiplication by \( 9.64\mu \text{M kg}^{-1}\text{Gy}^{-1} \).

In optically analysed Fricke dosimetry the mean absorbed dose \( (D) \), can be calculated from:

\[
D = \frac{\Delta A}{L \cdot G(X) \cdot \rho \cdot \varepsilon}
\]

where \( \Delta A \) is the increase in absorbance due to irradiation, \( L \) the length of light path in the photometer cell, \( \rho \) the density of the Fricke solution \((1.024\text{gcm}^{-3}\) for standard solution\), \( \varepsilon \) is the molar extinction coefficient and \( G \) the radiation chemical yield.

It is also straightforward to express the Fe\(^{3+}\) yield \( (\Delta[Fe^{3+}] \) as a function of the absorbed dose:

\[
\Delta[Fe^{3+}] = \frac{D \cdot G(Fe^{3+}) \cdot 10 \cdot \rho}{9.64 \cdot 10^6}
\]

As established in (5), it is possible to assess the absorbed dose knowing the Fe\(^{3+}\) yield. Optical methods have shown to be particularly suitable to this aim. Furthermore, when xylenol orange is added to the standard Fricke solution, the absorption peak shifts towards the visible range at above 580nm.

Fricke gel vials have been uniformly irradiated with a cobalt bomb and they have been optically analysed by means of spectrophotometry. The relative absorbances (respect to a non irradiated sample) at different wavelengths have been measured and the results are reported in Fig. 5.

**Figure 5**: Relative absorbance spectra for different absorbed doses.
In view of the obtained results for the spectrophotometric analysis, a suitable dose-response curve has been performed in order to establish the calibration factor. Therefore, absorbances have been integrated in a 20nm range around the peak (580nm). The obtained integration (summation) values have been plotted against the corresponding absorbed dose, as reported in Fig. 6.

**Figure 6:** Fricke gel dosimeter dose-response (black solid squares) and corresponding linear fit (red solid line) by means of spectrophotometry. Fit results: $\Delta A = (1.61 \pm 0.03) \times D + (0.36 \pm 0.23)$, $R^2 = 0.99895$.

3.2 3D dose imaging for arc therapy by means of Fricke gel dosimeter layers

The proposed method has been applied to a typical co-planar 90° arc irradiation by means of a cobalt bomb (Theratron 80, Canada). The planned dose (1200cGy at isocentre) has been delivered during the whole 90° arc, which has been attained with the gantry rotation from 135° up to 225°. Five Fricke gel dosimeter layers have been carefully positioned inside the designed PMMA phantom avoiding air gaps within the irradiated volume. The samples have been placed at selected positions respect to the incident beam axis in order to achieve suitable dose mappings. Single layers, which provide bidimensional information (averaged within the 4mm thick sensitive material layer) have been used to assess, by means of dedicated cubic spline algorithms, the bidimensional dose distributions at intermediate positions between dosimeters. In addition, beam symmetry respect to central axis has been assumed in order to use twice each measurement layer (except the central one), therefore completing a suitable 9-slices sequence as shown in Fig. 7.

**Figure 7:** Tomographic-like sequence for 3D dose imaging.
Dosimeters have been imaged following the procedure mentioned above in 2.1.2. Once the slice sequence was assessed, it was straightforward to employ the “in-house” software applying the dedicated algorithms for 3D reconstruction.

**Figure 8:** Fricke gel dosimeter 3D dose distribution by means of tomographic-like reconstruction: projection on principal planes (a) and three (80% in green, 90% in blue and 100% in red) isodose surfaces (b). (The $z=0$ plane corresponds to the central plane, *i.e.* gantry angle 180°).

![Figure 8](image)

**Figure 9:** Monte Carlo 3D dose distribution by means of tomographic-like reconstruction: projection on principal planes (a) and three (80% in green, 90% in blue and 100% in red) isodose surfaces (b). (The $z=0$ plane corresponds to the central plane, *i.e.* gantry angle 180°).

![Figure 9](image)

Fig. 8 reports the obtained 3D dose distribution visualizing projections onto principal Cartesian planes at the isocentre and reconstructing isodose surfaces corresponding to normalization at the isocentre. With the aim of performing analogue procedure also for the Monte Carlo simulations, suitable adaptations have been introduced in order to produce outputs containing bidimensional information averaged on 4mm thick layers in correspondence to the simulated Fricke gel dosimeters. The dedicated Monte Carlo calculation has been performed by means of simulating $10^7$ primary tracks, uniformly subdivided in 90 different source positions describing the 90° arc (1° step length). Therefore, the same 3D reconstruction and visualization algorithms become applicable to the MC calculation. The obtained results for the 3D reconstruction of the simulated 90° arc irradiation are shown in Fig. 9.

Also, central layers have been chosen for bidimensional qualitative comparison, as reported in Fig. 10. In order to compare quantitatively, the first attempt was to perform vertical (longitudinal) and horizontal (transversal) profile comparison for the central layer distributions. The obtained results are reported in Fig. 11.
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**Figure 11:** Profile comparisons between Fricke gel dosimeters (red solid circles) and Monte Carlo simulations (black open triangles) at the central layer corresponding to the 90° arc irradiation: longitudinal profiles (a) and transversal profiles (b).

4. Discussion and conclusions

As expected, the preliminary characterization of the xylenol orange infused Fricke gel dosimeters have shown a linear response for optical analysis methods, even within the visible spectrum range. Therefore, in order to achieve absorbed dose spatial resolution, suitable thin layers have been employed, opposite to the standard spectrophotometric cuvette vials, only useful for uniform irradiation measurements. The visible light transmission analysis method, based on the commercially flatbed-like scanner has shown to be capable for dose imaging by means of Fricke gel dosimeter layers.

Qualitative comparisons between Fricke gel dosimeters and Monte Carlo simulations show overall reasonable agreement, presenting maximum absorbed doses towards the same regions and similar isodose surfaces, neglecting the shapes.

On the other hand, the obtained results for the 3D dose reconstruction and profile comparisons between Fricke gel dosimeter layers and adapted Monte Carlo simulations evidence significant quantitative disagreements, mainly due to intrinsic limitations about geometrical characterization of the incident beam in the simulation as well as eventual sensitivity differences between piled up dosimeters. However, it is possible to introduce suitable mechanisms in order to avoid or minimize
those unwanted effects by means of dedicated kernels for incident beam definition and performing a (uniform) pre-irradiation process devoted to establish the corresponding sensitivity for each sample. It should be emphasised that the here proposed novel methods (scanned Fricke gel dosimeter layers and dedicated Monte Carlo simulations) were positively capable of 3D dose imaging. In addition, the “in-house” software has proved to be a suitable, versatile and user-friendly tool for 3D dose imaging. Due to the feasibility of the proposed method for conventional arc therapy, it may constitute a promising tool for modern techniques, like 3D IMAT. However, the present method requires significant improvement in order to be applied for accurate dose verification.

Acknowledgements

Authors are particularly grateful to Instituto Privado de Radioterapia Oncológica (Córdoba, Argentina) for providing access to cobalt bomb and TAC facilities, as well as for the valuable contributions and support from Lic. D. Venencia.

REFERENCES