Characterization of radiochromic PVA-GTA Fricke gels for dosimetry in X-rays external radiation therapy

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Abstract

Quality assurance procedures required in the modern radiotherapy would greatly benefit by the development of tissue equivalent dosimeters able of rendering 3D dose profiles with high spatial resolution. In this scenario, Fricke gel (FG) dosimeters could be good candidates, but some limitations have restricted their interest in clinical practice. Recently, formulations based on gel matrices of poly(vinyl-alcohol) (PVA) chemically cross-linked with glutaraldehyde (GTA) have shown improvements as compared to FGs with natural matrices. Purpose of this study is the characterization of the dosimetric properties of radiochromic PVA-GTA Fricke gel dosimeter by means of absorption spectroscopy measurements.

Xylenol Orange Fricke gel dosimeters, prepared in spectrophotometry cuvettes using 9.1 w/w of Mowiol®-PVA and 26.5 mM of GTA, were uniformly irradiated with a ^{137}Cs source and with 6 and 15 MV X-rays generated by a medical linear accelerator.

UV-VIS absorbance spectra collected at consecutive times post-irradiation showed that a time of approximately fifteen minutes is sufficient to reach a stable value of the absorbance, indicating the achievement of a chemical equilibrium in the complexation processes between Fe^{3+} and XO.

The analysis of the change of the absorbance spectra shape with the cumulated dose demonstrated that a linear dose-response curve of PVA-GTA Fricke gel dosimeters is obtained in the entire investigated dose interval 0.5-15 Gy by choosing properly the wavelength used for the absorbance measurements.

Furthermore, PVA-GTA Fricke gel dosimeters proved to be nearly water- and tissue-equivalent and characterized by a response independent on the energies and dose rates in the investigated intervals. These findings suggested that PVA-GTA Fricke gels are promising tools for dosimetry applications in X-rays external radiation therapy.

Keywords

Fricke gel, poly(vinyl alcohol), glutaraldehyde, tissue equivalence, dosimetry

1. Introduction

Modulated modern radiation therapy would greatly gain from the development of reliable systems for three dimensional dose mapping with the level of accuracy and precision required for quality assurance procedures [1,2]. Several approaches currently studied are based on the imaging of radiation-induced chemical changes of a tracer compound suspended in a continuous medium, such as a gel, rigid or deformable plastics, or inelastic material [3]. This paper is focused on Fricke gel (FG) dosimetry [4]. In Fricke gel dosimeters, ionizing radiation induces radiolysis of water, followed by well-established reactions oxidizing ferrous ions (Fe^{2+}) to ferric ions (Fe^{3+}), with a conversion yield proportional to the absorbed dose (up to saturation) [5].

The distribution of the resulting Fe^{3+} is used to produce a 3D image of the absorbed dose by Magnetic Resonance Imaging (MRI) [6-8] or by optical imaging, provided that a suitable metallic-ion indicator is employed [9-12]. The most used metallic-ion indicator is Xylenol Orange (XO). XO molecules absorb light around 430 nm. After irradiation, the generated Fe^{3+} ions are chelated by XO and the resulting complexes give light absorption above 500 nm. Therefore, it is possible to quantify the dose absorbed by Fricke gel dosimeters by evaluating the variation of their absorbance [5].

Unfortunately, poor stability of Fricke gels due to the diffusion of ferric ions within natural gel matrices like gelatine and agarose, imposes constraints upon the time between the irradiation and read-out process. [13].

Among the various strategies proposed for limiting this drawback [14-16], recently, formulations based on gel matrices of poly(vinyl-alcohol) (PVA) chemically cross-linked with glutaraldehyde (GTA) have shown improvements as compared to FGs with natural matrices [17,18]. Accordingly, the interest toward PVA-GTA Fricke gel dosimetry is gaining importance, as attested by the increasing literature about this topic [19-27].

In this manuscript, driven by the results shown in *Marini et al.* [19], additional studies concerning the properties of PVA-GTA Fricke gel dosimeters have been carried out. In particular, after the analysis of the water- and tissue-equivalence of this gel matrix, a study of the time-formation of the dosimetry signal in PVA-GTA Fricke gels due to Fe^{3+} ions production and complexation was carried out. Afterwards, absorbance spectral analyses of PVA-GTA Fricke gel dosimeters were performed to characterize their response as a function of dose, dose rate and energy, in the typical intervals of interest for X-rays external radiation therapy applications.

2. Materials and methods

2.1 PVA-GTA-Fricke gel dosimeters preparation

The preparation of PVA-GTA Fricke gel dosimeters was carried out considering the procedure described in [19], but using a different PVA. The PVA Mowiol®18-88 (molecular weight 130000 Da; degree of hydrolysis 86.7-88.7%, Sigma Aldrich) was selected for this study because of its high purity [28] and favorable properties. Indeed, complete dissolution of Mowiol®18-88 in water can be easily obtained in approximately 40 minutes at 70°C, without the use of an autoclave [19] or open vessel microwave digestion [20] as required for other PVA compounds.

All batches of Fricke gel dosimeters were prepared using ultrapure water obtained by a water purification system (Milli-Q® Direct, EMD Millipore, Germany) and analytical grade reagents: 0.5 mM ferrous ammonium sulfate hexahydrate (Carlo Erba); 25.0 mM sulfuric acid (Suprapur®, Sigma Aldrich); 26.5 mM of glutaraldehyde (GTA, Sigma Aldrich) and 0.165 mM Xylenol Orange tetrasodium salt (XO) (Riedel-de Haën). PVA solution (final concentration 9.1 % w/w) was prepared by dissolving dry PVA in ultrapure water (80% of the total water volume, resistivity 18.2 MΩ·cm). Initially, the incorporation of PVA in water took place at room temperatures under rapid stirring (~500 rpm) for about 5 minutes to avoid the formation of aggregates of polymer granules. Next, the temperature was raised up to 70 °C with a progressive reduction of the stirring speed (~150 rpm) to limit the incorporation of oxygen into the solution. After the complete dissolution, the PVA solution was left to cool down at room temperature.

Afterwards, Fricke-XO solution was prepared by adding sulfuric acid (two-thirds of the total amount), ferrous ammonium sulfate and Xylenol Orange sodium-salt in this order into water (10% of the total water volume) with moderate stirring. Finally, GTA solution was prepared by adding GTA and the remaining sulfuric acid into water (the remaining 10% of the total water volume).

FG dosimeters were obtained by slowly incorporating Fricke solution into the PVA solution and, subsequently by adding the GTA solution. After one minute of gentle stirring to achieve homogeneity, the final solution was poured into poly(methyl methacrylate) cuvettes (10 mm optical path length) closed with polypropylene cuvette stoppers and sealed with Parafilm™. After the complete gelation, all the Fricke gel dosimeters were kept

refrigerated at the controlled temperature of 6°C for one day and brought back to room temperature 1 hour before the irradiations and spectrophotometric measurements.

2.2 Radiological water- and tissue-equivalence

In order to verify the radiological water-equivalence [29] of the PVA-GTA-gels, the values of density, mass energy absorption coefficients for photons and stopping power for electrons were assessed and compared with those of water and soft tissue (ICRU 44).

The PVA-GTA-gels density was measured at room temperature (25°C) by using calibrated vessels with a capillary neck and an analytical balance with precision of 0.1 mg. The uncertainty of density was obtained as the standard error of the mean value over ten different samples.

The values of mass energy absorption coefficient and stopping power of PVA-GTA-gels, water and soft tissue were calculated as a weighted average of mass energy absorption coefficients and stopping powers of the chemical element constituents, respectively [30]. The chemical formulas and elemental compositions of the media of interest, reported in Table 1, were used for the calculations, together with the National Institute of Standards and Technology (NIST) physical reference data [31].

Table 1 - Elemental compositions (% weight fractions) of water, soft tissue (ICRU 44), GTA, PVA, and PVA-GTA-gels.

Materials	Chemical Formulas	w_H (%)	w_O (%)	w_N (%)	w_C (%)
Water	H_2O	11.111	88.889	-	-
Soft tissue (ICRU 44)	-	10.117	76.183	2.600	11.100
GTA	$C_5H_8O_2$	8.000	32.000	-	60.000
PVA	C_2H_4O	9.091	36.364	-	54.545
PVA-GTA-gels	-	10.920	83.977	-	5.103

2.3 Samples irradiation

Preliminary irradiations of PVA-GTA Fricke gel dosimeters were performed with an IBL 437 C ^{137}Cs blood irradiator at the "Fondazione IRCCS Istituto Nazionale dei Tumori" of Milano (Italy). One FG dosimeter

inside a cuvette was placed in the center of the irradiation canister to guarantee dose uniformity and irradiated to a dose of approximately 5 Gy.

Afterwards, the irradiations were carried out in a simple geometry with 6 MV and 15 MV X-rays beams generated by a linear accelerator (LINAC) Varian Clinac-2100 (Varian Medical Systems, CA, USA) at "ASST Grande Ospedale Metropolitano Niguarda" of Milano (Italy).

The LINAC was calibrated following the IAEA TRS-398 code of practice (IAEA 2000) [32] using a Farmer type PTW Freiburg 30013 ionization chamber (IC) (PTW, Freiburg GmbH, Germany). For the calibration, the IC was placed in a water phantom at a depth of 10 cm, using as reference conditions a source surface distance (SSD) of 100 cm and a field size 10 cm x 10 cm, for all the X-rays beams energies.

In all the experiments, at least three samples of the same batch were irradiated simultaneously. The samples were placed horizontally within a solid water slab phantom (RW3, PTW Freiburg, Goettingen, slab dimensions: 30 cm x 30 cm x 1cm) with the central plane of the cuvettes at a depth of 10 cm from the phantom surface. All the irradiations were performed using the source detector distance (SDD) of 100 cm (*i.e.* distance between the source and the central plane of the cuvettes). Uniformity of dose within the cuvette volumes was achieved by using a 20 cm × 20 cm field size at the position of the dosimeters and by delivering the total dose with two parallel-opposed beams. A sketch (not in scale) of the irradiation set-up with additional details is shown in Figure 1.

2.4 Absorbance Measurements

In order to monitor the formation of the absorbance signal due to the Fe^{3+}-XO complexation occurring during the first minutes after the irradiation, preliminary absorbance measurements were carried out in situ by using a compact thermally cooled UV-VIS spectrometer (Prime X, B&WTec Inc, USA). The sample, inside a cuvette holder (BCH103A, B&WTec Inc, USA), was illuminated by a halogen lamp. Silica optical fibers were used as light-guides between the various optical components (i.e. the lamp, the sample holder and the compact spectrometer). Absorbance spectrum of one sample, in the interval 460-660 nm, was collected before the irradiation with the blood irradiator. Afterwards, absorbance spectra were collected at consecutive times post-irradiation, starting from 40 seconds up to 75 minutes, in about 1.25 second steps.

For the following dosimetric characterization, the absorbance measurements were performed in laboratory using a Cary 100 UV-Vis spectrophotometer (Agilent Technologies, Santa Clara, CA, USA) in the wavelength interval 360-720 nm. Since in the conventional gel dosimetry, the absorbed dose is correlated to absorbance variation of the dosimeters following irradiation, absorbance spectra were acquired using one un-irradiated sample for each batch as reference sample. The reference sample was always kept near the samples to be analyzed in order to reproduce the same effect of auto-oxidation inside the dosimeters. The measurements were performed about one hour after the irradiation [19].

2.5 Dosimetric characterization

The dose response and energy dependence of the PVA-GTA Fricke gel dosimeters were studied by irradiating the samples to increasing doses in the interval 0.5-15.0 Gy, with 6 MV and 15 MV X-rays, using dose rates of 208.5 cGy/min and 232.8 cGy/min, respectively. Dose-response curves for the two energies were derived by plotting the values of absorbance measured at different wavelengths, versus the absorbed dose.

Dose rate dependence was studied by irradiating the dosimeters to a dose of 6.0 Gy with 6 MV X-rays, using different dose rates in the interval 69.5-347.5 cGy/min, by changing the LINAC pulse frequency in the range from 80 to 400 Monitor Units (MU)/min.

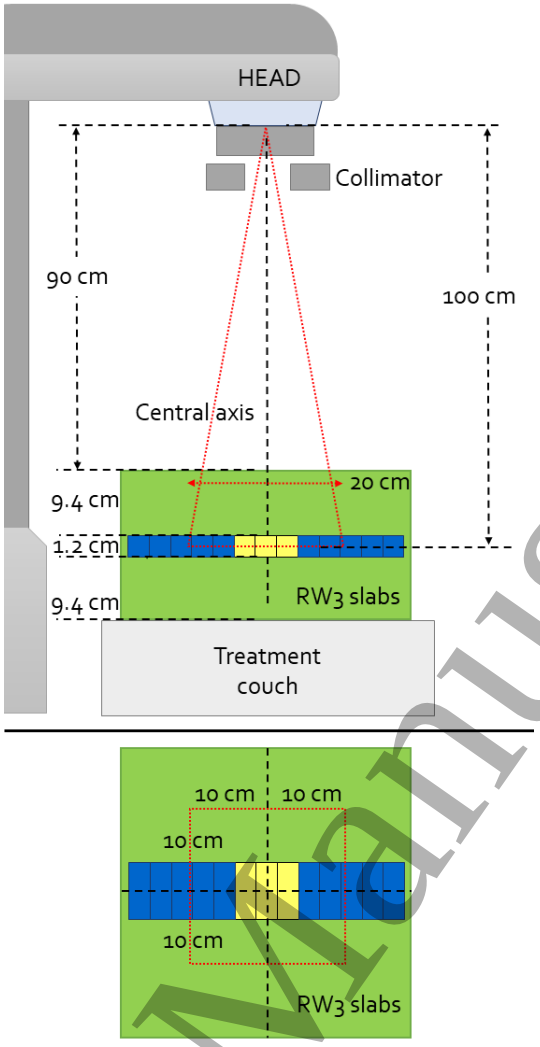

Fig. 1 - Lateral and top views of the setup used for the irradiation of PVA-GTA Fricke gel dosimeters (not in scale). Solid water (RW3) phantom in green; cuvettes filled with Fricke gel dosimeters in light yellow. The blue rectangles are additional cuvettes filled with ultrapure water used to ensure density uniformity over the entire irradiated volume. The red lines indicate the irradiation field.

3 Results and discussions

3.1 Radiological water- and tissue-equivalence

The density of PVA-GTA gels was assessed equal to 1.031 ± 0.005 g/cm^3, i.e. slightly higher than water and soft tissue density values (1.000 g/cm^3 – [31]).

Figure 2 shows the comparison between the mass energy absorption coefficients for photons of these media. Similarly, Figure 3 shows the mass collision stopping power for electrons related to gels, water, and soft tissue. The differences between the mass energy absorption coefficients for photons of PVA-GTA gels, water, and soft tissue are lower than 1.5% in the energy interval extending from 0.1 MeV to 10 MeV (Figure 2), i.e. the energy interval of interest in X-rays external radiation therapy. At lower energies the differences increase, with a maximum deviation between gels and soft tissue of approximately 7.0% around 0.03 MeV.

In the energy interval 0.1-10 MeV, the differences between the mass collision stopping power for electrons of PVA-GTA gels, water and soft tissue are lower than 1.0%. Slightly higher differences, within 1.6%, were observed between the mass collision stopping power of the gels and soft tissue in the interval 10-100 MeV.

As reasonably expected considering the chemical composition of PVA-GTA gels, the results of Figure 2 and 3 confirmed the nearly radiological water- and tissue-equivalence of the gel matrix in the energy interval of interest in X-rays external radiation therapy.

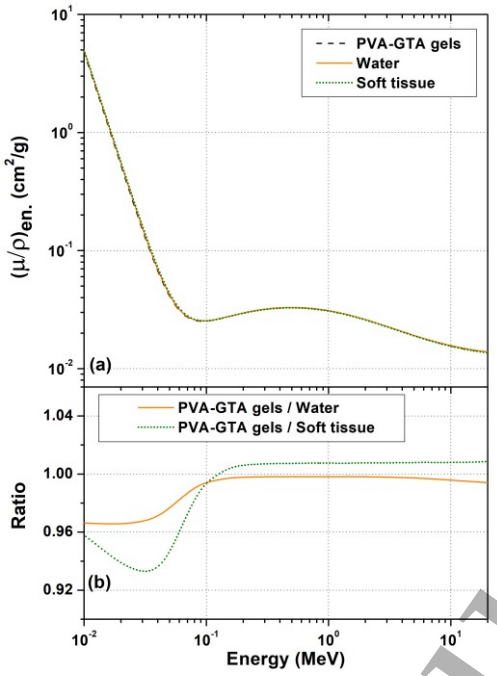

Fig. 2 - (a) Mass energy absorption coefficients for photons of PVA-GTA gels (black dashed line) water (orange solid line), and soft tissue (green dotted line) as a function of energy. (b) Ratio between mass energy absorption coefficients for photons of PVA-GTA gels and water (orange solid line), and ratio between mass energy absorption coefficients for photons of PVA-GTA gels and soft tissue (green dotted line).

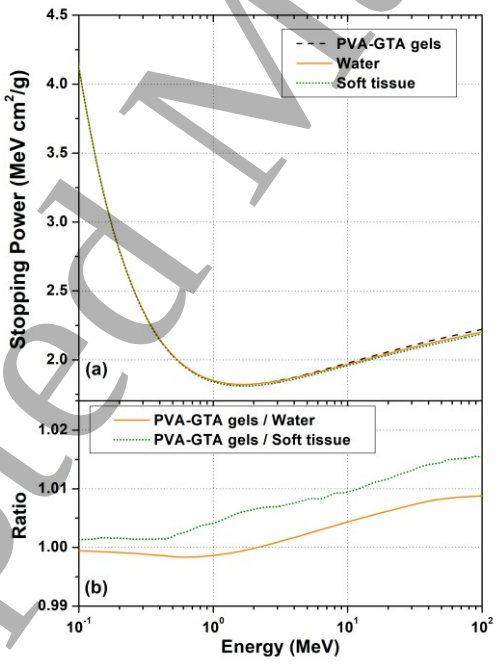

Fig. 3 - (a) Mass collision stopping power for electron of PVA-GTA gels (black dashed line) water (orange solid line), and soft tissue (green dotted line) as a function of energy. (b) Ratio between mass collision collisional stopping power of PVA-GTA gels and water (orange solid line), and ratio between mass collision collisional stopping power of PVA-GTA gels and soft tissue (green dots line).

3.2 Absorption spectra measurements

Figure 4 shows the time course the absorbance at the wavelength value of 585 nm (*i.e.* the wavelength generally used for optical analysis of Fricke gel dosimeters [5,11,12]) related to Fe^{3+}-XO complexation process monitored in the first 75 minutes after the irradiation of the PVA-GTA Fricke gel sample.

After the first acquisition, performed 40 seconds post-irradiation, the absorbance increased rapidly and reached saturation in less than 15 minutes, indicating the achievement of the chemical equilibrium of XO-Fe^{3+} complexation.

These results obtained with the PVA-GTA matrix are in line with previous data available in the literature and related to Fricke gel dosimeter made with natural gel matrices irradiated with MV X-rays used in radiation therapy [33] and with a Co-60 source [34].

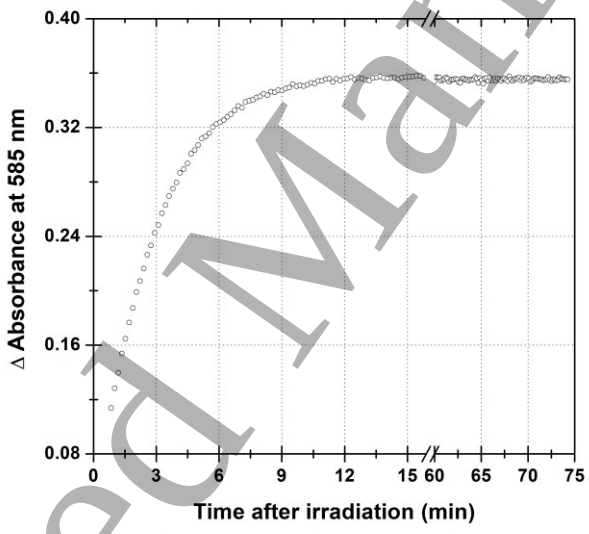

Fig. 4 – Absorbance over time at the wavelength of 585 nm measured in PVA-GTA Fricke gel dosimeters after irradiation with the ^{137}Cs sources.

The typical absorbance spectra of PVA-GTA Fricke gel dosimeters irradiated at various doses up to 15.0 Gy with 6 MV X-rays, acquired after the achievement of chemical equilibrium in the complexation processes between Fe^{3+} and XO, are shown in Figure 5.

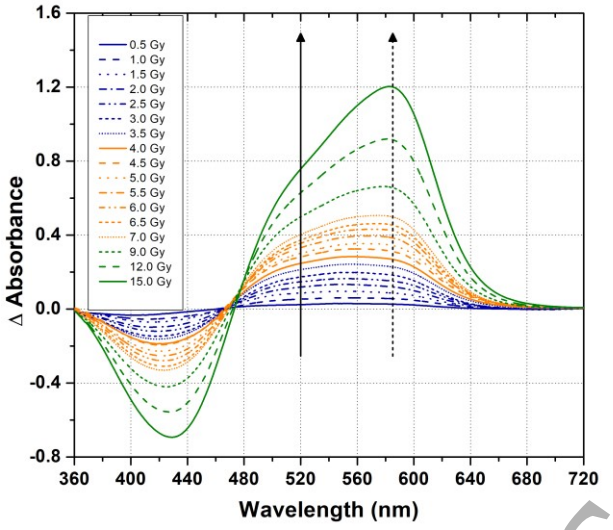

Fig. 5 – Absorbance spectra of PVA-GTA gel dosimeters irradiated to increasing doses (up to 15.0 Gy). The solid and dashed arrows are related to the main absorbance peaks (520 nm and 585 nm) respectively. An un-irradiated sample was used as reference.

The absorbance spectra of the studied gel dosimeters were characterized by a broad absorption peak in the wavelength region between 500 nm and 600 nm. The spectra show a main absorption around 585 nm (dashed black arrow in Figure 5), with a shoulder extending in the lower wavelength region (solid black arrow in Figure 5).

As expected, the absorbance of PVA-GTA Fricke gel dosimeters increased with increasing the absorbed dose in the wavelength region between 480 nm and 660 nm. Similarly, a decrease of the absorbance around 430 nm with increasing the radiation dose occurred. Such features characterized also the traditional FG dosimeters prepared with natural gel matrices [5], and confirm that the use of poly(vinyl-alcohol) cross-linked with glutaraldehyde does not modify either the operating principle of the dosimeters or the optical properties of XO-Fe^{3+} complexation.

Furthermore, in the investigated gels the shape of the absorbance spectra changed with varying the radiation dose, as pointed out in Figure 6 where selected spectra of Figure 5 were normalized dividing each spectrum for the absorbed dose.

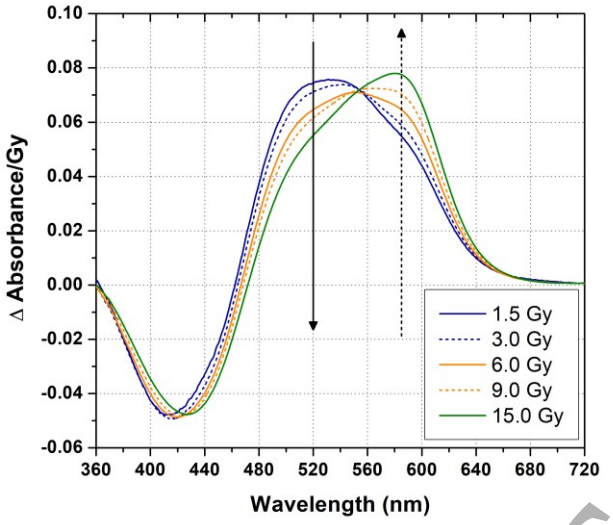

Fig. 6 - Example of absorbance spectra of PVA-GTA gel dosimeters, divided by the absorbed dose. The solid and dashed arrows are related to the main absorbance peaks (520 nm and 585 nm) respectively. An un-irradiated sample was used as reference.

The normalized absorbance spectra of each dosimeter showed an isosbestic point around 555 nm, suggesting the presence of two XO-Fe^{3+} complexes, giving two absorption peaks of which the measured one is the convolution [35,36]. The presence of the isosbestic point (Figure 6) is a demonstration of the balance between two events.

As a result, the normalized absorbance around 585 nm increased with the dose (dashed black arrow in Figure 6) whereas a decrease around 520 nm can be observed in the spectra of Figure 6 (solid black arrow in Figure 6).

Such behavior proved to have an important effect in the correct evaluation of the dose-response curve of the PVA-GTA Fricke gel dosimeters, as pointed out in the following section.

3.3 Dose response curves

Figure 7 shows the dose response curve of the PVA-GTA Fricke gel dosimeters irradiated at various doses in the interval 0.5-15.0 Gy with 6 MV X-rays, obtained by measuring the absorbance at 585 nm (i.e. the wavelength with the maximum absorbance value and generally used in the literature for such analyses). For doses above 5.0 Gy a linear behavior (R^2=0.99982, solid orange line in Figure 7) was observed with a slope of the fitted straight line equal to 0.081±0.001 Gy^{-1} through 10 mm of optical path. Such finding is in agreement

with the results recently published by *Marini et al.* [19] about the dose response curve of similar gel dosimeters studied in the range 5-30 Gy using 6 MV X-rays. Here, in order to investigate the dosimetric features of PVA-GTA Fricke gels for doses below 5 Gy, irradiations were performed from 0.50 Gy to 2.00 Gy in 0.25 Gy steps, and from 2.00 Gy to 7.00 Gy in 0.50 Gy steps.

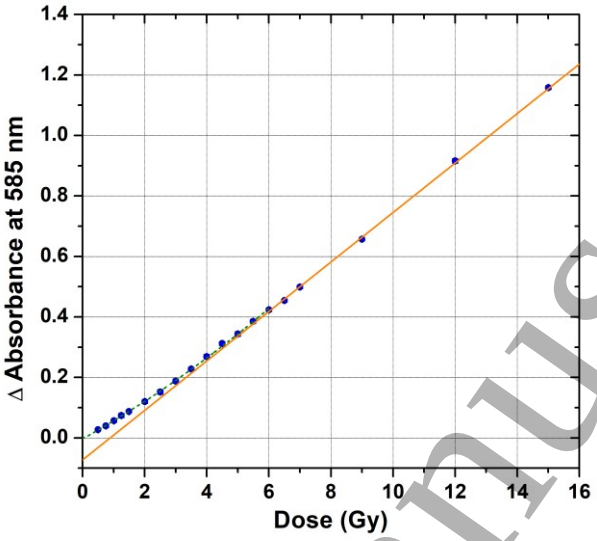

Fig. 7 - Absorbance at 585 nm of PVA-GTA Fricke gel irradiated at various doses in the interval 0.5-15.0 Gy using 6 MV X-rays. Each point is the mean of absorbance data from at least three samples at 585 nm. Error bars (1 standard deviation) are smaller than the plot symbols. The solid orange line is the linear fit to the experimental data between 5.0 Gy and 15.0 Gy. The dashed green curve is a parabolic fit to the experimental data between 0.5 and 6.0 Gy.

Below 5.0 Gy the results revealed a dose response curve different from the linear one obtained by considering only doses above 5.0 Gy. In fact, in the dose interval 0.5 Gy-6.0 Gy, a fit of the quadratic function to the experimental data $y=A+xB+x^2C$ (with A=-0.0016±0.0013, B=0.056±0.002 and C=0.023±0.001) provided a satisfactory description of the dose-response curve (R^2=0.99976, dashed green curve in Figure 7).

It must be pointed that the signal of an ideal dosimeter should be linearly proportional to the absorbed dose over the entire dose range of interest. As a matter of principle, in PVA-GTA Fricke gel dosimeters such condition can be obtained by integrating the absorbance over the broad spectral interval 480-680 nm, as shown in Figure 8. Indeed, the fitted straight line in Figure 8 (slope = 8.87±0.05 Gy^{-1}, intercept = -0.05±0.30) provided a good (R^2=0.9998) description of the experimental data over the entire dose interval 0.5-15 Gy. However, this approach is not practical for measuring 3D images of the absorbed dose distributions in gel dosimeters. Indeed, optical computed tomography scanners able to reconstruct 3D optical attenuation maps of the gel, making use

of lasers or LEDs as light sources [37,38], do not cover the whole absorbance spectral interval required to guarantee the complete linear dose-response.

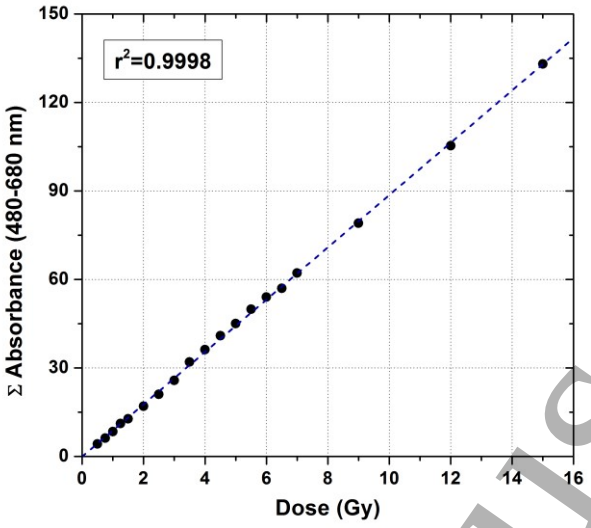

Fig. 8 – Integrated absorbance from 480 nm to 680 nm of PVA-GTA Fricke gel irradiated at dose interval 0.5-15.0 Gy using 6 MV X-rays. Each point is the mean of absorbance data from at least three samples. Error bars (1 standard deviation) are smaller than the plot symbols. The dashed blue line is the linear fit to the experimental data.

This limitation can be easily overcome by exploiting the observed change of the absorbance spectra shape with the radiation dose (Figure 6), and reconstructing the dose-response curve using the absorbance values measured at the wavelength of the isosbestic point. Indeed, the dose-response curve obtained by using the absorbance values at 555 nm showed a linear trend over the entire investigated dose interval, as illustrated in Figure 9.

Figure 9a shows the experimental data together with the linear fit. The random pattern of the residual plot (Figure 9b) together with the R^2 value (0.99987) demonstrate the reliability of the linear model. The values of -0.004 ± 0.003 and 0.071±0.002 Gy^{-1} were found for the intercept and the slope of the fitted straight line, respectively. It can be noted that the intercept is comparable with the zero value, demonstrating the direct proportionality between the absorbance and the absorbed dose. Furthermore, the slope of the linear regression indicated a sensitivity of the studied PVA-GTA Fricke gel dosimeters higher than that previously obtained in gelatine-based Fricke gel dosimeters using the same wavelength for the analysis (0.058 ± 0.001 Gy^{-1}) [15].

Figure 9c shows the relative standard deviation (RSE, *i.e.* the ratio of the standard deviation to the mean) *vs* the absorbed dose. The RSE value decreased with increasing the dose: for doses higher than 6.0 Gy, the RSE

was lower than 1.5%. However, for doses lower than 2.0 Gy the RSE was higher than 4.5%. These data suggest that, currently, the investigated PVA-GTA FG are mostly promising in quality assurance procedures of hypofractionated radiation treatments, i.e. treatments characterized by a dose per fraction much higher than 2 Gy. In fact, these treatments typically require suitable patient specific quality assurance practices. Conversely, further improvements in the dosimetric performances of the PVA-GTA FG dosimeters are still required for their use in conventional treatments regimes (2 Gy per fraction).

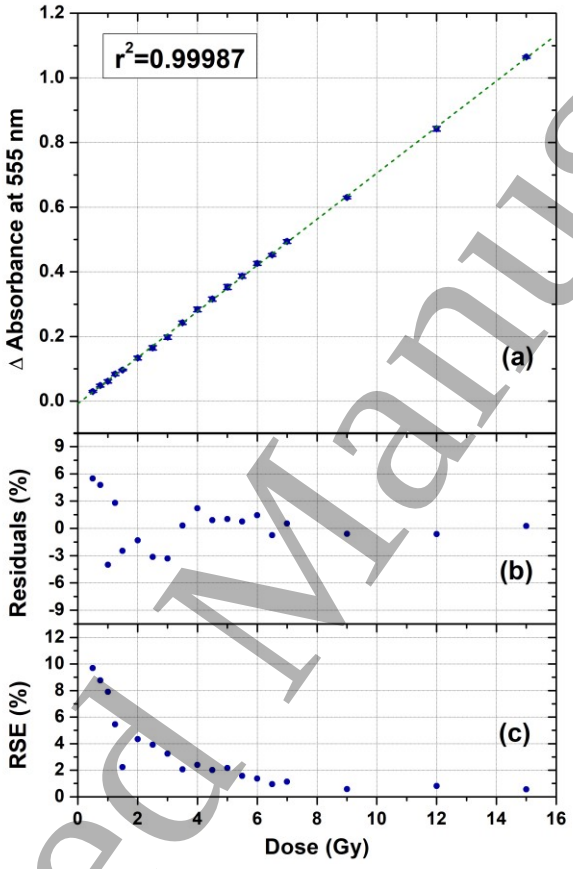

Fig. 9 - (a) Absorbance at 555 nm of PVA-GTA Fricke gel irradiated at various doses in the interval 0.5-15 Gy using 6 MV photon beams. Each point is the mean of measurements at 555 nm on at least three samples. Error bars (1 standard deviation) are smaller than the plot symbols. The dashed green line is the linear fit to the experimental data. (b) Residual plot (c) Relative Standard Errors (RSE) *vs* absorbed dose.

3.4 Dose-rate and energy dependence

The dose-response curves of the PVA-GTA Fricke gel dosimeters irradiated with 6 MV and 15 MV X-rays were evaluated from the absorbance spectra at main absorption peak (585 nm) and at the isosbestic absorbance point (555 nm). The results are shown in Figure 10. No differences between the dose-response curve at 6 MV and 15 MV were observed, independently of the wavelength used for the absorbance evaluation. As previously

pointed out, linearity over the entire dose interval was achieved by considering the absorbance values at 555 nm, for both the investigated energies.

Figure 11 shows typical absorbance spectra of PVA-GTA Fricke gel dosimeters irradiated to the same dose of 6 Gy with 6 MV X-rays using different dose-rates in the interval 69.5-347.5 cGy/min. The differences among the absorbance values were lower than 1.5% over the entire spectral region, *i.e.* of the same order of magnitude of the observed intra-batch sample variability (Figure 9c).

Therefore, it can be concluded that the PVA-GTA Fricke gel dosimeters maintain the desired properties of independence of the response of the dose rate and of radiation energy characterizing the Fricke gel dosimeters based on traditional gelling agents [33,39-41], at least in the investigated intervals.

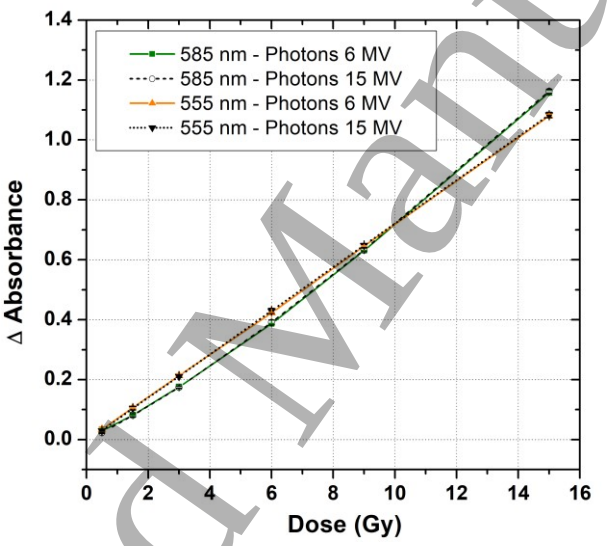

Fig. 10 – Absorbance at 585 nm and 555 nm of PVA-GTA Fricke gel irradiated at various doses in the interval 0.5-15.0 Gy using 6 MV and 15 MV X-rays. Each point is the mean of measurements on at least three samples. Error bars (1 standard deviation) are smaller than the plot symbols. Lines connecting points are for guiding the eye.

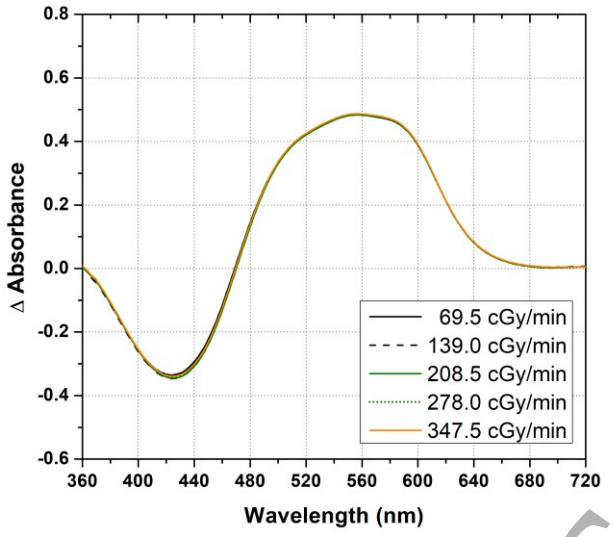

Fig. 11 – Absorbance spectra of PVA-GTA gel dosimeters irradiated at 6.0 Gy using 6 MV X-rays, varying the dose rate from 69.5 cGy/min to 347.5 cGy/min. An un-irradiated sample was used as reference.

4. Conclusions

The dosimetric properties of Fricke gel dosimeters based on poly(vinyl alcohol) as gelling agent and glutaraldehyde as cross-linker were studied by spectrophotometry. The results suggested that a time of approximately fifteen minutes after the irradiation is sufficient to reach a stable value of the absorbance, indicating the achievement of a chemical equilibrium in the complexation processes between Fe^{3+} and XO.

The analysis of the change of the absorbance spectra shape with the cumulated dose demonstrated that a linear dose-response curve of PVA-GTA Fricke gel dosimeters can be obtained in the entire investigated dose interval 0.5-15.0 Gy by optimizing the choice of wavelength to be used for the absorbance measurements. This finding could be exploited for the improvement of the optical computed tomography scanners used for 3D dose mapping in gel dosimeters, alternative to the MRI.

As expected because of their chemical composition, PVA-GTA Fricke gel dosimeters proved to be nearly water- and tissue-equivalent and characterized by a response independent of the energies and dose rates in the investigated intervals.

Such features, together with the low Fe^{3+} diffusion rate characterizing the PVA-GTA gel networks, [19-21], make these dosimeters promising tools in X-rays external radiation therapy applications. Further studies are currently in progress with the aim to improve the precision of the optical response of PVA-GTA FG dosimeters

irradiated to low doses (*i.e.* < 2 Gy), element required for the possible transition of these systems in the clinical practice.

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