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Optical response of the FXG solution to different phantom materials

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ABSTRACT

The purpose of this work is to evaluate the performance of the Fricke xylenol gel (FXG) solution developed at IPEN, prepared with 270 Bloom gelatine (made in Brazil), for clinical electron beams to the reference depth, using different phantom materials. The colour change, optical absorption spectra, intra and inter-batches reproducibility, dose-response, lower detection limit, energy and dose rate dependent response and response uniformity were studied. The excellent results obtained indicate the viability of employing this solution in 2D spectrophotometric dosimetry (could be extended to 3D MRI dosimetry) to be applied in quality assurance for clinical radiotherapy treatment planning of superficial tumours being treated with clinical electron beams.

1. Introduction

In order to obtain the quality control in radiotherapy treatments using clinical electron beams, measurements such as absorbed dose determination are performed and the recommended reference medium for this purpose is water (Andreo et al., 2004). However, when problems such as need of waterproofing sheaths to ionization chambers, other phantom materials (plastic phantoms) can be used (Williams and Thwaites, 1993). The purpose of this work is to evaluate the performance of the Fricke xylenol gel (FXG) solution developed at IPEN, prepared with 270 Bloom gelatine (made in Brazil), for clinical electron beams to the reference depth, using different phantom materials such as water and plastic [virtual water and polymethylmethacrylate (PMMA)] phantoms (Andreo et al., 2004).

2. Materials and methods

2.1. FXG solution preparation

The Fricke gel solutions were prepared (Olsson et al., 1989) using 5% by weight of 270 Bloom gelatine from porcine skin, ultra-pure water, 50 mM sulphuric acid (H_2SO_4), 1 mM sodium chloride (NaCl), 1 mM ferrous ammonium sulphate hexahydrate or Mohr's salt [$Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$] and 0.1 mM xylenol orange ferric ions indicator ($C_{31}H_{28}N_2Na_4O_{13}S$). After preparation the FXG samples were conditioned in PMMA cuvettes measuring $10 \times 10 \times 45$ mm^3 to perform the irradiations and measurements. The Fricke gel samples were stored under refrigeration ($(4 \pm 1)^\circ$C) and light protected during about 12 h (Olsson et al., 1989).

2.2. Irradiations

Each three FXG samples set (Fig. 1b), prepared in order to obtain the arithmetic mean of three measurements, was maintained 30 min at room temperature and light protected before irradiation. The samples sets were irradiated with clinical electron beams using a VARIAN® model CLINAC 2100C linear accelerator (HIAE) and different phantom materials (Figs. 1 and 2): MEDINTEC® liquid water phantom [PMMA $40 \times 40 \times 40$ cm^3 walls filled with tri-distilled water ($\rho = 1.00$ g cm^{-3})], CIVCO® virtual water phantom [plates of different thicknesses measuring 30×30 cm^2 and $\rho = 1.03$ g cm^{-3}] and PMMA phantom [plates of different thicknesses measuring 30×30 cm^2 and $\rho = 1.19$ g cm^{-3}]. In all irradiations using liquid water phantom each samples set of FXG solution was packed with polyvinyl chloride (PVC) film in order to avoid contact of the dosimetric solution with tri-distilled water. A PMMA holder (Fig. 2b) was always used to positioning the Fricke gel samples sets to be irradiated at the reference depth using virtual water and PMMA phantoms. The irradiation parameters used are presented in Table 1.

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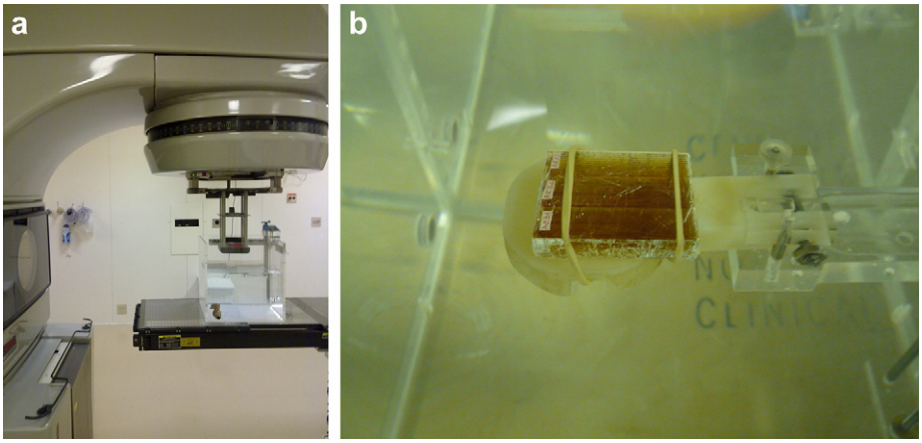

Fig. 1. Experimental set up for FXG samples irradiations with clinical electron beams in the CLINAC 2100C linear accelerator. Liquid water phantom positioned to be irradiated (a) and an FXG samples set submerged in water phantom at the reference depth (b).

2.3. Evaluation

The evaluation technique employed was the optical absorption (OA) spectrophotometry using an SHIMADZU® model UV-2101PC spectrophotometer (IPEN) in the wavelength range from 190 to 900 nm. All optical measurements were performed about 30 min after irradiation.

An E.M.B.® model PRENDOGRAV light box (IPEN) was used to better colour change visualization.

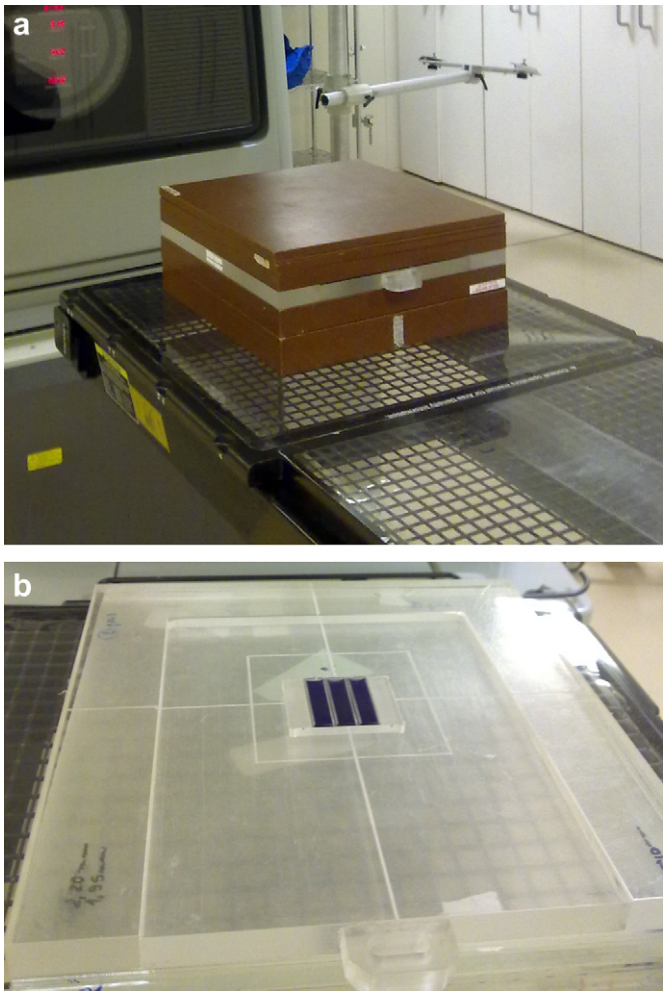

Fig. 2. Experimental set up for FXG samples irradiations with clinical electron beams in the CLINAC 2100C linear accelerator. Virtual water phantom (a) with the FXG samples set positioned at the reference depth and PMMA holder (b) used for positioning the FXG samples set to be irradiated in virtual water and PMMA phantoms.

2.4. Parameters studied

The colour change, optical absorption spectra, intra and inter-batches reproducibility, dose-response, lower detection limit, energy and dose rate dependent response and response uniformity were studied for the three different phantom materials used.

Each presented value corresponds to the average of the measurement of three samples and the error bars the standard deviation of the mean. The background values corresponding to the spectrophotometric measurements of non-irradiated Fricke gel samples were subtracted from all absorbance values presented.

3. Results and discussion

3.1. Colour change

The radiation induced colour change presented by FXG solution conditioned in PMMA cuvettes, non-irradiated and irradiated with absorbed doses of 0.05–21 Gy, 12 MeV electron beam and dose rate of 400 cGy min^{-1} using virtual water phantom is presented in Fig. 3. The colour range extends from yellow-gold (non-irradiated solution) to violet (21 Gy) and this behaviour also can be observed in FXG samples irradiated with different electron energies, dose rates and different phantom materials studied.

Table 1
Irradiation parameters to the different phantom materials.

Irradiation parameters	Phantom materials
	Liquid water, virtual water and PMMA phantoms
Reference depth (cm)	0.8–2.4
Backscatter thickness (cm)	5.0
Absorbed dose (Gy)	0.05–21
Dose rate (cGy min^{-1})	80–400
Energy (MeV)	4–16
Incidence angle (°)	90
Gantry position (°)	180
Treatment table position (°)	180
Radiation field size (cm^2)	10 × 10

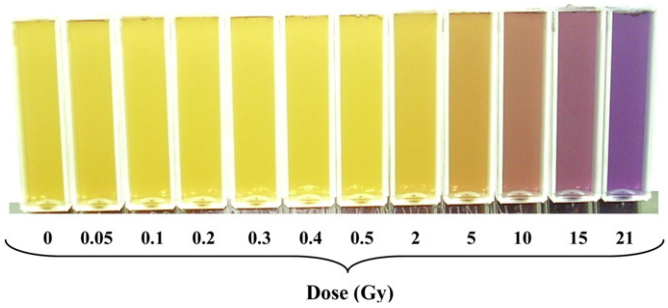

Fig. 3. Radiation induced colour change presented by FXG solution non-irradiated and irradiated with 12 MeV electron beam using a virtual water phantom.

3.2. OA spectra

The optical absorption spectra obtained from Fricke gel samples non-irradiated and irradiated with absorbed doses between 0.05 and 21 Gy, 12 MeV electron beam and dose rate of 400 cGy min^{-1} using PMMA phantom is presented in Fig. 4.

The Fricke gel solution studied presents two absorption bands, as expected: one at 441 nm, corresponding to Fe^{2+} ions initially present in non-irradiated FXG solution and other at 585 nm, corresponding to Fe^{3+} ions generated by radiation induced Fe^{2+} ions oxidation. The band at 441 nm tends to disappear depending on the dose as the band at 585 nm is intensified with increasing dose.

The dosimetric wavelength was fixed in 585 nm, the same established by Bero et al. (2001).

The optical absorption spectra of FXG samples irradiated with different electron energies, dose rates and different phantom materials studied present the same behaviour observed in Fig. 4.

3.3. Intra and inter-batches reproducibility

The intra and inter-batches reproducibility of the spectrophotometric response of the Fricke gel solution irradiated with clinical electron beams were evaluated for the three used phantoms.

To analyze the intra-batch reproducibility five samples sets with three cuvettes each one of a single batch, subjected to the same experimental conditions were irradiated with 12 MeV electron beam, absorbed dose of 1 Gy and dose rate of 400 cGy min^{-1} for each phantom material. The intra-batch reproducibility obtained for the different phantom materials studied is better than ±0.3%.

To evaluate the inter-batches reproducibility four samples sets also with three cuvettes each one of different batches subjected to the same experimental conditions were irradiated with 16 MeV electron beam, absorbed dose of 1 Gy and dose rate of 400 cGy min^{-1} for each phantom material. The inter-batches reproducibility obtained for the different phantom materials studied is better than ±1%.

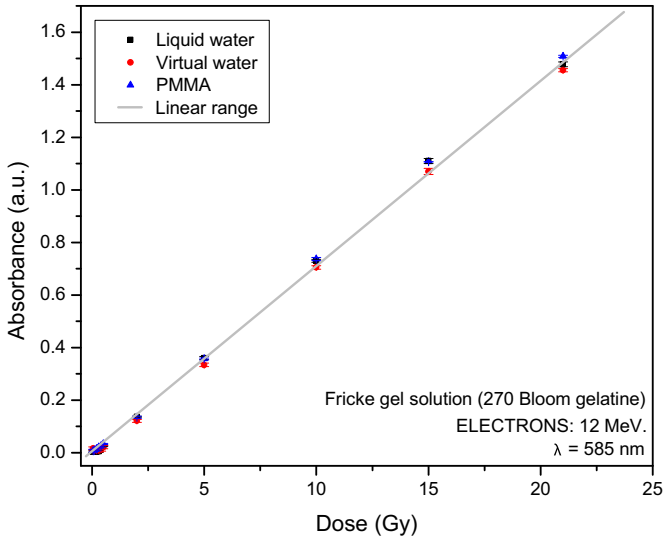

Fig. 5. Spectrophotometric dose-response curves of the FXG solution irradiated with 12 MeV electron beam using different phantom materials.

3.4. Dose-response

The spectrophotometric dose-response curves of the Fricke gel solution irradiated with absorbed doses between 0.05 and 21 Gy, 12 MeV electron beam and dose rate of 400 cGy min^{-1} using liquid water, virtual water and PMMA phantoms is presented in Fig. 5. The FXG solution presents a linear behaviour over the dose range

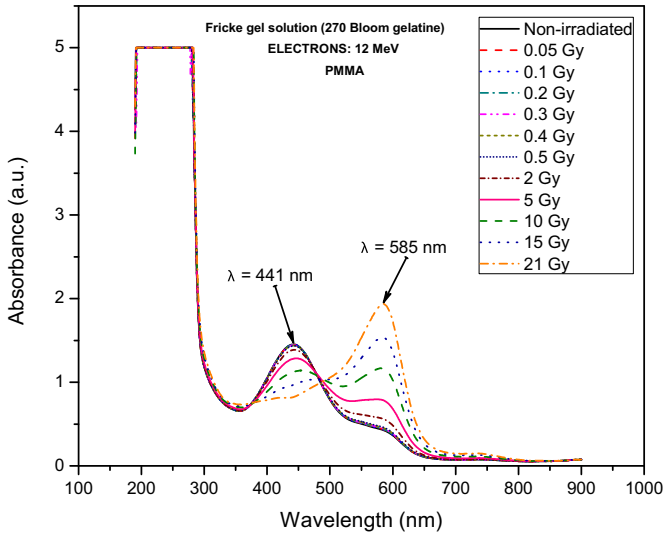

Fig. 4. Optical absorption spectra of the Fricke gel solution non-irradiated and irradiated with 12 MeV electron beam using PMMA phantom.

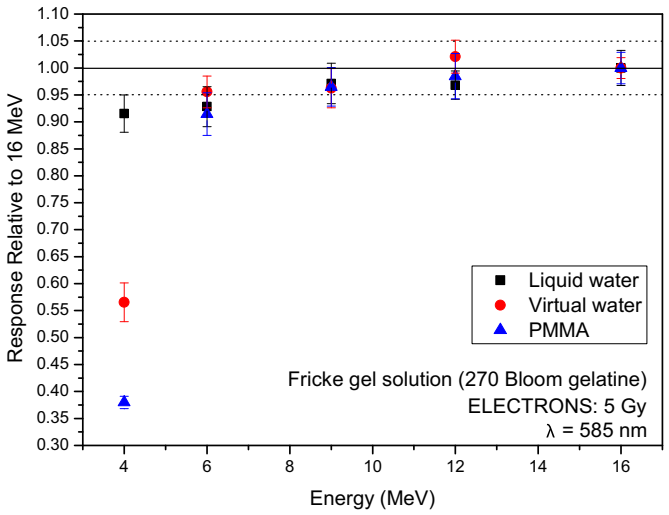

Fig. 6. Relative energy dependent spectrophotometric responses of the Fricke gel solution irradiated with clinical electron beams using different phantom materials.

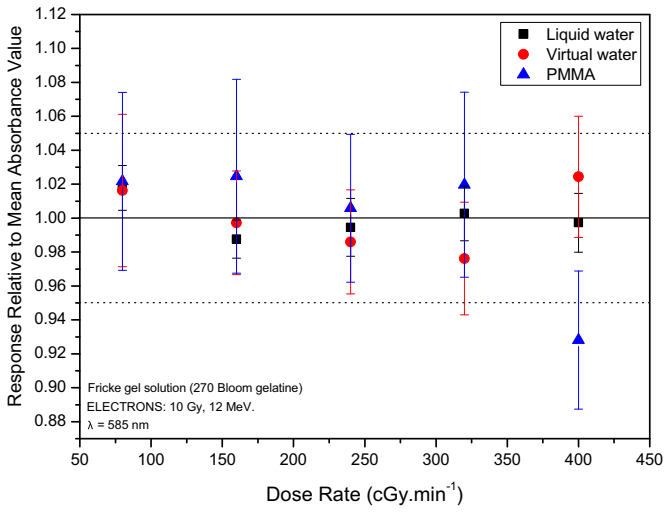

Fig. 7. Dose rate responses of the FXG solution irradiated with 12 MeV electron beam using different phantom materials.

studied to clinical electron beams and the difference relative to the liquid water phantom between the absorbance values obtained (±6%) for the FXG solutions using virtual water and PMMA phantoms can be explained by the different densities of these materials.

The lowest dose obtained with the linear accelerator used is 0.05 Gy and therefore, for practical purposes, this dose will be considered the experimental lower detection limit for the different phantom materials studied.

3.5. Energy dependent response

The energy dependent spectrophotometric responses relative to 16 MeV electrons of the FXG solution irradiated with electron energies between 4 and 16 MeV, absorbed dose of 5 Gy and dose rate of 400 cGy min^{-1} using the three different phantom materials studied are presented in Fig. 6.

The energy dependent spectrophotometric response of the Fricke gel solution presents maximum variation better than ±10% to 6 MeV electrons for liquid water, virtual water and PMMA phantoms in the energy range studied.

The optical response for 4 MeV electrons presents high energy dependent response for different phantom materials used probably because of dose gradient in the FXG samples set due to the fast decrease of dose as a function of the reference depth (cm.phantom $material^{-1}$) that occurs on irradiations with low energy electrons.

3.6. Dose rate response

The dose rate dependent responses relative to the mean absorbance value of the FXG solution irradiated with dose rates from 80 to 400 cGy min^{-1}, 12 MeV electrons and absorbed dose of 10 Gy using different phantom materials are presented in Fig. 7. The dose rate dependent response obtained for liquid water, virtual water and PMMA phantoms is better than ±2%, except at dose rate of 400 cGy min^{-1} to PMMA phantom.

3.7. Response uniformity

In order to verify the homogeneity of the FXG solution the spectrophotometric response uniformity was studied. For this purpose the four faces of each PMMA cuvette of the FXG samples sets were irradiated at 90° in relation to the clinical electron beams (normal incidence) with 12 MeV electron beam, 5 Gy and 400 cGy min^{-1} using different phantom materials.

The cuvettes used have two optical faces parallel to each other (called faces one and three) and two no optical faces (faces two and four). The OA measurements were always performed with the face one (reference face) perpendicular to the light beam of the spectrophotometer. The optical response uniformity of the FXG solution obtained is better than ±5% for liquid water, virtual water and PMMA phantoms to the dose and energy studied.

Considering the spectrophotometric results presented for the Fricke gel solution irradiated using liquid water, virtual water and PMMA phantoms can be observed that different phantom materials can be used, however, if necessary, appropriate corrections must be made when the PMMA phantom is used.

4. Conclusions

The FXG solution developed at IPEN prepared with 270 Bloom gelatine made in Brazil provides excellent results when irradiated with clinical electron beams in the dose and energy ranges studied using different phantom materials. These results indicate the viability of employing this solution in 2D spectrophotometric dosimetry (could be extended to 3D MRI dosimetry) to be applied in quality assurance for clinical radiotherapy treatment planning of superficial tumours (less than 5 cm deep) being treated with clinical electron beams (Strydom et al., 2005).

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