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Energy dependent response of the Fricke gel dosimeter prepared with 270 Bloom gelatine for photons in the energy range 13.93 keV–6 MeV

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ABSTRACT

The spectrophotometric energy dependent response to photons with effective energies between 13.93 keV and 6 MeV of the Fricke xylenol gel (FXG) dosimeter developed at IPEN, prepared using 270 Bloom gelatine, was evaluated in order to verify the possible dosimeter application in other medicine areas in addition to radiosurgery, for example, breast radiotherapy and blood bags radiosterilization. Other dosimetric characteristics were also evaluated. The obtained results indicate that the FXG dosimeter can contribute to dosimetry in different medical application areas including magnetic resonance imaging (MRI) evaluation technique that permits three-dimensional (3D) dose distribution evaluation.

1. Introduction

The Fricke gel dosimeters have been widely studied for radiotherapy [1] and radiosurgery [2–4] applications because of their tissue equivalence, ease of moulding them into any desired shape and size [5] and ability to evaluate 3D dose distributions with high spatial resolution [6,7] using the MRI technique. The dosimetry is based on the oxidation of ferrous (Fe^{2+}) to ferric (Fe^{3+}) ions by action of the ionizing radiation proportional to the absorbed dose [6,8]. The accurate absorbed dose determination can potentially be performed for quality control in medical procedures using ionizing radiation in fields other than radiosurgery, such as breast radiotherapy and blood bags radiosterilization for instance.

The High Doses Laboratory of IPEN has been studying the Fricke gel solution produced using 270 Bloom gelatine from porcine skin, commercially available in the local market at low cost. The studied solution presents excellent dosimetric performance [7,9–12] and can be applied in ^{60}Co gamma radiation field, using both spectrophotometric and MRI evaluation techniques.

In this work the spectrophotometric energy dependent response of the FXG dosimeter developed at IPEN was evaluated by photon irradiation with effective energies between 13.93 keV (X-rays) and 6 MeV (clinical photon beams), in order to verify the possible dosimeter application in other areas of medicine. Dosimetric characteristics such as dose rate and angle dependent response, response repeatability and reproducibility, response stability, dose response and useful dose range were also evaluated.

2. Materials and methods

2.1. FXG solutions preparation

Different batches of FXG solutions were prepared using 5% by weight 270 Bloom gelatine from porcine skin [7,9], tri-distilled water, 50 mM sulphuric acid (H_2SO_4), 1 mM sodium chloride (NaCl), 1 mM ferrous ammonium sulphate hexahydrate [$Fe(NH_4)_2(SO_4)_2 \cdot 6H_2O$] and 0.1 mM xylenol orange, ($C_{31}H_{28}N_2Na_4O_{13}S$), i.e., ferric ions indicator [13]. Immediately after preparation the dosimetric solutions were conditioned in SARSTEDT® polymethyl methacrylate (PMMA) cuvettes with the following characteristics: two parallel optical faces, 10 mm of optical path length and of dimensions $10 \times 10 \times 45\ mm^3$. The cuvettes containing Fricke gel solutions were sealed with polyvinyl chloride (PVC) film for the spectrophotometric measurements.

2.2. Samples irradiation

The dosimetric solutions were maintained under refrigeration ($(4 \pm 1)\ ^\circ C$), light protected for approximately 12 h [13] and were at 30 min at room temperature and were also light protected before irradiation. The FXG samples were irradiated (in the reading cuvettes) employing the following radiation sources:

- PANTAK–SEIFERT® model ISOVOLT 160 HS and RIGAKU–DENKI® model GEIGERFLEX low-energy X-rays machines, both

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Table 1
Irradiation parameters of PANTAK–SEIFERT® and RIGAKU–DENKI® low-energy X-rays machines [14,15].

Low-energy X-rays machines							
PANTAK–SEIFERT®	Radiation quality	Additional filtration (mmAl)	Tension (kV)	Half-value layer (mmAl) First	Second	Air kerma rate (mGy/s)	Effective energy (keV)
	T-25	0.4	25	0.279	0.410	2.762	13.93
	T-50(b)	1.0	50	1.079	1.690	4.027	22.08
	T-50(a)	4.0	50	2.411	2.890	0.821	30.48
	RQR7	2.5	90	2.950	4.620	4.960	33.05
	RQR8	2.5	100	3.240	5.200	6.000	34.40
	RQR9	2.5	120	3.840	6.310	8.120	37.05
	RQR10	2.5	150	4.730	7.790	11.680	40.75
RIGAKU–DENKI®	Filtration (mmAl)	Tension (kV)	Current (mA)	Exposure rate (mC/kg/min)		Effective energy (keV)	
	0.682	40	30	16.4		17.7	

of the Instruments Calibration Laboratory of IPEN, with the irradiation parameters presented in Table 1. The current used in the PANTAK–SEIFERT® system was always 10 mA and the source–cuvette distance was always 50 cm;

- GAMMACELL model 220 and PANORAMIC model FIS 60-04 ^{60}Co gamma radiation sources (both of the Intense Radiation Sources Laboratory of IPEN);
- KELEKET BARNES FLAXARAY® model IS ^{60}Co teletherapy system (Instruments Calibration Laboratory of IPEN) and
- VARIAN® model CLINAC 6EX clinical photon accelerator (6 MeV photon energy) of the Faculty of Medicine of the Hospital of the Clinic of Sao Paulo University.

The absorbed dose range was between 0.4 and 40.0 Gy. All irradiations were performed in free air. Electronic equilibrium (PMMA plates 3 mm thick) and depth of dose maximum (RMI-457 solid water plates 15 mm thick) conditions were used to irradiations with ^{60}Co gamma radiation and 6 MeV photons, respectively. In samples irradiated with X-rays with effective energies between 13.93 and 40.75 keV the optical response was corrected to radiation absorption ($e^{-\mu x}$) in the PMMA cuvettes walls.

2.3. Samples evaluation

The well-established optical absorption (OA) spectrophotometry evaluation technique [16,17] was employed using a SHIMADZU® model UV2101-PC spectrophotometer (High Doses Laboratory of IPEN) and wavelength range 190–900 nm. Immediately after solutions were prepared and after 30 min of irradiation, the optical absorption measurements were performed.

The dosimetric wavelength was determined for each analyzed solution. This wavelength was used to obtain all the absorbance values reported. All presented results correspond to the average of absorbance values of three FXG samples and the error bars the standard deviations of the mean. The type B uncertainties were not considered. The background value (non-irradiated solution) was subtracted of all average values, except the values used for spectrophotometric response stability determination.

2.4. Parameters studied

The energy dependent response (effective energy range 13.93 keV–6 MeV), dose rate (dose rate range 9.3×10^{-3}–2.55 kGy/h) and angle (incidence angle from 0° to 180°) dependent response, response repeatability and reproducibility (different batches) were studied to verify the behavior of FXG dosimeter for different photon energies and irradiations conditions.

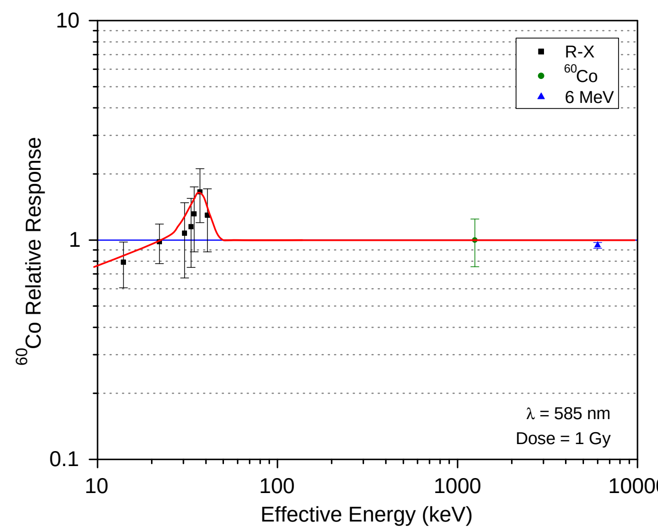

Fig. 1. Spectrophotometric energy dependent response of the Fricke gel solution.

3. Results and discussion

The optical absorption spectra obtained from Fricke gel solutions irradiated with X-rays for all studied effective energies (13.93–40.75 keV) and clinical photon beams (6 MeV) are the typical ones obtained from ^{60}Co gamma radiation [10,11].

3.1. Energy dependent response

The spectrophotometric energy dependent response curve relative to ^{60}Co radiation is presented in Fig. 1. The solutions were always irradiated with absorbed dose of 1 Gy. The maximum energy dependent response, 30%, is observed to 37.05 keV, as expected considering the photoelectric effect region and the low effective atomic number of the Fricke gel solution (7.42). The obtained results indicate that the studied FXG solution does not present energy dependent response for photon energies higher than 50 keV in the studied energy range.

3.2. Dose rate dependent response

The spectrophotometric dose rate dependent response of the irradiated Fricke gel solution is presented in Fig. 2. The FXG samples were irradiated with absorbed dose of 30 Gy, in different radiation sources (^{60}Co gamma radiation and 6 MeV photons) and the dose rate range was 9.3×10^{-3}– 2.55 kGy/h.

The maximum variation of the spectrophotometric response as a function of dose rate for the different ^{60}Co irradiation systems used was $\pm$10%, and that can be explained considering the different irradiation geometries that are better than $\pm$4% for 6 MeV photons. According to these results it is recommended to calibrate Fricke gel solutions always with the same dose rate used in the measuring system evaluated.

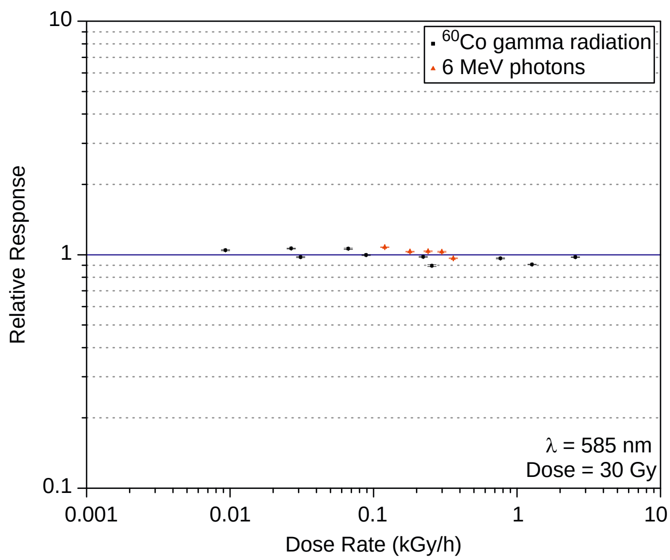

Fig. 2. Spectrophotometric response relative to the mean value of the FXG solutions as a function of dose rate.

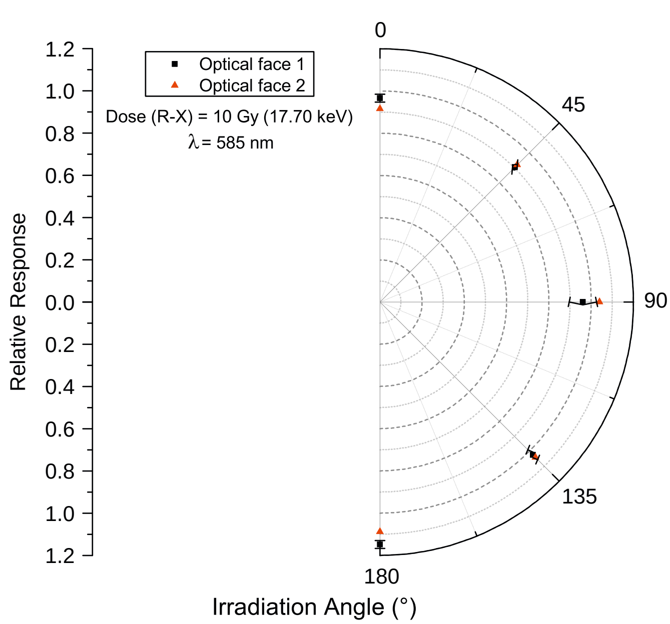

Fig. 3. Spectrophotometric angle dependent response relative to the mean value of the Fricke gel samples of 17.70 keV X-rays.

3.3. Angle dependent response

FXG solution samples were irradiated with 17.70 keV X-rays and ^{60}Co gamma radiation and absorbed dose 10 Gy with incidence angles 0°, 45°, 90°, 135° and 180°. Thirty minutes after irradiation the optical response of the two optical faces of each cuvette was evaluated.

The relative angle dependent is presented in Fig. 3. The maximum angle dependent response for effective energy of 17.70 keV is better than $\pm$10%. For samples irradiated with ^{60}Co gamma radiation no angle dependence was observed.

3.4. Response repeatability and reproducibility

The repeatability of the non-irradiated FXG solution was better than $\pm$0.24%.

The reproducibility for different batches of the non-irradiated and irradiated (20 Gy of ^{60}Co gamma radiation) Fricke gel solutions considering batches produced with different

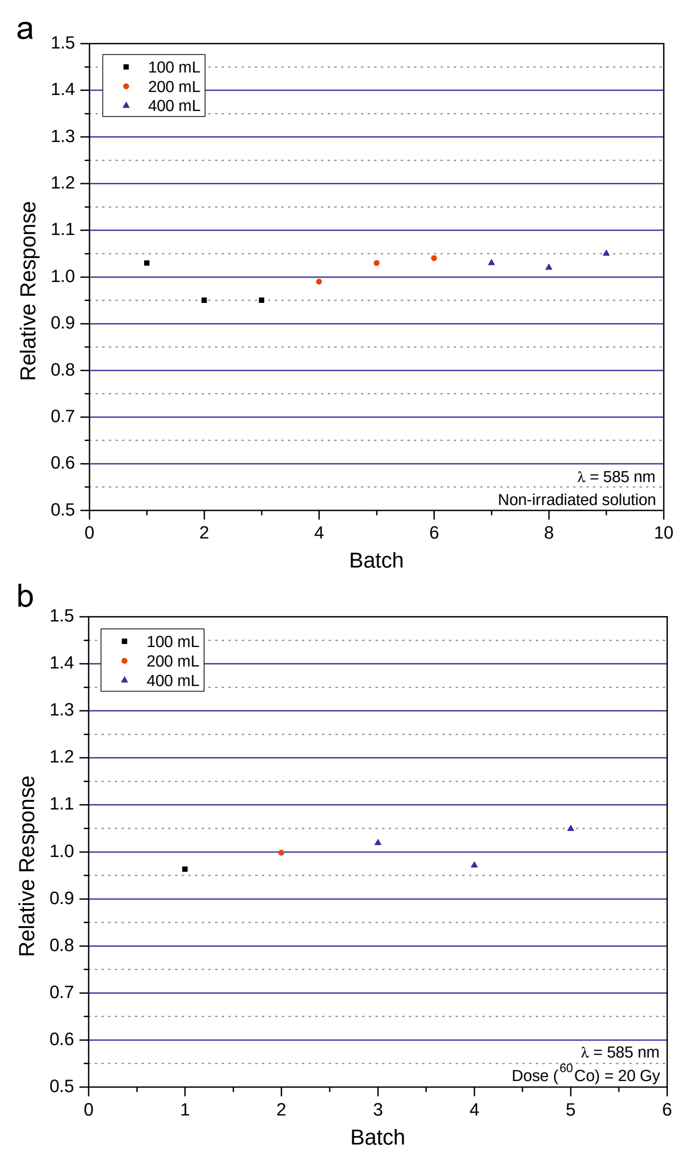

Fig. 4. Spectrophotometric response (relative to the mean value) reproducibility of the non-irradiated (a) and irradiated (b) Fricke gel solution for different solution batches.

volumes (100, 200 and 400 mL) is better than $\pm$ 5%, as shown in Fig. 4. In this test the solutions were prepared under same experimental conditions, except the room temperature, which was different because the solutions were prepared on different days.

For better reproducibility it is recommended that samples be prepared always under the same room temperature, whereas there is temperature influence on the Fe^{2+} ions natural oxidation [10].

3.5. *Additional studies*

3.5.1. *Response stability*

The Fricke gel samples irradiated with 6 MeV photons (5 Gy) were maintained under two different storage conditions: under refrigeration ((4 $\pm$ 1) °C) and light protected (condition 1) and at room temperature and environmental light (condition 2).

The first measurement (reading zero) of the irradiated samples maintained at conditions 1 and 2 was carried out 30 min after irradiation. After reading, the samples maintained in condition 1 remained in this condition for 30 min before the next measurement. For both storage conditions the measurements were repeated within:

- each 1 h during the first 24 h;
- each 24 h, after the second day of analysis until the end.

The results of spectrophotometric response stability of the irradiated FXG solution in the first 4 h after irradiation are presented in Fig. 5.

The FXG solution presents more significant intensification of the absorbance values in condition 2, similar to the behavior observed when the solution was irradiated with ^{60}Co gamma radiation (10 Gy) [10].

There was no evidence of fungi and the dosimetric solution remained in solid form at room temperature throughout the analysis period (six days).

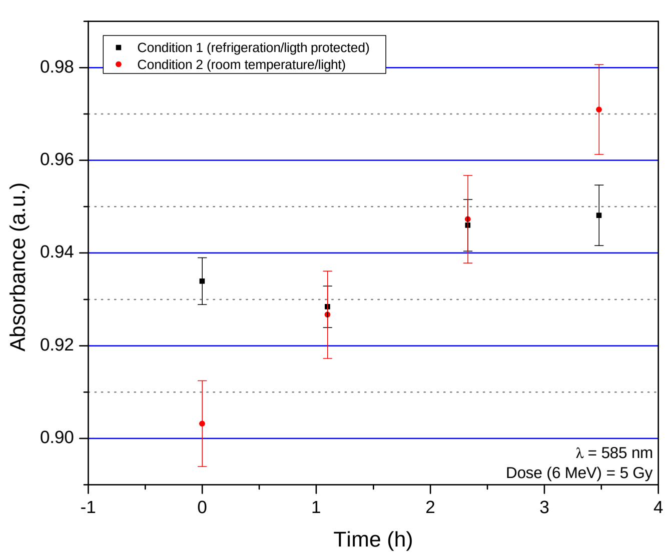

Fig. 5. Spectrophotometric response stability of the irradiated Fricke gel solution in the first 4 h after irradiation.

3.5.2. *Dose response*

The spectrophotometric dose response curve of the Fricke gel solution irradiated with 6 MeV photons and absorbed doses between 0.4 and 40.0 Gy is presented in Fig. 6.

The spectrophotometric response presents linear behavior between 0.4 and 30.0 Gy, similar to the irradiated solution with ^{60}Co gamma radiation (0.5–30.0 Gy) [11].

FXG samples were also irradiated with X-rays (13.93 and 17.70 keV) with absorbed doses between 1 and 10 Gy and the dose response curves, corrected to cuvettes wall absorption, were also obtained.

The dose response curve obtained for 13.93 keV X-rays is presented in Fig. 7.

The dosimetric solution also presents, as expected, a linear spectrophotometric response in the studied dose range.

According to the results obtained the useful dose range for FXG dosimeter prepared using 270 Bloom gelatine can be considered to be 0.4–30.0 Gy.

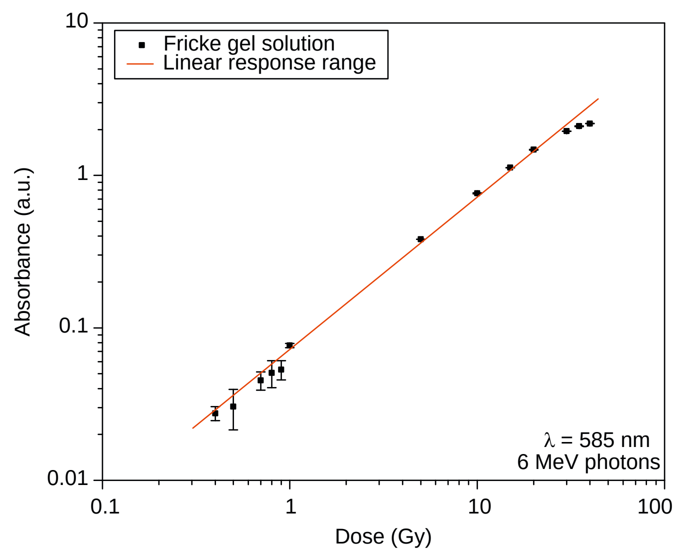

Fig. 6. Spectrophotometric dose response of the Fricke gel solution as a function of absorbed dose.

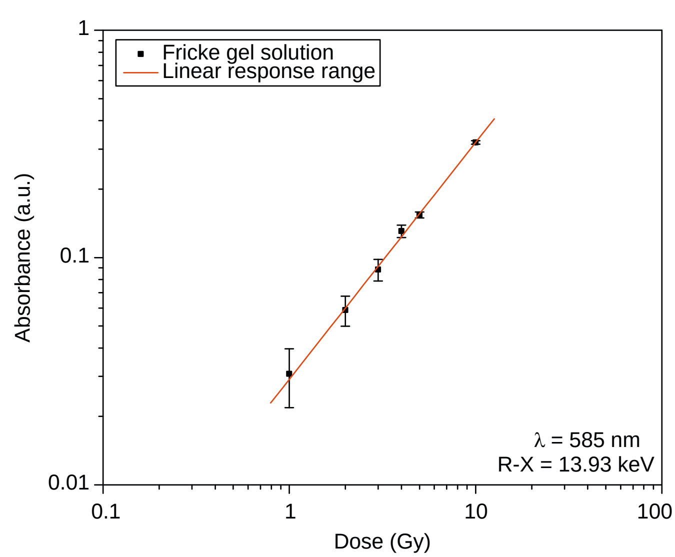

Fig. 7. Dose response curve of the Fricke gel solution to 13.93 keV X-rays.

4. Conclusions

The results obtained for the Fricke gel dosimeter prepared with 270 Bloom gelatine from porcine skin using the OA spectrophotometry evaluation technique are very satisfactory and they complement the previous work performed using ^{60}Co gamma radiation. These results indicate that the studied solutions present dosimetric properties adequate to be used as radiation dosimeters in different medical areas and can be extended to the MRI evaluation technique that permits 3D dose distribution evaluation [7].

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