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MRI study of radiation effect on Fricke gel solutions

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Abstract

The quality control optimization of medical processes that use ionizing radiation in the treatment of diseases like cancer is a key element for patient safety and success of treatment. The major medical application of radiation is radiotherapy, i.e. the delivery of dose levels to well-defined target tissues of a patient with the purpose of eliminating a disease. The need of an accurate tumour-edge definition with the purpose of preserving healthy surrounding tissue demands rigorous radiation treatment planning. Dosimetric methods are used for dose distribution mapping region of interest to assure that the prescribed dose and the irradiated region are correct. The Fricke gel (FXG) is the main dosimeter that supplies visualization of the three-dimensional (3D) dose distribution. In this work the dosimetric characteristics of the modified Fricke dosimeter produced at the Radiation Metrology Centre of the Institute of Energetic and Nuclear Research (IPEN) such as gel concentration dose response dependence, xylenol orange addition influence, dose response between 5 and 50 Gy and signal stability were evaluated by magnetic resonance imaging (MRI). Using the same gel solution, breast simulators (phantoms) were shaped and absorbed dose distributions were imaged by MRI at the Nuclear Resonance Laboratory of the Physics Institute of Sao Paulo University.
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Keywords: Fricke gel dosimeter; 3D dose distribution; Gamma radiation; MRI dosimetry

1. Introduction

The use of magnetic resonance imaging (MRI) in the clinical field has the advantage of using non-ionizing radiation capable of providing excellent soft-tissue contrast, and to produce images of any arbitrary plane (Gambarini et al., 1997; Olsson et al., 1991). Fricke gel dosimetry is based on the fact that ferrous ions are oxidized to ferric ions upon irradiation. Since ferrous and ferric ion concentrations, as with any other paramagnetic impurities (Rabbani et al., 1983), affect nuclear magnetic resonance (NMR) relaxation rate, the concentration of ferric ions in the Fricke solutions can be determined using MRI and can be used to obtain the three-dimensional (3D) dose distribution from ionizing radiation soon after irradiation. The MRI pixel signal intensity in the image depends on local spin– spin and spin–lattice relaxation times, therefore, in the irradiated gel the pixel intensity will vary spatially according to the dose distribution in the gel (Bero et al., 1999; Gore et al., 1984; Schreiner, 2004). The dosimetric characteristics of the modified Fricke dosimeter such as gel concentration dose response dependence, xylenol orange addition influence, gamma dose response between 5 and 50 Gy, and signal stability were evaluated using the MRI technique. Using the same gel solution breast simulators (phantoms) were shaped and 3D absorbed dose distribution was imaged by MRI.

2. Materials and methods

The Fricke gel solutions were prepared using 50 mM sulphuric acid, 1 mM ferrous ammonium sulphate, 1 mM sodium chloride, 0.1 mM xylenol orange and 1%, 5% and 10% of porcine gelatin 270 Bloom. Acrylic cuvettes were filled with Fricke gel solution and sealed. The samples were maintained at 5 °C in a dark environment for 12 h until solidification and then were irradiated with gamma radiation in air at electronic equilibrium using a Gammacell source, with doses between 5 and 50 Gy and a dose rate of 3.28 kGy/h. In Fig. 1 each

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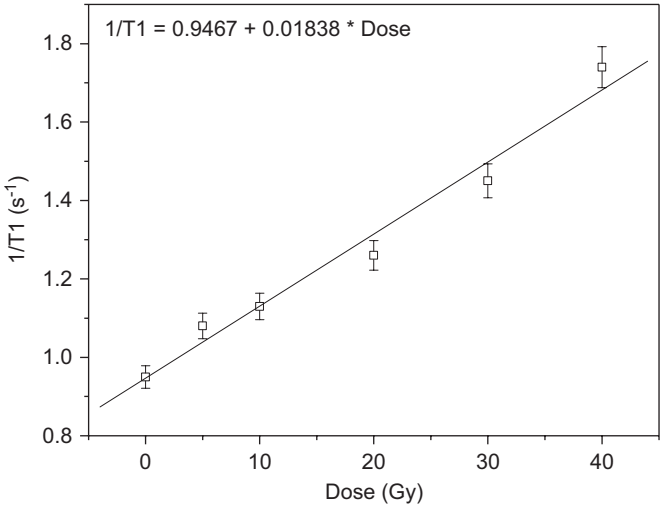

Fig. 1. FXG- proton relaxation time (1/$T$1) as a function of absorbed dose.

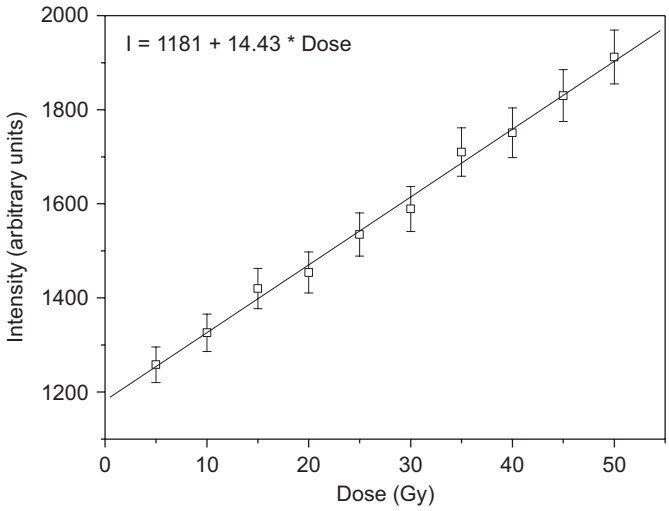

Fig. 2. FXG dose–response curve: signal intensity as a function of absorbed dose.

data point represents an average of three measurements and the standard deviation of the mean (1σ) is shown. The samples were maintained at least 30 min at room temperature before the MRI evaluations. The T_1 weighted MRI signals were obtained by a Philips Gyroscan S15/ACS scanner (1.5 T) with a quadrature head coil, using the Inversion Recovery sequence with the following parameters: TR = 367 ms, TI = 300 ms and TE = 18 ms. The MRI signal intensities of irradiated cuvettes were used to calibrate the response in terms of absorbed dose.

3. Results

The MRI dose response of FXG samples prepared using gel concentrations between 1% and 10%, without and with addition of 0.1 mM xylenol orange agent in the gel solution does not change significantly, less than 3%, comparing with the dose response curve presented in Fig. 2 that shows uncertainty associated with the fit of 3%.

The inverse of the proton relaxation time (1/$T$1) as a function of absorbed dose obtained using different samples is shown in Fig. 1. The proton relaxation time $T$1 was measured in the same magnetic field with a homemade spectrometer. The signal intensity as a function of absorbed dose is shown in Fig. 2. The dose–response curve of Fricke gel samples irradiated with ^{60}Co γ rays in the dose range between 5 and 50 Gy presents a linear behaviour, and each point represents the arithmetical mean of three measurements.

Table 1 presents the average MR signal intensity (arbitrary units) as a function of radiation dose and the standard deviation of the mean (three FXG samples for each dose).

The spontaneous oxidation of Fe^{2+} ions present in the gel depends on the purity of the constituents, manipulation and storage conditions. Images were obtained for different time intervals after the irradiation to determine the stability of the dosimeter. The radiation induced reactions (Bero et al., 2000) and the dose response need a short period, approximately 10 min, to stabilize before the MRI measurements. The MR

Table 1
Signal Intensity (arb. unit) as a function of radiation dose

Absorbed dose (Gy)	MR signal intensity (arb. unit)	Standard deviation (%)
0	1056	2.9
5	1257	2.4
10	1326	1.7
15	1419	3.0
20	1454	2.2
25	1534	2.0
30	1589	3.2
35	1709	3.0
40	1751	2.6
45	1830	1.9
50	1912	1.0

images of irradiated sample with 15 Gy of ^{60}Co gamma radiation were obtained 30 min after irradiation and during the next 8 days after irradiation. The relative MRI signal intensities are shown in Fig. 3, indicating that the Fe^{3+} concentration increases until stabilization after 5 days post-irradiation. The signal intensity obtained after 8 days was 3.5 times more than the initial intensity. This results indicates that the time between the preparation and irradiation of the gels must be well defined.

The sagital, coronal and axial planes of a Fricke gel breast phantom irradiated with ^{60}Co γ radiation were imaged by MRI. The images were taken with a field of view of 15 × 10 cm^2, slice thickness of 2 mm and the Inversion Recovery sequence with TR = 367 ms, TI = 300 ms and TE = 18 ms. A MR image of sagital plane slice is presented in Fig. 4 and a typical MR image coronal plane slice iso-dose (arbitrary units) contours is shown in Fig. 5. The image clearly indicates that the dose distribution was not uniform in the phantom volume and that the dose distribution can be evaluated in the target volume.

In the Fig. 6 is shown an axial plane slice RM image of FXG breast phantom irradiated with ^{60}Co γ radiation (20 Gy)

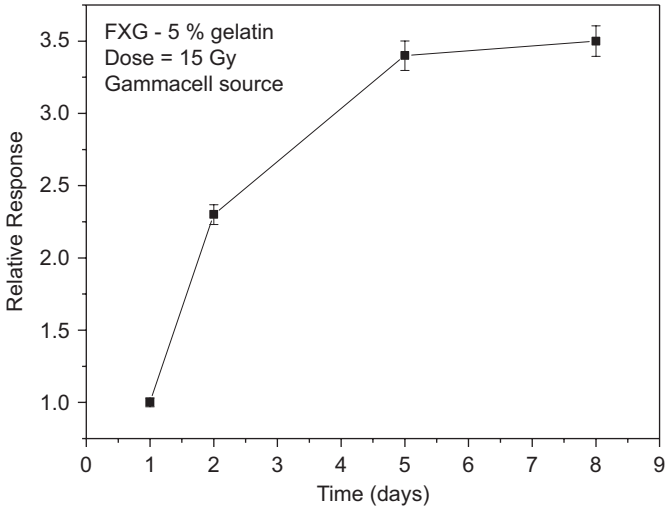

Fig. 3. Relative long term FXG stability.

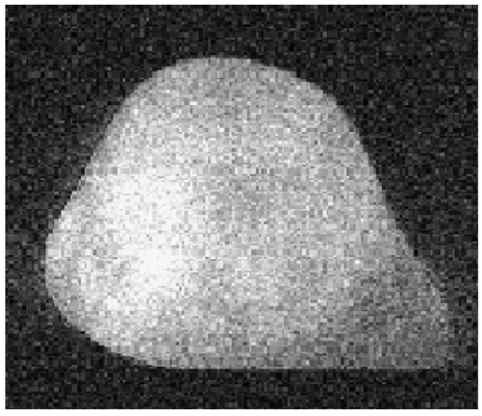

Fig. 4. MR image of FXG breast simulator sagital plane slice.

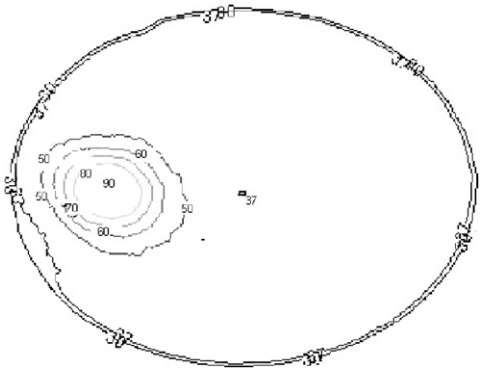

Fig. 5. Typical MR image of a coronal plane slice iso-dose (arbitrary units) contours of FXG breast simulator.

and its representative intensity histogram. An image of a cystic mass simulator inserted in the breast phantom can be observed. The image brightness increases with decreasing $T1$ which correspond to increasing radiation dose.

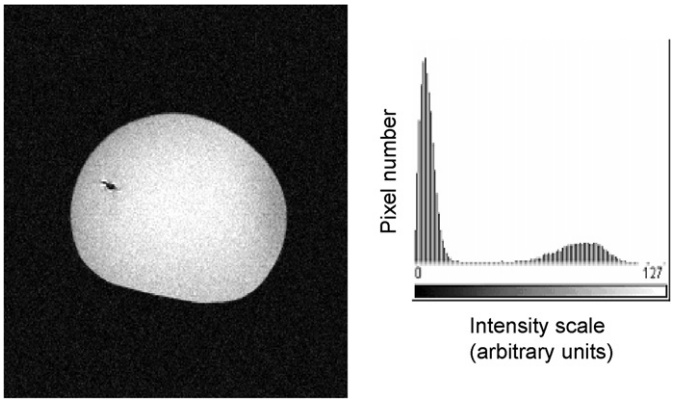

Fig. 6. Axial plane slice with a cystic mass simulator MR image and intensity histogram of a FXG breast phantom irradiated with ^{60}Coγ radiation (20 Gy).

4. Conclusion

The Fricke gel dosimeter is inexpensive and easy to prepare. The gelatin is tissue equivalent and can be used to cast into different shapes and volumes.

The porcine gelatin quality 270 Bloom can be used and presents good results. Gelatin concentration of 5% provides phantoms with good mechanical resistance, excellent gel consistency and adequate room temperature stability for sufficient time to perform the MR images.

The xylenol orange addition, necessary to Fricke gel measurements using the spectrophotometry technique, is not necessary for MR imaging technique.

The Fricke gel simulators constitute a promising instrument in 3D dose distribution evaluations.

The MRI technique provides excellent phantom images with very good contrast for different radiation doses. This method can be successfully used to produce a 3D map of the absorbed doses in a phantom and help to plan a radiation strategy in radiotherapy treatments.

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