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Effect of perchloric acid on the performance of the Fricke xylenol gel dosimeter

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HIGHLIGHTS

- Perchloric acid enhances the radiation sensitivity of the ferrous xylenol orange gel.
- The gel, either with or without the acid, shows a linear dose response in the range 1–15 Gy.
- Storage environment factors need to be well controlled to minimize dose errors.

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ABSTRACT

The conventional ferrous xylenol orange (XO) gel (FXG) dosimeter is being wildly investigated for radiotherapy dose measurements. Upon irradiation, its color turns red due to oxidation of Fe^{2+} into Fe^{3+}, which forms a complex with xylenol orange. The effect of perchloric acid (PCA) on the dosimetric properties of the gel in the dose range of 1–15 Gy was investigated using visual spectrophotometry. FXG-PCA responds to radiation dose linearly and exhibits higher radiation sensitivity than the conventional gel dosimeter. PCA in a concentration of 20 mM enhances the radiation sensitivity ~44%. Stability of the absorbances of both the gels during storage under various conditions was investigated, and the uncertainty of dose measurements was estimated.

1. Introduction

Radiation therapy uses chemical dosimeters of many types (Khan, 2010). Among them are mixtures of ferrous ions with xylenol orange (XO) (Davies and Baldock, 2008); acrylate monomers (Hiroki et al., 2013); radiochromic dyes, such as leuco crystal violet (LCV) (Babic et al., 2009); Gafchromic films (Devic, 2011; Farah et al., 2014) and gelatin containing Ag^{+} (Soliman, 2014). One of the common dosimeters in this category is based on the Fricke system and contains, in addition to the ferrous ions, xylenol orange in gelatin (FXG) (Fricke and Morse, 1927; Fricke and Hart, 1966; Core et al., 1984; Galante et al., 2008). It exhibits excellent water and tissue equivalence below 100 keV of photon energy (Keall and Baldock, 1999). Upon a γ-ray exposure, ferrous ions in the gel get oxidized into ferric ions, which form bonds with XO; this process is accompanied by a change of the color of the gel (Bero et al., 2001; Davies and Baldock, 2008). The radiation sensitivity of this system is high, and the absorbance of such dosimeters grows linearly with the dose up to 25 Gy (Davies and Baldock, 2008). However, oxidation of Fe^{2+} continues even after the end of irradiation, which shifts the dose response function with time.

Various additives were previously proposed to improve the radiation sensitivity of FXG to radiotherapeutic doses (Davies and Baldock, 2008; Pirani et al., 2009; Jin et al., 2012). In this work, we studied effects of perchloric acid (PCA) on the radiation sensitivity and dosimetric performance of the conventional FXG. We have found that PCA in the FXG gel decreases the dependence of the absorbance of the Fe^{2+}-XO complex on the acid concentration and decreases the sensitivity of the materials to added components described by Gay and Gebicki (2002). We studied the stability of the dose response of both the gel types (FXG and FXG-PCA) under various environmental conditions. In addition, the overall uncertainty of dose measurements in a radiotherapeutic γ-ray facility with both the dosimeters was estimated.

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2. Materials and methods

2.1. Gel dosimeter preparation

Four batches of FXG solutions were prepared, each containing 4% (wt) of gelatin (300 Bloom Gelatin from porcine skin, Sigma-Aldrich) and 0, 10, 20 or 30 mM of perchloric acid (Aldrich, 70% ACS Reagent Grade). The mixtures also contained 50 mM of sulfuric acid, 1 mM of ferrous ammonium sulfate hexahydrate (Aldrich) and 0.1 mM of the ferric ion indicator XO (Oxford Laboratory, India). All the mixtures were stirred magnetically at 30 °C then transferred into polymethyl methacrylate (PMMA) capped cuvettes ($1 \times 1 \times 4.5$ cm^3) and allowed to form transparent gels overnight in a refrigerator at ~6 °C.

2.2. Irradiation and measurement procedures

The prepared gels were exposed to γ-rays from a ^{60}Co radiotherapy unit (PHOENIX Theratron®, MDS Nordion, Canada) at room temperature. The dose rate of the unit was measured according to the IAEA TRS 398 protocol with a calibrated ionization chamber (IAEA, 2006). We irradiated the gels in the cuvettes positioned into a cubic wax phantom ($10 \times 10 \times 10$ cm^3). The gels were irradiated with four fields at the gantry angles of 0, 90, 180 and 270°, a fixed collimator angle (0°) and a fixed square field size (10×10 cm^2) at a source-to-surface-distance (SSD) of 80 cm. These conditions had previously been used in the output calibration; the dose rate at the center of the phantom was reported as 1.2 Gy/min.

The optical absorbances of the cuvettes (1 cm light path) were measured with a double-beam SPECORD® spectrophotometer (Analytik Jena AG, Jena, Germany) in the wavelength range of 300–600 nm. Absorbances at 570 nm were used in the analysis.

3. Results and discussion

3.1. Dose response functions and radiation sensitivity

Fig. 1 shows dose response curves for FXGs with various PCA concentrations in the dose range of 1–15 Gy. The dependences of the absorbances on the dose are linear with correlation coefficients (r^2) of 0.9996, 0.9910, 0.9998, and 0.9998 for the gels with 0, 10, 20, and 30 mM PCA, respectively. Fig. 2 shows the slope of linear dose response function (radiation dose sensitivity) as a function of the PCA concentration in the gel. Addition of PCA increases the radiation sensitivity of the gel, and the increase can be described by a quadratic polynomial function with $r^2 = 0.9999$. The radiation sensitivity reaches 0.0915 Gy^{-1} at 20 mM PCA and decreases slightly at higher concentrations of PCA. An increase in the PCA concentration from 0 to 20 mM enhances the sensitivity ~44%. These results show that PCA in the concentration range 0–30 mM improves the radiation sensitivity and the linearity of the dose response of the conventional gel.

3.2. Pre- and post-irradiation color stability

Figs. 3 and 4 show the net absorbances at 570 nm as functions of the storage time for unirradiated and irradiated conventional and PCA-containing gels, respectively. Both gels were stored at room temperature (~25 °C) in the dark and under laboratory light, as well as at ~10 °C in a refrigerator. The unirradiated and irradiated conventional gels (Fig. 3) stored at 10 °C exhibit good stability with an increase of their responses within only 1–4% during the initial 24 h of storage, depending on the absorbed dose. However, their absorbances increased significantly with the time

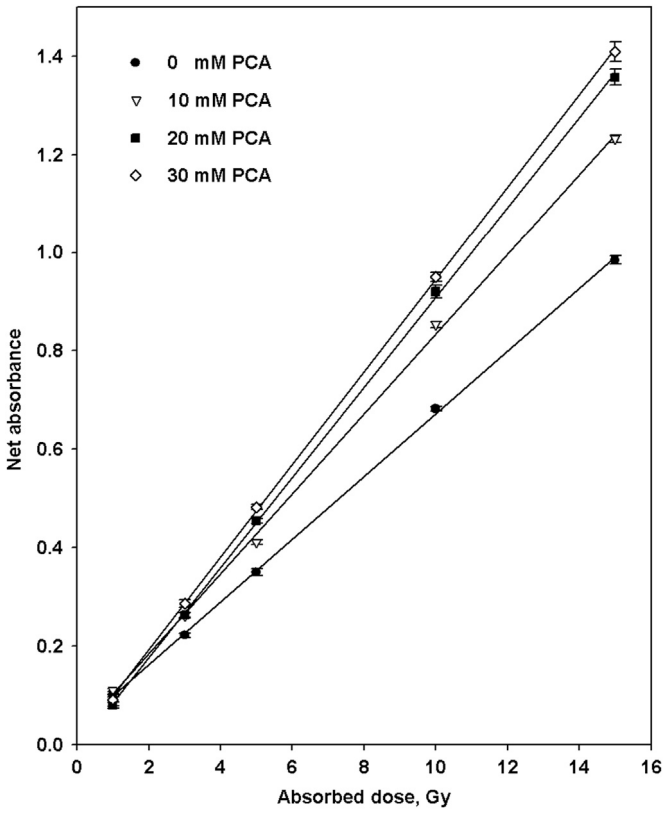

Fig. 1. Dose response functions of the FXG dosimeters containing different concentrations of PCA (570 nm).

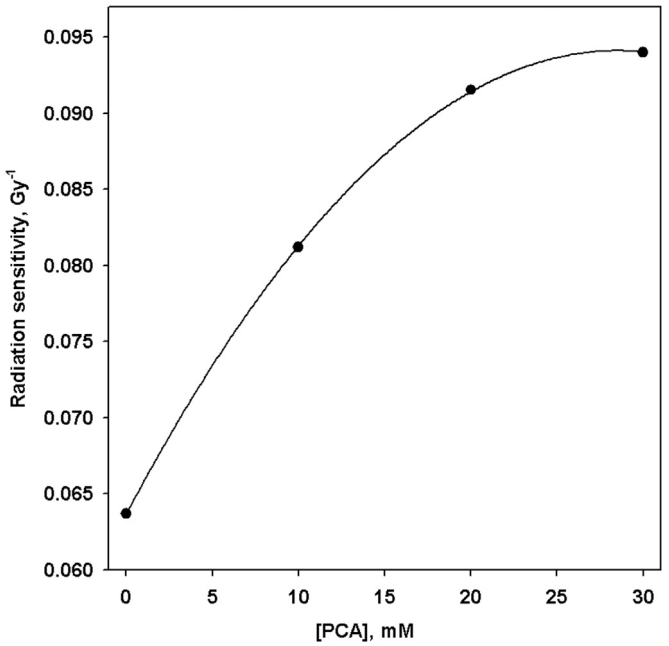

Fig. 2. Radiation dose sensitivity of the FXG dosimeters as a function of the PCA concentration in the dose range of 1–15 Gy.

of storage at room temperature, both in the dark and in the light. The increases after 24 h of storage were in the ranges of (13–25)% and (20–30)% for the gels stored in the dark and in the light, respectively.

The absorbances of unirradiated PCA-FXG gels (Fig. 4) stored at 10 °C grew with time initially and tended to stabilize after 48 h of storage. By contrast, the absorbances of the gels stored at room