A gelatin-free model system for the study of the basic radiation-induced polymerization in PAG dosimeters

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1. Introduction

The primary goal of radiation therapy is to deliver a high radiation dose to a target volume while minimizing the dose to surrounding healthy tissue. The conformal radiation therapy approaches that achieve this are technically complex and the precise verification of the resulting three-dimensional (3D) dose distribution is required. Polyacrylamide gel (PAG) dosimeters with MRI and optical CT provide the required 3D dosimetry with high spatial resolution. Many basic studies have characterized these chemical dosimeters that polymerize under radiation [1,2]. However, studying the fundamental properties of the radiation-induced polymerization in PAG dosimeters is complicated by the presence of the background gelatin matrix. We have developed a gelatin-free model system for the study of the basic radiation-induced polymerization further.

In this presentation we show results of investigations on gelatin-free dosimeters containing equal amounts of acrylamide and \(N,N'\)-methylene-bisacrylamide (named Aqueous Polyacrylamide, APA, dosimeters). The dosimeters were prepared with three different total monomer concentrations (2, 6, and 8% by weight). Nuclear magnetic resonance (NMR) spin-spin and spin-lattice proton relaxation measurements at 20 MHz, and gravimetric analyses performed on all three dosimeters, show a continuous degree of polymerization over the range of dose 0.5 – 25 Gy. The developed NMR model explains the relationship observed between the relaxation data and the amount of cross-linked polymer formed at each dose. This model may be extended with gelatin relaxation data to provide a fundamental understanding of radiation-induced polymerization in the conventional PAG dosimeters.

2. Materials and methods

The method used for the manufacture and gravimetric analysis of the APA dosimeters has been previously described [3]. The composition of the APA dosimeters was varied in the amounts of 2, 6 and 8%T, 50%C of acrylamide and \(N,N'\)-methylenbis-acrylamide (Fisher Scientific, Nepean ON), with distilled water as the remaining constituent.

All of the APA samples were irradiated in a water-filled polystyrene tank using a Cobalt-60 beam from a T-780C unit (Theratronics, Kanata ON). A 10 x 10 cm\(^2\) irradiation field was used and the test tubes within each %T batch were irradiated to absorbed doses in the range 0.5 to 25 Gy at a dose rate at \(d_{\text{max}}\) of 1.0 Gy min\(^{-1}\). NMR relaxometry measurements were performed 24 hours later at 20 MHz on a dedicated bench top spectrometer (Maran 20/35 spectrometer, Resonance Instruments Ltd., Witney,
UK). The spin-spin or transverse relaxation times ($T_2$) were measured using a CPMG pulse sequence (TE=1 ms, TR=23 s). The spin-lattice or longitudinal relaxation times ($T_1$) were measured using an inversion recovery pulse sequence. Measurements were made at $28 \pm 0.2^\circ$C, the operating temperature of the spectrometer.

3. Results and discussion

A continuous degree of radiation-induced polymerization from 0.5 to 25 Gy was observed in the spin-spin proton relaxation rates and gravimetric analyses of all three APA dosimeters with varying %T concentrations (see figures 1 and 2, respectively). A similar trend was noticed with the spin-lattice proton relaxation rate-dose response, with none of the dosimeters exhibiting the go/no go transition reported previously for the 8%T agarose-free BANANA gel [4]. The spin-spin and spin-lattice proton relaxation rates together with the fraction of monomer that has polymerized within the irradiated APA show a constant increase with dose until a saturation dose of approximately 5, 10 and 15 Gy is reached for the 2, 6 and 8%T concentrations, respectively. These results confirm the preliminary work presented earlier [3], and also provide additional data to determine a correlation between the NMR relaxation measurements and gel fraction analyses.

**Figure 1.** The spin-spin relaxation rate, $R_2$, dose response curves for APA dosimeters with three different total monomer concentrations. Measurements were at 20 MHz. The uncertainty in the relaxation rates is the size of the data points.

**Figure 2.** The dose dependence of gel fraction (by weight), i.e., the fraction of monomer converted to polymer for four different total monomer concentrations. To provide clarity, 5% uncertainty in all weight fractions is indicated on the 8%T data points only.

Figure 3 shows a plot of $R_2$ versus weight percent of polymer. A linear relationship is observed between the spin relaxation data and the amount of polymer formed. This correlation can be explained with an NMR model assuming fast exchange. Within each APA dosimeter there are three distinct spin groups: monomer, polymer and water protons [5]. The water protons (the main group) are further divided into those hydrating monomer, polymer and bulk water. The monomer protons and water protons hydrating monomer may be combined with the bulk water proton pool since all of them have similar inherent relaxation rates. Under the fast exchange limit between hydration and bulk water protons, the observed relaxation rate, $R_{\text{observed}}$, is:

$$R_{\text{observed}} = p_{\text{poly}} R_{\text{poly}} + (1 - p_{\text{poly}}) R_{\text{bulk}}$$ (1)
where $p^{\text{poly}}$ is the fraction of water protons in the polymer pool, $R^{\text{poly}}$ is the inherent relaxation rate of the polymer and $R^{\text{bulk}}$ is the inherent relaxation rate of the bulk water proton pool.

The fraction of protons in the polymer pool, $p^{\text{poly}}$, is given by:

$$p^{\text{poly}} = k^{\text{poly}} \times [\text{poly}]$$  \hspace{1cm} (2)

where $k^{\text{poly}}$ is the fraction of water protons hydrating the polymer per percent weight of polymer and $[\text{poly}]$ is the percent weight of polymer. Substituting equation (2) into (1) and simplifying with the expression, $r^{\text{poly}} = k^{\text{poly}} (R^{\text{poly}} - R^{\text{bulk}})$, where $r^{\text{poly}}$ is the polymer relaxivity (the ability of the polymer to enhance the spin-spin or spin-lattice relaxation of water protons), one obtains the following relation:

$$R^{\text{observed}} = r^{\text{poly}}[\text{poly}] + R^{\text{bulk}}$$  \hspace{1cm} (3)

Equation (3) supports the linear relationship between the observed relaxation data and the amount of cross-linked polymer formed at each dose as seen in figure 3. Figure 4 shows a plot of $R_2$ and $R_1$ relaxivities as a function of $%T$. As $%T$ or the total monomer concentration by weight increases, the amount of polymer formed has greater ability to enhance the spin-spin and spin-lattice relaxation of water protons.

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**Figure 3.** The spin-spin relaxation rates, $R_2$, plotted against percent weight fraction of polymer formed in the dosimeter for all three APA total monomer concentrations. To provide clarity, 5% uncertainty in the polymer weight was added to the 8%T data points only. The uncertainty in the relaxation rates is the size of the data points.

**Figure 4.** (a) The spin-spin and (b) spin-lattice relaxivities plotted against $%T$ or total monomer monomer concentration by weight. All samples contained equal amounts of the two co-monomers or 50%C.
4. Conclusion

APA dosimeters can provide basic information for PAG dosimetry. The fraction of monomer that polymerizes and thus, the polymer weight is easily quantified by gravimetric analyses. An NMR model supports the correlation observed experimentally between the relaxation data and the amount of cross-linked polymer formed at each dose. Extending the model with gelatin relaxation data may provide a fundamental understanding of radiation-induced polymerization in the conventional PAG dosimeters.

Acknowledgments

Research funding has been provided by the Kingston Regional Cancer Centre and the Canadian Institutes of Health Research.

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