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Original paper

A new less toxic polymer gel dosimeter: Radiological characteristics and dosimetry properties

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ABSTRACT

Purpose: A new polymer gel dosimeter recipe was investigated that may be more suitable for widespread applications than polyacrylamide gel dosimeters, since the extremely toxic acrylamide has been replaced with the less harmful monomer 2-Acrylamido 2-Methyl Propane Sulfonic acid (AMPS).
Methods: The new formulation was named PAMPSGAT. The MRI response (R2) of the dosimeters was analyzed for conditions of varying dose, dose rate, and temperature during scanning. Radiological properties of the PAMPSGAT polymer gel dosimeter were investigated.
Results: The dose-response (R2) of AMPS/Bis appears to be linear over a dose range 10–40 Gy. The percentage of difference between the R2 values for imaging at 15 °C and MRI room temperature is about 4.6% for vial with 40 Gy absorbed dose which decreased to less than 1% for imaging at 20 °C. The percentage difference of Zeff of PAMPSGAT gel and soft tissue was less than 1% in the practical energy range (100 KeV–100 MeV). The electron density of the PAMPSGAT polymer gel was 2.9% higher than that of muscle. Results showed that the sensitivity of PAMPSGAT polymer gel dosimeter irradiated by ^{60}Co (energy = 1.25 MeV) is about 27.7% higher than that of irradiated using a 6 MeV Linac system.
Conclusions: Temperature during MRI scanning has a small effect on the R2 response of the PAMPSGAT polymer gel dosimeter. Results confirmed tissue equivalency of the PAMPSGAT polymer gel dosimeter in most practical energy range. The PAMPSGAT polymer gel dosimeter response depends on energy and dose rate.

1. Introduction

The use of dosimetry gels has the potential to provide high-resolution measurements of dose in modern radiotherapy technique to verify dose distributions. Furthermore, use of dosimetry gels minimizes the disadvantages of volume averaging, non-water equivalence or need for dose perturbation correction.

Gore et al. [1] first applied ferrous sulfate chemical dosimeter to gel dosimetry, used in conjunction with nuclear magnetic resonance (NMR) imaging to obtain quantitative dose distributions. However, the use of radiation sensitive polymer gels for the purpose of radiation dosimetry, as currently used, is as a result of the work undertaken by Maryanski et al in 1993. They introduced polymer gel dosimetry as a useful tools in measuring three dimensional dose distributions by magnetic resonance imaging (MRI) [2]. Prior to 2001, gel dosimeters had to be prepared under hypoxic conditions. Fong et al. proposed a new formulation by addition of antioxidant to the gel composition which can be made under conditions of normal oxygenation [3]. Polymer gel dosimeters utilize the mechanism of radiation-induced polymerization of monomers, where radiolysis products join small monomer molecules together. The amount of polymer produced by radiation is proportional to the absorbed dose. To preserve spatial information of the absorbed dose, polymer structures hold in place using a gel matrix. Some MRI contrast parameters such as spin-spin relaxation rate are changed due to the irradiation. Hence, high spatial resolution 3D maps of dose have been obtained by MR scanning. In addition to the MRI [4], other imaging modality have been used for gel dosimeters read out including optical-computerized tomography (optical-CT) [5], x-ray CT [6] and ultrasound [7].

Numerous authors have investigated the applications of dosimetric gels for different treatment techniques such as Intensity Modulated Radiation Therapy (IMRT) [8], Brachytherapy [9] and Streotactic Radiosurgery (SRS) [10]. However, one major limitation of polymer gel dosimetry is the toxicity of its chemical compounds, which may endanger an operator's safety. Recently, a new less toxic polymer gel dosimeter has been proposed with striking performance characteristics

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[11]. This new polymer gel dosimeter was named PAMPSGAT. PAMPSGAT is a normoxic polymer gel dosimeter that uses 2-Acrylamido-2-Methylpropan-sulfonic acid (AMPS) as a monomer.

An ideal polymer gel dosimeter should display water/tissue equivalent radiological properties. A useful procedure for evaluating the radiological properties of materials is to investigate their effective atomic number (Zeff), number of electrons per gram (Ne) and mass density (ρm) [12,13].

The most important dosimetry properties of polymer gel are a linear dose response and independence of the response from energy, dose rate and temperature during evaluation. Previous study showed a slight energy and dose rate dependence in some polymer gel dosimeters [14].

In a previous study the linearity of the dose response, the effect of the antioxidant (Tetrakis Hydroxymethyl Phosphonium Chloride (THPC)) concentration, and post irradiation time effects on the sensitivity of the PAMSGAT polymer gel dosimeter have been investigated [11]. The present study used MRI technique to readout response of the PAMPSGAT gel and focused on the dependence of radiological and dosimetry properties of the PAMPGAT polymer gel dosimeter. The dependence of the radiological properties on the incident photon energy was also explored.

2. Material and methods

2.1. Gel manufacture

The experimental procedures were based on the publication by Abtahi for PAMPSGAT polymer gel dosimeter [11]. Gelatin (porcine skin, type A, 300 Bloom, Sigma Aldrich, USA) (8 wt%) was dissolved in 90% of the water (high-pressure liquid chromatography (HPLC) grade, obtained from Direct-Q 3 UV water purification system, Millipore, France) (86 wt%) at the temperature of 50 °C. N,N'-methylene-di-acrylamide (Bis, Merck, For electrophoresis for molecular biology) (3 wt%) was dissolved at 50 °C. After the gelatin–crosslinker mixture had cooled to approximately 37 °C the 2-Acrylamido 2-Methyl Propane Sulfunic acid (AMPS, Merck, ≤99%)) (3 wt%) was added to the mixture. The antioxidant Tetrakis Hydroxymethyl Phosphonium Chloride (THPC, Sigma Aldrich, USA, 80% solution in water) (150 mM) was first dissolved in the remaining 10% of the water, and then added to the solution at the temperature of 35 °C. The resulting PAMPSGAT gel solution were transferred into glass test tubes (10 mm outside diameter, 50 mm length), and then closed with polyethylene screw caps and sealing films. The fabricated gel test tubes cooled to room temperature slowly and then stored in a refrigerator at the temperature of 5 °C.

2.2. Radiological properties

Density of the un-irradiated PAMPSGAT polymer gels was determined using a density meter (Anton Paar GmbH, Austria). The density, ρ, of the polymer gel was determined at different temperatures from 20 °C to 40 °C. The experimental standard deviation of the ρ was obtained by performing at least three measurements. According to the volume thermal expansion coefficient formula, the variation in volume due to temperature variations is given by [15]

$$V - V_0 = \alpha_v V (T - T_0) \tag{1}$$

where α_v is the expansion coefficient, and V and V_0 are the volumes at temperatures T and T_0, respectively. Volume, mass and density are related as the following formula

$$V = \frac{m}{\rho}$$

Hence, Eq. (1) can be rewritten as

$$\rho = \frac{\rho_0}{1 - \alpha_v T_0 + \alpha_v T} \tag{2}$$

In the present study, energy dependent Z_{eff} values are calculated using Auto-Z_{eff} software developed by Taylor et al. [13]. Auto-Z_{eff} software determines the Z_{eff} via exploitation of the smooth correlation between atomic cross section and atomic number [13]. For a more detailed discussion, the interested reader is referred elsewhere [16,17].

The number of electrons per gram was computed according to the formulae

$$\rho_e = \rho_m . N_A . \sum_i w_i . \left(\frac{Z_i}{A_i}\right) \tag{3}$$

where ρ_e is the electrons density, ρ_m is the mass density, N_A is the Avogadro's number and w_i is the fraction by mass of the ith element of atomic number Z_i and atomic mass A_i [18].

2.3. Irradiation

A batch of PAMPSGAT polymer gel dosimeter was prepared and irradiated by a linear accelerator system (Elekta SL 75/25, UK) approximately 24 h after producing the gel. For this purpose the vials filled with the PAMPSGAT gels were placed in a water phantom at 5 cm depth to ensure adequate depth-dose buildup and photon scatter (lateral and backscatter) conditions. The water phantom was used for keeping the vials stored in irradiation room and its temperature was measured using a thermometer. After the water phantom temperature equilibrated with room temperature (21 ± 0.5 °C), the gel dosimeter vials were placed in the water phantom and stored for a period of 1 h prior to the irradiation in order to stabilize their temperature. Seven vials of PAMPSGAT gels were irradiated to the dose of 10, 15, 20, 30, 40, 50 and 60 Gy at depth of maximum dose (d_{max}) and one vial was not irradiated to be used as the reference/control vial. The irradiation was performed at 10 × 10 cm^2 field size and 100 cm source to surface distance (SSD) and a dose rate of 458 cGy/min. Delivered absolute dose values at the vial positions were verified using a calibrated Farmer-type ionization chamber (Scanditronix-Wellhöfer, model FC65-P, Germany).

Dependence of PAMPSGAT gel dosimeter on photon energy and dose rate was studied for 1.25 MeV from Co-60 and 6 MV from a linear accelerator system. Hence, a separate PAMPSGAT batch was prepared and irradiated by a cobalt 60 radiation source (Theratronics, Theratron 780-C, Canada) approximately 24 h after producing the gel. The irradiation was performed at 10 × 10 cm^2 field size, 80 cm source to surface distance (SSD) and a dose rate of 95 cGy.min^{-1} at the midline of the test tub. Various radiation doses of 10, 15, 20, 30, 40, 50 and 60 Gy were delivered to the different separate vials and one vial was not irradiated to be used as the reference/control vial. Delivered absolute dose values at vial positions were verified using a calibrated Farmer-type chamber (0.6 cm^3, PTW, Germany) based on the IAEA TRS 398 protocol [19]. Furthermore, two doses of 10 and 15 Gy with photon energies of 10 and 18 MeV and dose rates of 358, 230 and 90 cGy/min were also tested. Except for ^{60}Co irradiation which was indicated in Fig. 4, all other PAMPSGAT polymer gel dosimeters were from the same batch.

2.4. PAMPSGAT polymer gel dosimeter evaluation

The polymer gel dosimeters were imaged using a 1.5 T MRI scanner (Siemens Avanto, Germany) in a transmitter/receiver head coil. The imaging was performed 24 hrs. after irradiation. A slice-selective multi spin-echo sequence with 32 equidistant echoes and a CPMG radio-frequency scheme was applied. The parameters of the sequence were as follows: echo time (TE) of 20–640 ms, repetition time (TR) of 4 s, matrix size of 512 × 512, slice thickness of 5 mm, number of averages of 2 and resolution of 2.56 pixels per mm. B1 Shim was used according to the FOV size and slice thickness. The total scan time was 35 min and 48 s. The TR and TE parameters were selected considering previous studies on multiple spin–echo sequences for 3D polymer gel dosimetry