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Investigation of dose characteristics in three-dimensional MAGAT-type polymer gel dosimetry with MSE MR imaging

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Abstract

A new type of normoxic polymer gel dosimeter, named MAGAT responses well to absorbed dose even when manufacturing in the presence of normal levels of oxygen. The aim of this study was to evaluate dose response, diffusion effect and cumulated dose response under multiple fractional irradiations of the MAGAT gel dosimeter using Multiple Spin-Echo (MSE) Magnetic Resonance (MR) sequence. Dose response was performed by irradiating MAGAT-gel-filled testing vials with a 6 MV linear accelerator and a linear relationship was present with doses from 0 to 6 Gy, but gradually, a bi-exponential function result was obtained with given doses up to 20 Gy. No significant difference in dose response was present between single and cumulated doses ($p > 0.05$). For study of diffusion effect, edge sharpness of the $R2$ map imaging between two split doses was smaller than 1 cm of dose profile penumbra between 20% and 80%. In conclusion, the MAGAT polymer gel dosimeter with MSE MR imaging is a promising method for dose verification in clinical radiation therapy practice.

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Keywords: MAGAT; Gel dosimetry; Dose response; MR imaging

1. Introduction

Gel dosimetry is a rapid developing and progress technique that enables three-dimensional radiation dose measurement and mapping. Fricke-agarose gel was an original recipe in gel dosimetry, consists of ferrous sulphate in an aqueous gel matrix [1]. After irradiation, the ferrous ion converts to ferric ions and corresponds to a change in para-magnetism. Chemical changes in Fricke-agarose gel dosimeter can be detected and imaged by nuclear magnetic resonance (NMR) or MR imaging. However, its major limitation in dose measurement is that ferric ions in gel quickly diffuse with time after irradiation and thus deteriorates MR image quality.

Another type of gel dosimeter is a polymer gel which consists of monomer in aqueous gel matrix [2]. After irradiation, polymerization plays an important role in polymer gel, which presents higher spatial integrity in dose response. One of most often used polymer gels, called polyacrylamide gel (PAG), is known to be susceptible to atmospheric oxygen during gel manufacturing [3]. Due to its nature of free radicals easily produced by oxygen molecules, the gel needs to be prepared under an environment with hypoxic atmospheric conditions. Recently, a 'normoxic' polymer dosimeter (MAG) is developed that can be prepared within a normal oxygen level environment [4]. Of the MAG dosimeters, the MAGAT, with an entire new formulation introduced by Deene et al. [5], uses methacrylic acid (MAA)

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and tetrakis (hydroxylmethyl) phosphonium chloride (THPC) as a monomer and an oxygen scavenger respectively, presents superior dose response and exempts from ionic diffusion.

Multiple spin-echo (MSE) and $T2$ relaxation rate ($R2$) in MR imaging are commonly used for gel dosimetry. Several studies have investigated linear dose responses of the normoxic polymer gels in low dose regions [6]. It would be valuable and thus are the aims of this study to further explore its basic dose characteristics of the MAGAT gel dosimeter, including diffusion effects, polymerization and cumulative dose response under multiple fractional irradiations to higher dose regions by using MSE and $R2$ MR imaging sequences.

2. Materials and methods

2.1. MAGAT formulation and irradiation

According to Hurley et al. [7], the optimized concentration of the MAGAT formulation consisted of 9% methacrylic acid (Sigma Aldrich, monomer purity >98%), 6% gelatin (Sigma Aldrich, 300 Bloom, Type A) and 10 mM THPC solution (Sigma Aldrich, 80% solution in water). This MAGAT-type normoxic polymer gel was prepared on a bench top under normal atmosphere conditions. The prepared solution was then poured into 13 testing vials, each with 25 mm diameter and 115 mm length. A cylindrical phantom, with a size of 155 mm diameter and 75 mm length was also prepared and filled with the MAGAT gel. All the vials and the cylindrical phantom were placed in a refrigerator allowing them slowly cooling into solid forms.

Each testing vial was further wrapped by a 2 cm bolus and placed into a $15 \times 10 \times 20\ \text{cm}^3$ styrofoam holder, preventing the MAGAT gel dosimeter from backscattering radiation contaminations. The vials then received irradiation doses, ranging from 0 to 20 Gy correspondingly, by a 6 MV linear accelerator with a $15 \times 15\ \text{cm}^2$ radiation field size of two parallel-opposed beams.

For study of diffusion effect with fractional doses, the upper-half of the cylindrical phantom was irradiated by a 2 Gy dose with $20 \times 40\ \text{cm}^2$ field size of a half-beam blocked technique. The MAGAT gel was then placed for two more days and the right-half of the phantom was irradiated a 4 Gy dose by further rotating the collimator to a quadrant (90°). Thus, the cylindrical phantom was emerged with doses of 0, 2, 4, 6 Gy, respectively. Among the given doses, the 6 Gy dose was a cumulated dose from 2 Gy and 4 Gy (2 days later) given at different irradiation times.

2.2. MRI scan and data analysis

All testing vials and the cylindrical phantom were then inserted into an acrylic container. The MAGAT gels within the container were placed to the MRI scanning room for at least one day before imaging, ensuring that all the MAGAT gels were equilibrating to room temperature. MR image scanning was performed at temperature of 20.5 ± 0.5 °C with a 1.5 T MRI scanner (Siemens Medical System, Berlin, Germany). Multiple spin-echo MR sequences were employed to acquire a series of $T2$-weighted based images. All the images were obtained from 16 equidistant spin-echoes with TE 22.5 ms, TR 5000 ms, 3 mm slice thickness, 256×256 matrix size, 1 NEX and 256 mm FOV in both frequency and phase encoding directions.

The $T2$ MR images were then downloaded to a PC and image-processed by using MATLAB (Math Works, Inc.) software and a $R2$ map image was pixel-by-pixel reconstructed from the multi-echo images [8]. Two dose response curves of the MAGAT gels in testing vials and phantom, as resulting respectively from single irradiation dose up to 20 Gy and multiple fraction irradiation dose within 0–6 Gy, were formed via careful ROI selections within the $R2$ map image. These two curves should provide sufficient evidences on exploring the study of cumulated dose effect.

Diffusion effect was evaluated by studying the sharpness between adjacent two quadrants in the $R2$ phantom image. The sharpness was determined by measuring adjacent quadrants edge penumbra within normalized dose ranges 20–80%, referred as FWHM(20,80).

3. Results and discussion

Fig. 2 shows two dose response curves of the MAGAT gels. The $R2$ fitting had a bi-exponential function of $R2 = 47.48 \cdot e^{-0.012D} - 40.67 \cdot e^{-0.14D}$, R-square $= 0.99$ in doses ranging from 0 to 20 Gy (Fig. 2(a)). Flattening part in the curve was mainly resulted from saturated polymers of the MAGAT gels received from high dose irradiation, which was similar to the study of Hurley et al. [7], hence the MAGAT gel might not be a good candidate reporting accurate dose response in high dose region due to its nature characteristics of polymerization. However, in low dose region, a better linear relationship with slope of $3.37\ \text{s}^{-1}\ \text{Gy}^{-1}$ from dose within 0–6 Gy was obtained (Fig. 2(b)). This is because higher concentration of monomer (9% MAA) and oxygen scavenger (10 mM THPC) were used in this study, compared with the slope $2.79\ \text{s}^{-1}\ \text{Gy}^{-1}$ obtained from Bayreder et al. [9], which formulated with 8% gelatin, 5% MAA and 2 mM THPC. It was therefore suggested that a new concentration MAGAT gel was more suitable for use at dose less than 6 Gy. Meanwhile, a bi-exponential regression could be employed for fitting response curves at higher dose regions (>6 Gy).

Furthermore, in comparing with other type of dosimeter, such as the PAGAT polymer gel which used conventional acrylamide as monomer and reported less dose response about $0.192\ \text{s}^{-1}\ \text{Gy}^{-1}$ [3], while the MAGAT gel presents significantly higher sensitivity in dosimetry by adapting optimal formulation in manufac-