Uncertainty Analysis in MRI-based Polymer Gel Dosimetry

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ABSTRACT

Background: Polymer gel dosimeters combined with magnetic resonance imaging (MRI) can be used for dose verification of advanced radiation therapy techniques. However, the uncertainty of dose map measured by gel dosimeter should be known. The purpose of this study is to investigate the uncertainty related to calibration curve and MRI protocol for MAGIC (Methacrylic and Ascorbic acid in Gelatin Initiated by Copper) gel and finally ways of optimization MRI protocol is introduced.

Materials and Methods: MAGIC gel was prepared by the Fong et al. instruction. The gels were poured into calibration vials and irradiated by 18 MV photons. 1.5 Tesla MRI was used for reading out information. Finally, uncertainty of measured dose was calculated.

Results: Results show that for MAGIC polymer gel dosimeter, at low doses, the estimated uncertainty is high (≈ 18.96% for 1 Gy) but it reduces to approximately 4.17% for 10 Gy. Also, with increasing dose, the uncertainty for the measured dose decreases non-linearly. For low doses, the most significant uncertainties are σ_{R0} (uncertainty of intercept) and σ_a (uncertainty of slope) for high doses. MRI protocol parameters influence signal-to-noise ratio (SNR).

Conclusion: The most important source of uncertainty is uncertainty of R2. Hence, MRI protocol and parameters therein should be optimized. At low doses, the estimated uncertainty is high and reduces by increasing dose. It is suggested that in relative dosimetry, gels are irradiated by high doses in linear range of given gel dosimeter and then scaled down to the desired dose range.

Keywords

MRI, Gel Dosimetry, Uncertainty Analysis, Radiation Therapy

Introduction

Nowadays, polymer gel dosimeters are used as a three-dimensional (3D) dosimeter. When polymer gel dosimeters are placed under irradiation, their monomers polymerize as a function of absorbed dose. Based on the specific physical change that has occurred in the irradiated gel, different imaging systems can be used to read dose information out. These imaging techniques are magnetic resonance imaging (MRI), optical CT, x-ray CT and ultrasound, but among these techniques MRI is the most popular [1-3].

Polymerization of gel changes its magnetic properties which can be detected by measuring the spin-lattice relaxation time T1 or the spin-spin relaxation time T2. T2 or the spin-spin relaxation rate R2 (=1/T2) are the most sensitive to dose change; hence, a majority of MRI-based

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polymer gel dosimetry studies has used R2 value for dose measurements [1, 4].

For R2 measurement, a collection of T2-weighted images are used and also different imaging sequences can be used. Single spin-echo sequence is the simplest sequence in which R2 value in each pixel can be acquired from two differently T2 weighted images. Another one is multiple spin-echo sequence that can provide R2 maps with higher signal-to-noise ratio [1, 5].

Application of polymer gel dosimetry in dose verification of radiotherapy will be completed after discussing the measurement uncertainty [6]. There are some factors that affect the uncertainty of dose determination such as accuracy of calibration curve, ageing dynamics of the polymer gel, B1-field (magnetic field of radiofrequency wave of MRI) inhomogeneity and finally MRI protocol. It should be noted that the choice of MRI pulse sequence and parameters therein are a major source of uncertainty and should be optimized [7].

In this paper, uncertainty analysis related to calibration curve and MRI protocol for MAGIC gel are investigated and finally ways to optimization MRI protocol are introduced.

Material and Methods

MAGIC gel was prepared by Fong et al. instruction. Briefly, gelatin was soaked in water for 0.5 hr. The contents were stirred by heart-stirrer at 50°C till a clear solution was obtained, at this time hydroquinone was added. The temperature was brought down to 38°C and appropriate amounts of ascorbic acid, CuSO4.5H2O and Methacrylic acid were added and the contents were stirred further [8]. The gels were poured into calibration vials and irradiated using a Varian 2100 linear accelerator and 18 MV photons [3]. To obtain calibration curve, a set of glass gel vials were used (0-10 Gy). The calibration vials were placed in a water tank (40×40×40) and irradiated with 18 MV photons using 20×20 open field and SSD 100cm.

A multiple spin-echo sequence with 32 echoes was used for reading out polymer-gel dosimeters. The parameters of sequence were as follows: TR= 5000 ms, TE =22–704 ms, slice thickness 5 mm, pixel size 1×1 mm^2 and two acquisitions. After MRI imaging by 1.5 T scanner (Siemens, Symphony), R2 values were calculated using an in-house made MATLAB (MathWorks Inc.) code. The calibration data were fitted with a linear equation as represented as [9]:

$$R2=aD+b \qquad (1)$$

Where D is absorbed dose, coefficients of a and b represent slope and offset of the calibration curve, respectively.

By propagating the uncertainties of parameters in the calibration equation, Eq. (1) and the $R2$ values, the uncertainty of measured dose values can be estimated. The uncertainties of coefficients, the slope a and the offset b, in Eq. (1) can be estimated by the calibration data [9, 10]. With the estimated uncertainty of $R2$, for any pixel in $R2$ map, the uncertainty of the dose can be calculated by the following equation [10]:

$$\frac{\sigma_D}{D}=\sqrt{\left(\frac{R2\sigma_a}{D}\right)^2+\left(\frac{a\sigma_{R2}}{D}\right)^2+\left(\frac{\sigma_{R0}}{D}\right)^2} \qquad (2)$$

This equation considers two main uncertainties in gel dosimetry: uncertainty due to calibration curve and uncertainty from R2 map. The related uncertainties of slope (a) and intercept ($R0=b$) are σ_a and σ_{R0}, respectively.

To estimate uncertainty of $R2$ values, $R2$ values in a number of pixels were measured and standard deviation of the measured $R2$ values was calculated.

Results and Discussion

Figure 1 shows calibration curve ($R2$ as a function of absorbed dose) that relates measured $R2$ and absorbed dose, the standard deviation of $R2$ value was approximately 1%. Table 1 shows calibration data for this work

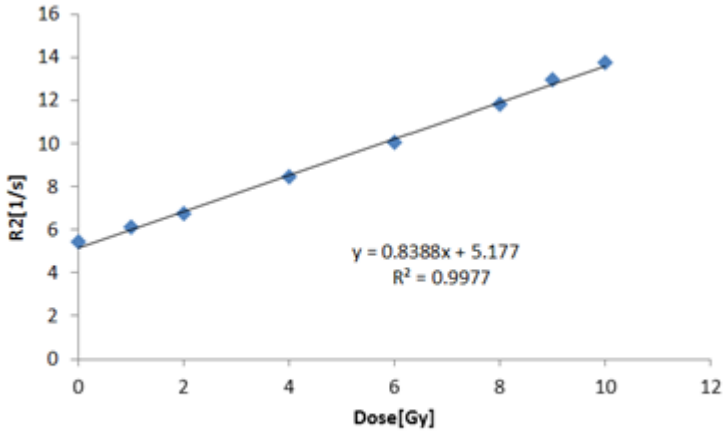

Figure 1: Calibration Curve for MAGIC Gel Dosimeter

Table 1: Summary of Calibration Data

Investigator	a± σ_a	R0± σ_{R0}	σ_{R2}	R^2
This work	1.19 ± 3.02%	5.17 ± 2.28%	1%	0.9973
Gustavsson	4.29 ± 2.2%	1.36 ± 4.4%	2%	0.998

and another study [11]. It should be noted that R^2 is coefficient of the determinant *R*2.

Gustavsson et al. [11] investigated the feasibility of using MAGIC polymer gel dosimetry for intensity modulated radiation therapy (IMRT) verification. In this study, imaging parameters were as follows: 32 echo, TE=22.5 ms and NEX=2 (number of excitation). Table 1 shows that although R^2 value is better for Gustavsson study, the uncertainty value of R_0 for this study is better. Therefore, R^2 value is not a good indicator for assessing quality of calibration.

By simply replacing the uncertainty values of 3.02%, 2.28% and 1% for *a*, *b* and *R*2, respectively, in Eq. (2), the uncertainty for the measured dose was obtained (see Table 2). Figure 2 represents the uncertainty (%) of measured dose as a function of dose (Gy).

Oldham et al. [10] investigated the potential of BANG gel for dose verification of tomotherapy. They uniformly irradiated gels with different doses for studying uncertainty of dose. After calibration process and replacing related parameters in Eq. (2), they concluded that for BANG gel the smallest uncertainty on the dose is achieved for high doses (≈ 3% for 8 Gy) increasing to ≈ 10% for 1 Gy. Also with increasing dose, the uncertainty decreases non-linearly.

Watanabe and Gopishankar [9] examined the accuracy of tomotherapy treatment planning and radiation delivery using BANG3 polymer gel dosimeter with a 3T MRI. In the uncertainty analysis, they found that low doses had biggest uncertainty and high doses had smallest uncertainty. Moreover, the uncertainty for the measured dose decreases non-linearly with increasing dose (i.e., 30% at 0.5 Gy and 5.8% at 4 Gy).

Table 2 shows that for MAGIC polymer gel dosimeter at low doses, the estimated uncertainty is high (≈ 18.96% for 1 Gy) but reduces to approximately 4.17% for 10 Gy. Figure 2 shows that with increasing dose, the uncertainty for the measured dose decreases non-linearly. These results confirm the findings of other mentioned researches and it can be at-

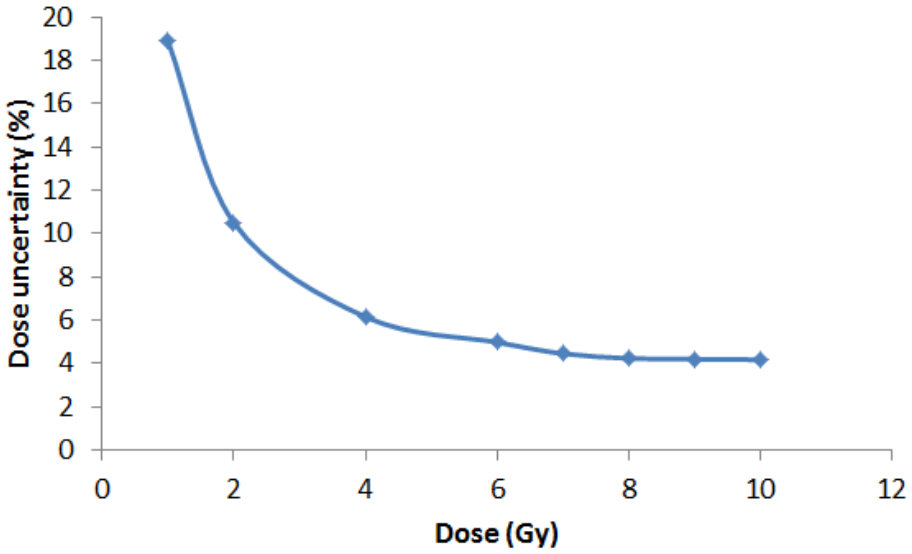

Figure 1: Dose Uncertainty in Dose Map Calculated using Eq. (2)

Table 1: Uncertainty (%) Values for Different Doses

Dose	1	2	4	6	8	9	10
Uncertainty (%)	18.96%	10.5%	6.14%	4.97%	4.23%	4.19%	4.17%

tributed to the fact that with increasing dose, $R2$ value increases and this decreases the uncertainty level. The different values in uncertainty of a given dose for this work and other mentioned works are related to different types of gel dosimeter and MRI parameters used.

It should be noted that, for low doses the most significant uncertainties are σ_{R0} and σ_a for high doses.

An interesting point is that when only relative dose distribution is considered, we can estimate the uncertainty of doses by neglecting the uncertainties of coefficients a and b in the calibration equation Eq. (1). The uncertainty of relative dose is $\sqrt{2}$ times the uncertainty of $R2$ [9, 12]. Therefore for this study, the uncertainty of measured dose is about 1.5% with one standard deviation or 3% for two standard deviations.

In polymer gel dosimetry, usually multiple spin-echo sequence is used because it provides $R2$ maps with higher signal-to-noise ratio. In this sequence, echo spacing (ES), number of echoes, repetition time (TR) and even voxel size should be optimized.

In this study for MR imaging, calibration vials and organ-specific gels were placed in a water tank and then water tank positioned in the head coil. Imaging process was performed in two stages. In the first stage, an inversion recovery pulse sequence was performed to measure T1 value of the polymer gel. In the second stage, multiple spin-echo sequence for $R2$ measurement with mentioned parameters (see materials and method section) was used. Firstly, TR was set to four times the T1 value, but because of long time need to scanning, TR reduced to 5000 ms. It should be noted that the first echo of 32 echoes train because of 180° RF pulse errors was omitted. Another parameter is voxel size that was $1\times1\times5$ mm^2 (5 mm is slice thickness). By altering slice thickness from 3

mm to 5 mm, SNR improved.

It is misunderstanding that always by increasing the number of echoes, the $R2$ value can be estimated more accurately. Longest echoes with signal intensity about noise can result in significant errors in $R2$ estimation. Hence, in this work it was incorporated in $R2$ calculation MATLAB code, a section that echoes which signals are under a specified threshold to be omitted from $R2$ calculation. Theoretical derivations for the optimization of echo time spacing and number of echoes for $R2$ measurements can be found in some articles [7, 13, 14].

Conclusion

Polymer gel dosimetry can be used as a 3D dosimeter for dose verification of advanced radiation therapy techniques. However, the uncertainty of dose map measured by gel dosimeter should be known. The uncertainty in measured dose has two sources: uncertainty due to calibration curve and uncertainty from $R2$ map. The most important source of uncertainty is uncertainty of $R2$. Hence, the MRI protocol and parameters therein should be optimized. In this study, by using Eq. (2) and current data, we concluded that for MAGIC gel and special MRI protocol at low doses, the estimated uncertainty is high (≈ 18.9% for 1 Gy) but reduces to approximately 4.17% for 10 Gy and with increasing dose, the uncertainty decreases non-linearly. Based on current results, it is suggested that in relative dosimetry, gels are irradiated by high doses in linear range of given gel dosimeter and then scaled down to the desired dose range.

Future works will be focused on the effect of B1-inhomogeneity on uncertainty of measured dose and methods to reduce this effect.

Conflict of Interest

None

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