Preliminary study of normoxic PAGAT polymer gel dosimeter by adding formaldehyde

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Abstract. The performance of normoxic PAG (nPAG) gel dosimeter with respect to spatial integrity, temperature sensitivity and dose-rate dependency makes it more reliable than PAG gel dosimeter. As a 3D dose distribution measurement in dosimetry, nPAG gel dosimeter with THPC as anti-oxidant, named PAGAT was studied. 2.9% mass concentration of the formaldehyde solution was added into PAGAT to solidify the gel, named PAGAT-f. The melting point of PAGAT-f polymer gel was increased by adding formaldehyde and can be stored at room temperature after gel preparation without refrigeration. After irradiation with a 9 MV LINAC, magnetic resonance imaging (MRI) is employed as readout modality. It’s found that by adding formaldehyde, R\textsubscript{2}-dose response of PAGAT-f is similar to PAGAT but the dose response sensitivity of PAGAT-f is better than that of PAGAT at low doses. The results prove the feasibility and good temporal stability of PAGAT-f for dose distribution measurement.

1. Introduction

As a novel radiotherapy technique, intensity-modulated radiation therapy (IMRT) is able to deliver high doses of radiation to the target volume without harming the surrounding tissues. It’s realized by the modulation of radiation fields with multileaf collimators that conform the radiation fields during the irradiation [1]. Due to the requirement of accurate radiotherapy, dose distribution becomes complex in IMRT and thus an effective dose measurement is necessary in quality assurance (QA).

Traditional ion chamber is one dimensional measurement and film dosimetry is two-dimensional measurement for dose distribution. Three-dimensional polymer gel dosimeters work on the principle of radiation-induced polymerization which is proportional to the absorbed dose and proportionately affects the spin-spin relaxation time of the gel. The performance of normoxic PAG (nPAG) gel dosimeter with respect to spatial integrity, temperature sensitivity and dose-rate dependency makes it more reliable than PAG and normoxic MAG gel dosimeter [2]. PAG type gel containing N, N'-methylene-bis-acrylamide, acrylamide, water and gelatin was studied by Oldham and Maryanski [3, 4], which is not normoxic. PAGAT is a promising polyacrylamide-based gel in dose distribution verification, which was proposed by Venning [5, 6]. The normoxic gel is composed of water, gelatin, N, N'-methylene-bis-acrylamide, acrylamide and THPC as anti-oxidant. De Deene [7] used ascorbic acid as anti-oxidant to compare nMAG and nPAG type gel dosimeters.
Temperature is a factor that may disturb the ability of gel-based dosimeter to precisely measure dose distributions in that at low temperatures (~25°C) the gel will melt, and three-dimensional dose information is lost [2]. PAGAT gel was stored in a 4 °C refrigerator to solidify [6, 8]. Formaldehyde was used to increase the melting point of MAGIC type gel [9-11] and MAGAT type gel [12] as both of them were not solid at room temperature [13]. 3% in volume concentration of the formaldehyde solution was added into MAGIC gel and the melting point of it increased from 25 °C to 69 °C [9]. In this paper, we add 2.9% in mass concentration of the formaldehyde solution into PAGAT to solidify the gel, named PAGAT-f. Dose response of PAGAT-f and PAGAT was compared to show the potential of PAGAT-f in clinical application.

2. Materials and methods

2.1. Gel preparation
4.9 % gelatin (Type A, Bloom 300, Sigma-Aldrich) was firstly mixed with 86.4 % ultra pure distilled water in a flask stirred magnetically and heated to 50 °C. When the gelatin was completely dissolved, the heater was turned off and the gel was cooled to about 38 °C. After that, 2.9% acrylamide (Energy Chemical) and 2.9% N, N'-methylene-bis-acrylamide (Energy Chemical) was added into the flask. After the dissolution of acrylamide and bis, 2.9 % formaldehyde solution and 10 mM THPC (Energy Chemical) were added. Stirring was keeping during the whole mixing process. The gel was pour into plastic bottles for dose response measurement. PAGAT-f gel was stored at room temperature (~30°C).

| Component                        | Mass concentration |
|----------------------------------|---------------------|
| Ultra pure deionized water       | 86.4%               |
| Gelatin (Type A, Bloom ~300, Sigma-Aldrich) | 4.9%               |
| Acrylamide                       | 2.9%                |
| Bis                              | 2.9%                |
| THPC                             | 10 mM               |
| Formaldehyde (a water solution with 37% minimum and stabilized with 10% methanol) | 2.9% |

2.2. Irradiation and MRI acquisition
The gel was irradiated with a 9 MV beam LINAC. Dose range was 0, 5, 10, 15, 20, 30 Gy. Irradiation was performed with dose fraction 5 Gy/fraction and 10 Gy/fraction. The time interval between fractions was about 3 minutes. The irradiation was eight days after gel preparation. Figure 1 (a) shows the gel irradiation setup.

Magnetic resonance (MR) images were acquired five days after irradiation. MR spin echo images to evaluate $R_2$ were obtained with a 3.0 T scanner (Philips Achieva TX) with a head coil as shown in Figure 1 (b). The scanning room temperature was 18 °C. A 16-echo multi-spin echo (MSE) sequence was used for MR images. Detailed parameter is shown in Table 2. The gel was scanned 4 days and 12 days after irradiation in order to assess the temporal stability of it.
3. Results & Discussion

3.1. Dose response

Figure 2 shows the gel tube after irradiation. The gel becomes white opaque from initial transparent state. T2 weighted map was obtained after MR imaging as shown in Figure 3. A circle with a square of 250 mm2 was chosen for mean R2 calculation. R2 was measured with two slices at 5 mm and 10 mm from bottom respectively. R2 dose response was then fitted and compared with the R2-dose curve of Zhao [14] and Pourfallah [15] as shown in Figure 4. It’s observed that the dose response sensitivity of PAGAT-f is better than that of PAGAT. Fitted R2-dose relationship for 5 mm and 10 mm is $R2 = -0.001048d^2 + 0.08074d + 1.658$ and $R2 = -0.001224d^2 + 0.08683d + 1.687$ respectively, where $d$ is dose. R-square for each fitting curve is shown in Figure 4.

![Figure 1. (a) Gel irradiation setup and (b) MRI facility with a head coil.](image1)

![Figure 2. Gel tube after irradiation (from left to right: 0, 5, 10, 15, 20, 30 Gy).](image2)

Table 2. Sequence parameter of MRI.

| Parameter              | Units | Value   |
|------------------------|-------|---------|
| Echo spacing           | ms    | 22.5    |
| Maximum echo time (TE) | ms    | 360     |
| Repetition time (TR)   | ms    | 3000    |
| Field of view (FOV)    | mm    | 180     |
| Matrix size (MS)       | pixels| 512×512 |
| Slice thickness        | mm    | 4       |
| Number of excitations (NEX) |   | 2       |
3.2. Dose response sensitivity
Dose response sensitivity of PAGAT-f at 5 mm and 10 mm high slice from bottom, which is represented by $\frac{dR_2}{dd}$, is plotted as a function of absorbed dose as shown in Figure 5. The results are also compared with PAGAT sensitivity from Zhao [14] and Pourfallah [15]. $R_2$ sensitivity of PAGAT-f is better than that of PAGAT from 0 Gy to about 18 Gy. $R_2$ sensitivity of PAGAT-f is then less than that of PAGAT, making the saturation of $R_2$ dose response comes earlier for PAGAT-f.

3.3. Temporal stability and deviation
PAGAT-f gel dosimeter has great temporal stability as shown in Figure 6 (a). The $R_2$ was measured 4 days and 12 days after irradiation. The greatest deviation is only 3%. This proves good temporal stability of PAGAT-f gel dosimeter.
4. Conclusion
This paper adds formaldehyde into PAGAT to solidify the gel, named PAGAT-f. By adding formaldehyde, the melting point of PAGAT-f was increased and can be stored at room temperature. It’s found R2-dose response of PAGAT-f is similar to PAGAT but the dose response sensitivity of PAGAT-f is first better compared with PAGAT at low doses (<~18 Gy). R2 sensitivity of PAGAT-f is then less than that of PAGAT, making the saturation of R2 dose response comes earlier for PAGAT-f. The results preliminarily show the feasibility and good temporal stability of PAGAT-f for dose distribution measurement and clinical application. Further study will be focused on temperature dependency and dose fraction influence on PAGAT-f gel dosimeter.

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6. References
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