Application of a PAGAT/MgCl$_2$ gel for dose measurements in a 150 MeV proton beam

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Abstract. The purpose of this study is to evaluate the dose response of polyacrylamide-based gel (PAGAT) when irradiated with clinical proton beams. Recently inorganic salt additive in gel has been reported to improve dose sensitivity substantially. We attempted to add MgCl$_2$ (0.5M) to regular PAGAT gel in order to compensate its lower radiation sensitivity. The spin-spin relaxation rates ($R_2$) as dose readout was calculated from MR imaging after irradiation with 150MeV proton beam. The dose sensitivity was discussed from the slope at dose-$R_2$ response curve. As the result, the sensitivity of the gel with MgCl$_2$ is approximately 3 times higher than that of regular PAGAT gel without spoiling dose response stability under the various irradiation conditions such as dose rate and dose integration.

1. Introduction

Recent studies show that polymer gel detectors are the most promising three-dimensional dosimetric tools for external photon beam radiotherapy [1]. However, in dosimetric verification of clinical proton beams, strong suppression of Bragg peak due to LET has been reported in polymer gel measurements [2].

We have investigated the radiological characteristics of gel in an irradiation to proton beam, and reported the method to estimate dose using multi-Dose-$R_2$ relations [3] in consideration of beam location in the gel detector from incident point of beam [4]. In previous studies, a methacrylic-acid-based gel (MAG) has been used, which has advantage in radiation sensitivity, but disadvantage in dose response stability under the various irradiation conditions such as dose rate, dose integration and the thermal condition. While it has been reported that polyacrylamide-based gel (PAG) [5] had produced low-contrast images due to the low radiation sensitivity, but had an advantage in dose response stability [6].

Recently Hayashi et al. [7] have investigated the effect of inorganic salts on the dose sensitivity of MAGAT gel [8], and reported substantial increase in the radiological response of the gel with containing inorganic salt, especially MgCl$_2$ improved dose sensitivity approximately 3 times. Their results indicated that inorganic salts as additive acted as an accelerator for radiation-induced free-radical polymerization in gel. They have reported that inorganic salts are also effective in PAGAT gels [9] too [10].

In this study, we attempt MgCl$_2$ to add to PAGAT gel in order to compensate its lower radiation sensitivity without spoiling dose response stability in the irradiation of 150 MeV proton beam, and examine its improved response on the suppression of Bragg peak.
2. Materials and methods

We prepared two types of polyacrylamide-based gel for this study. One is a regular PAGAT gel consisting of water, gelatin, acrylamide as a monomer, \(N,N'\)-methylene-bis-acrylamide as a cross-linker and tetrakis-hydroxymethyl-phosphonium chloride (THPC) as an oxygen scavenger [11, 12]. The other has basically same composition as a regular PAGAT gel, but with \(\text{MgCl}_2(0.5\text{M})\) additive. We will refer to this gel from here on as PAGAT/MgCl\(_2\) gel. The compounded gelatin solution was divided into 12 cm test tubes for the measurements of spread-out depth dose in the gel. All samples were irradiated in a fixed horizontal 150 MeV proton beam at the facility of the Hyogo Ion Beam Medical Center. In irradiations, a test-tube-sample was set between two tough water phantoms (Kyoto Kagaku Co., WE-3015) and was placed along the beam line including 3 cm SOBP. First of all doses of 2, 4, 8, and 16 Gy were delivered to compare dose response of the above two type of PAGAT gels. At this time, the dose rate of 4 Gy/min typically applied in treatments was fixed in SOBP irradiations. Secondary the dose rate was varied to 1 Gy/min to examine the dose rate dependence on the response. And finally the dose integration property of the gel detector in the multiple field irradiations is examined by irradiating 3 Gy after 1 minute post-irradiation of 3 Gy to be compared with that of 6 Gy single exposure. MR analysis [13] was performed at 1.5T TOSHIBA Excelart Vantage scanner using Quadrature Torso coil 3 days after irradiation. MR images of samples were recorded with a double spin-echo sequence at echo times TE\(_1\)=30 ms, TE\(_2\)=250 ms with a repetition time TR=4 sec. Maps of the R\(_2\) were calculated from the signal intensity at TE\(_1\) and TE\(_2\). Relative R\(_2\) resolution was estimated to 5% in the R\(_2\) range less than eight.

3. Results and Discussions

3.1. Dose-R\(_2\) sensitivity

The dose responses of two types gel applied to proton beams are shown in Figure1. The data points were obtained by averaging R\(_2\) value at the central region of SOBP irradiated with different dose. The open circles show the R\(_2\) response in the regular PAGAT gel, and the solid circles show that in the PAGAT/MgCl\(_2\) gel in an irradiation. These were fitted by polynomial relation, but Dose-R\(_2\) response can be regarded as linear at dose less than 10 Gy. The R\(_2\) value in both gels at 0 Gy has no difference, but the average gradient at dose response curve for PAGAT/MgCl\(_2\) is about 3 times larger than that of regular PAGAT, and the gradient is getting close above 10 Gy closing to R\(_2\) maximum.

3.2. Dose profiles

Figure 2 shows depth dose profiles in PAGAT/MgCl\(_2\) gel at post proton irradiations with various amount of dose. A total of 12, 9, 6, 3 Gy were delivered to the SOBP of proton beam.
3.3. Dose-rate dependence

A comparison of depth dose profiles for a beam of 6 Gy at dose rate 4 Gy/min (open circles) and that at 1 Gy/min (solid circles) in PAGAT/MgCl$_2$ gel is presented in Fig. 3. The dose profile at 1 Gy/min gives overall 2-3% higher dose than that at 4 Gy/min. This result corresponds to the dose-rate dependence of the dose sensitivity in a proton beam which has been previously reported in MAG type gel, but it is very small in PAGAT/MgCl$_2$ gel compared to 25% deference in MAG type gel [4].

3.4. Dose-integration dependence

A comparison of depth dose profile of total of 6 Gy by single exposure and by double exposure (3 Gy + 3 Gy) is presented in Fig. 4. The profile in the double exposed PAGAT/MgCl$_2$ gel shows good overall agreement at depth with that in the single exposed gel.
4. Conclusion
In this work, we concerned with the R₂ dose response of PAGAT/MgCl₂ gel in the irradiation of proton beam. So far PAG type gel has been said not to be suitable for dose measurement for proton beam due to its low dose sensitivity [14]. However it became the most promising three-dimensional dosimetric tools for proton beam radiotherapy as the results of sensitivity and dose resolution improved by MgCl₂ additive. And for the SOBP profile in PAGAT/MgCl₂ gel, the suppression at the distal end is a quite small such as less than 5%. Recently the BANG3-Pro2 gel (MGS Research Inc), which was formulated specifically for proton beam dosimetry, showed no dose quenching in the Bragg peak region in the measurement by optical CT readout system [15]. But it is not sure that this gel has not observed dose quenching even in the R₂ dose response using MRI, which is more convenient readout in the clinical use. At the further direction of our study we will pursue PAGAT/MgCl₂ gel’s possibility to be used as QA tool for 3D dose verification in proton therapy by means of comparison the gel dose map to treatment planning system calculations.

5. References
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