MRI-based iPAGAT polymer gel dosimetry using fast recovery spin echo sequences

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Abstract. In an estimation of iPAGAT polymer gel dosimeters using a magnetic resonance imaging (MRI) system, the dosimetric characteristics were investigated with two echo sequences: a spin echo (SE) and a fast recovery fast spin echo (FRFSE) sequence. FRFSE can shorten total scan time compared to SE because of its short repetition time (TR) and long echo train length (ETL). Although the R2-dose response measured from FRFSE was decreased compared to SE, both responses were fitted quadratic curve with a high correlation coefficient. In addition, their calibrated dose distributions showed high conformity to the planned data in the three-dimensional (3D) gamma index, dose volume histogram (DVH) and surface rendering analyses; however, results of SE were a little superior to FRFSE. In conclusion, it is suggested that FRFSE can present the accurate characteristics of polymer gel dosimeters under the optimum parameters.

1. Introduction
Polymer gel dosimeters consist of radiosensitive materials and form chemical polymerizations by irradiation [1-4]. A major advantage of these gel dosimeters is their ability to record three-dimensional (3D) dose distribution when compared to two-dimensional (2D) dose distribution [5] such as films. In the readout and dosimetric analysis, magnetic resonance imaging (MRI), especially a single spin echo (SE) or multi-echo spin echo (MSE) sequence, is regarded as the first choice [6]. However, because the SE sequence generally takes a long time to scan and often limits the use of gel dosimeters to a clinical setting, other sequences that are capable of taking images in a shorter time compared to the SE sequence, while also maintaining image quality, seem to be required. In contrast, a fast recovery fast spin echo (FRFSE) sequence can shorten total scan time because of its short repetition time (TR) and long echo train length (ETL). The purpose of this study is to compare the dosimetric characteristics between two MRI sequences, SE and FRFSE, using a customized PAGAT polymer gel dosimeter with improved dose sensitivity (iPAGAT).
2. Materials and methods

2.1. Preparation of iPAGAT
A polyacrylamide-based gel dosimeter with improved dose sensitivity (iPAGAT) was prepared that we had developed in a previous study, containing 4.9% w/w gelatin, 2.9% w/w Acrylamide, 2.9% w/w \(N,N'-\text{methylenebisacrylamide} \), 10 mM THPC, and 0.3 M magnesium chloride (2.5% w/w) as a sensitizer [7-10]. First, the gelatin was added to distilled water and the solution was heated to 50°C in a water bath. Next, the other reagents were added and mixed using a hot magnetic stirrer while maintaining at 40°C. Finally, the solutions were poured into two cubic acrylic containers (10 × 10 × 10 cm\(^3\)), cooled down, and stored in an incubator at 20°C until irradiation.

2.2. Irradiation
A volumetric-modulated arc therapy (VMAT) plan with 6 MV photon beam and a single fraction of 2 Gy was created for the C-shape structure, in addition to a step-and-shoot intensity-modulated radiotherapy (IMRT) plan to obtain the dose calibration curve using the Eclipse treatment planning system (TPS). Both the VMAT and IMRT plans were irradiated to the iPAGAT dosimeters inserted into the IMRT Phantom (IBA Dosimetry, Germany) by the Novalis Tx linear accelerator (Varian/BrainLAB, Palo Alto, CA/Germany).

2.3. MRI readout
Two days after irradiation, the iPAGAT dosimeters were read out by the 3.0 T MRI system (Discovery MR750, GE Healthcare, Waukesha, WI). To enable dosimeters to adjust to the MRI scanning room temperature (approximately 21.5°C), they were stored in the MRI scanning room for a period of several hours prior to the readout. R2 measurements were performed employing three different MR pulse sequences as dual-echo SE (SE2), dual-echo FRFSE (FRFSE2) and quad-echo FRFSE (FRFSE4). The SE2 parameters were: TR = 7000 ms, TE = 20 and 250 ms, slice thickness = 3 mm, FOV = 256 × 256 mm\(^2\), matrix size = 256 × 256, NEX = 1, and scan time = 104 min. While the FRFSE2 parameters were: TR = 3000 ms, TE = 20 and 350 ms (the effective echo times were 22.176 and 349.272 ms), ETL = 128, slice thickness = 3 mm, FOV = 256 × 256 mm\(^2\), matrix size = 256 × 256, NEX = 4, and scan time = 22 min. And the FRFSE4 parameters were: TR = 3000 ms, TE = 100-500 ms (the effective echo times were 99.568, 199.136, 298.704 and 497.84 ms), ETL = 128, slice thickness = 3 mm, FOV = 256 × 256 mm\(^2\), matrix size = 256 × 256, NEX = 2.

2.4. 3D dose analysis
First, an R2 map images with each sequence was created on both phantoms, where the R2 value is known as the spin-spin relaxation rate and is the inverse of T2 relaxation time. Regarding SE2 and FRFSE2, R2 values were calculated using signals measured with two different echoes. On the other hand, regarding FRFSE4, R2 values were calculated from linear regression with four different echoes.

Secondly, an R2-dose response curve with each sequence was investigated on the basis of the R2 map image of the calibration phantom. And then, for the purpose of adjusting its dose levels to the C-shape phantom, this curve was calibrated by two different R2 values which were selected manually within the lowest and highest irradiated areas of the C-shape phantom.

Finally, all R2 values of the C-shape phantom with each sequence were translated to suitable dose values with the calibrated dose-response curve, thereby a dose map of the C-shape phantom was created. After that, the dose map of each sequence was compared to the planned theoretical one, and a conformity of them was investigated using the three-dimensional (3D) gamma index, dose volume histogram (DVH), and surface rendering analyses. These analyses were all performed using in-house-developed software.
3. Results
The irradiated iPAGAT dosimeters clearly precipitated (Fig. 1). Within the calibration phantom, the theoretical dose values of 9 divisions were 16.2, 66.0, 111.2, 161.4, 212.6, 256.5, 300.6, 352.2 and 394.5 cGy in ascending order. On all MRI sequences, the R2-dose responses of the calibration phantom were fitted quadratic curve with a high correlation coefficient (SE2: 0.999, FRFSE2: 0.999 and FRFSE4: 0.999), and they were calibrated in an approximate dose range of the C-shape phantom and fitted likewise (SE2: 0.999, FRFSE2: 0.999 and FRFSE4: 0.999) (Fig. 2).

![Figure 1](image1.png)

**Figure 1.** Irradiated iPAGAT dosimeters: step-and-shoot IMRT for the dose-response curve (a) whose doses were 16.2~394.5cGy and VMAT for the C-shape while avoiding core structure (b).

![Figure 2](image2.png)

**Figure 2.** R2-dose response curves of the iPAGAT calibration dosimeter on each MRI sequence: SE2 (a), FRFSE2 (b) and FRFSE4 (c).

In regard to the dose maps of the C-shape phantom, a considerable conformity to the planned one was observed on all sequences, namely the pass rates of the 3D gamma index analysis using 3%/3 mm criteria in the axial plane achieved more than 99% (SE2), 93% (FRFSE2) and 99% (FRFSE4) (Fig. 3). With respect to similarity of the DVH and surface rendering analyses, there were no significant difference visually among three sequences (Fig. 4).
Figure 3. Axial images of the 3D gamma index analysis compared between the planned dose map and the measured one with each MRI sequence: SE2 (a), FRFSE2 (b) and FRFSE4 (c).

Figure 4. DVH curves for the C-shape using the planned data and the measured one with each MRI sequence: SE2 (a), FRFSE2 (b) and FRFSE4 (c).

Figure 5. Surface rendering images of the 95% isodose volume for the C-shape using the planned data (red) and the measured one (blue): SE (a), FRFSE2 (b) and FRFSE4 (c).

4. Discussion
The readout technique of the uniquely recorded radiation dose in a polymer gel dosimeter using MRI was explored and well established in the previous study, and De Deene suggested that medical physicists should have an understanding of the basic principles of MRI, the optimization of quantitative imaging sequences, and protocols [11]. In this study, three MRI pulse sequences, namely dual-echo SE, dual-echo FRFSE and quad-echo FRFSE, were compared with the dosimetric characteristics of iPAGAT dosimeters. A foremost feature of a fast spin echo (FSE) sequence is that it can record plural different
areas of k-space simultaneously because of its rather long ETL. In other words, the k-space is divided into several sections and the scan time is shorter depending on ETL compared to standard SE sequences. Furthermore, the FRFSE sequence is an enforced recovery of transverse magnetization that cannot be absolutely relaxed to longitudinal magnetization, carried out by a negative 90-degree pulse following FSE data acquisition. By means of the above process, the image contrast can be acquired by much shorter TR compared to FSE. Papoutsaki researched dosimetric characteristics using two pulse MESE sequences and a new multi-echo single-shot turbo spin echo pulse sequence (MEHASTE) for VIPET polymer gel dosimetry, and both techniques showed a linear R2-dose response. And also, MEHASTE sequences were significantly faster than MESE sequences due to their inherent design (higher ETL factor) [12].

Although the above-mentioned FRFSE sequence techniques are very useful in clinical due to their short scanning time, there are also several problems in relation to performing T2 quantitative evaluation. One of such problems is the MT (Magnetization Transfer) effect that leads to a low image contrast caused by the excitation of wide-range of frequency protons including bound water and off resonance by the 180-degree pulse of other slices while multi-slices are acquiring. Also, the T2 filter effect, that is caused by the existing different TE signal data in k-space depending on the increase of ETL, leads to a blurred image. Furthermore, though several factors may contribute to the bright fat phenomenon with FSE, the dominant mechanism is thought to be T2 prolongation secondary to the disruption of J-coupling interactions that normally take place between adjacent fat protons; therefore, the signal of the non-irradiated region in the polymer gel dosimeter is not decreased with the FSE sequence due to the shorter 180-degree pulse interval compared to factor J.

Actually, the measured absolute R2 values of FRFSE sequence are not adequate against the SE sequence by less than approximately 30%, and the contrast of FRFSE images are visually lower than that of SE. On the 3D gamma index analysis of the C-shape phantom, remarkable disagreement between the FRFSE2 dose distribution and the planned one is observed on the posterior region to the PTV of the C-shape structure in the axial plane. This disagreement is significantly improved on the FRFSE4 dose distribution and its pass rate reaches nearly equal to SE, while those in the coronal and sagittal plane is still a little inferior to SE. Considering the above limitations, these results should be improved by optimum MRI conditions in further studies. Regarding the results of the DVH and surface rendering analyses on FRFSE4 sequence, some irregularities in their shapes stand out against other sequences, so an improvement of the in-house software is thought to be required. In addition, De Deene also reported that a difference in the temperature history between the calibration vials and verification phantom pre-irradiation has an effect on R2-dose sensitivity [13]. In this study, we used the same calibration phantom and a simple normalizing method as the “two-point” calibration to overcome the difficulties. Eventually, though an analysis of MRI with the FRFSE sequence is worthwhile in shortening its total time significantly, it seems to require more consideration on the comparison of 3D dosimetric characteristics against planned theoretical data.

5. Conclusion
In the MRI based iPAGAT polymer gel dosimetry with dose responses and distributions, the FRFSE sequence can shorten total scan time greatly compared with SE, so it has some possibility of rendering a clinical usage of polymer gel dosimeters more user-friendly. However, it has several issues of assuring image quality, and further improvement is required.

6. References
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