Basic characteristics of an AQUAJOINT®-based VIPET polymer gel dosimeter

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Abstract. The basic characteristics of a VIPET-type polymer gel dosimeter were assessed using AQUAJOINT® as a hydrogel matrix. The dosimeter exhibited a good dose response. The threshold dose was 0.5–0.6 Gy and the linear section of the response curve, in the range of 1.7–2.7 Gy, had a minimum dose response of 0.05–0.06 Gy. The dose-rate dependence was determined by the delivery of 200 MU for dose rates between 100 and 600 MU/min; the resulting value of R2 was 3.222 ± 0.036 (mean ± 1SD). A slight change in the value of R2 in the integration of the divided doses was observed; the R2 value was 3.059 ± 0.015 (mean ± 1SD) for a total irradiation of 200 MU. Gel samples of different volumes were irradiated and compared with a PAGAT polymer gel. The change in sensitivity of the AQUAJOINT®-based VIPET was smaller than that of the PAGAT.

1. Introduction
AQUAJOINT® is a heat-irreversible, physical hydrogel consisting of a water-soluble polymer and inorganic nanoparticles in water. Mixing the gel precursors of liquid A and B forms a self-standing hydrogel at room temperature through the electrostatic interaction of these components in water.

Normoxic N-vinylpyrrolidone polymer gel (VIPET) is a three-dimensional dosimetric tool with radiation-induced polymerization depending on the radiation dose [1]. AQUAJOINT®-based VIPET gel dosimeters have previously been reported, and the gels were irradiated using industrial 250 kVp X-ray equipment [2,3,4]. In this study, we present the preliminary measurement results of the basic characteristics of AQUAJOINT®-based VIPET gels irradiated by a 10 MV X-ray from a medical linear accelerator (LINAC), including the effect of container size, in comparison with a PAGAT polymer gel.

2. Materials and methods

2.1 AQUAJOINT®-based VIPET gel dosimeter fabrication
We prepared a dosimeter mixture by first dissolving the monomer N-vinyl-2-pyrrolidone (NVP), the bifunctional monomer N,N'-methylene-bis-acrylamide (BIS), oxygen scavenger tetrakis-(hydroxymethyl)phosphonium chloride (THPC), and AQUAJOINT® B-5 (Nissan Chemical Corporation, water content: 86%) in deionized water. The addition of AQUAJOINT® A-5 (Nissan Chemical Corporation, water content: 81%) to the aqueous solution yielded a homogeneous system comprising a gel matrix with monomers. The resultant mixture contained 8% NVP, 4% BIS, 50 mM THPC, 11% AQUAJOINT® A-5, and 11% AQUAJOINT® B-5. The resulting gel precursor was poured into polyethylene terephthalate (PET) vials of three sizes (mouth inner diameter × body diameter × total height) — 30 mL vials (14.8 mm × 30.5 mm × 78.7 mm), 50 mL vials (14.8 mm × 34.2 mm × 89 mm), and 100 mL vials (14.8 mm × 40.2 mm × 117.8 mm) — and into 500 mL fluorine-treated polypropylene vials (45.0 mm × 77 mm × 161 mm). The gel vials were then stored at 4 °C.

2.2 PAGAT gel dosimeter fabrication

PAGAT gel dosimeters [5] were prepared using 89% w/w deionized water, 3% acrylamide (AAm), 3% BIS, 5% gelatin (300 bloom), and 10 mM of THPC. Gelatin was added to stirred water in one portion at room temperature and was then stirred for 10 min, after which the solution was heated at 40 °C for 10 min. AAm and BIS were then added, in this order, to the gelatin solution which was subsequently stirred at 40 °C for 10 min. Next, THPC was added and the solution was stirred at 40 °C for 1 min. The resulting mixture was poured into the PET vials (30 mL, 100 mL, and 500 mL). The gel vials were then stored at 4 °C.

2.3 Sample irradiation

A sample vial was submerged in a water phantom, used to calibrate the monitor unit of the LINAC (figure 1). After aligning the center of the vial with the isocenter and securing it with a custom-made jig, the vial was irradiated from above. The applied X-ray energy was 10 MV, and the beam delivery parameters of the LINAC (CL-iX, Varian Medical Systems, Palo Alto, CA) were as follows: the source-to-axis distance (SAD) was 100 cm, the measurement depth was 10 cm, and the irradiation field size was 10 cm².

2.4 Validation items (basic characteristics)

The vials of AQUAJOINT® gel (50 mL) were irradiated and the basic characteristics were verified. Validation items were as follows: dose response (0–10.2 Gy, 0–2.5 Gy, and 1.7–2.7 Gy, 600 MU/min), dose rate characteristics (total 200 MU, 100–600 MU/min), and dose reproducibility (total 200 MU divided into 1, 2, 4, 10, 20, and 40 fractions, 600 MU/min).

2.5 Validation items (effect of container size)

Samples of AQUAJOINT®-based VIPET and PAGAT with different volumes (30, 100, and 500 mL) were used. All samples were left to stand at room temperature for 9 h and were then irradiated (0–8.5 Gy). Subsequently, the vials were stored in the dark at room temperature (24–25 °C) for 24 h (figure 2).
2.6 Scan and analysis of MRI
The magnetic resonance imaging (MRI) measurements of all samples were carried out 24 h after irradiation. The AQUAJOINT®-based VIPET and PAGAT were kept under the same conditions until they were imaged by MRI after irradiation, and the temperature returned to room temperature. Using the head coil, the isocenter plane at the time of irradiation was imaged with a T2 image using a multi-slice spin-echo sequence. The equipment and scan conditions used were as follows: 1.5-T MRI (Avant, Siemens Healthcare), TR = 4000 ms, TE1 = 30 ms, TE2 = 136 ms. The pixel size was 1.0 mm and the slice width was 3.0 mm. After converting the MRI image to the R2 image using the ImageJ software, the pixel value within the isocenter plane was read out.

3. Results and discussion

3.1 Basic characteristics of AQUAJOINT®-based VIPET
The response characteristics corresponding to the absorbed doses are shown in figure 3.

![Figure 3](image_url)

Figure 3. Basic properties of AQUAJOINT®-based VIPET polymer gel dosimeters.
(a) Dose–response curve.
(b) Dose–response characteristics (0–2.5 Gy)
(c) Dose–response characteristics (1.7–2.7 Gy)
(d) Integral dose characteristics.
(e) Integral dose characteristics.
The dose-R2 curve can be well approximated by a linear plot between 1 and 7 Gy. The usual dose prescribed by radiotherapy is in the range of 1.4–8.0 Gy, which shows that it had a sufficient dynamic range (figure 3(a)). The R2 value was gradually increased in the low dose range, and the threshold dose was approximately in the range of 0.5–0.6 Gy (figure 3(b)). To reduce the threshold dose, we are going to optimize the chemical compositions and gel preparation procedures. When the measurement was performed in the dose range (1.7–2.7 Gy), where linearity of the response curve was ensured, the minimum dose-response was in the range of 0.05–0.06 Gy (figure 3(c)).

The dose-rate dependence was determined by delivering 200 MU for dose rates between 100 and 600 MU/min, the resulting R2 value was 3.222 ± 0.036 (mean ± 1SD). No significant dose-rate dependence was observed (figure 3(d)). The dose reproducibility was confirmed by a total irradiation of 200 MU through multiple irradiations. When the number of divisions of irradiation was increased, the R2 value was slightly overestimated compared to the value obtained with a single irradiation. The change in the R2 value was 3.059 ± 0.015 (mean ± 1 SD).

3.2 Response characteristics of different volume samples
In this preliminary experiment, the difference of the R2 value of non-irradiated PAGAT samples was larger than that of the AQUAJOINT®-based VIPET (figure 4). The R2 values of 500 mL were -17.2% (PAGAT) and -7.1% (AQUAJOINT®-based VIPET), compared to that of the 30 mL samples.

The difference in sensitivities between samples of different volumes were reported to be caused by the effect of thermal history [6,7]. A report that verified the relationship between the temperature change inside the gel and the R2 value generated at the time of irradiation, concluded that the thermal history at the time of preparation of the gel is a cause of the sensitivity difference [8]. In contrast, as previously mentioned, the gel precursors of AQUAJOINT® liquid A and liquid B form a hydrogel at room temperature. It is considered that the thermal change during fabrication was small.

Converting the graph in figure 4 from dose vs. R2 to dose vs. ΔR2 shows that the variation of the R2 value is significant due to deference of the R2 value of un-irradiated samples. The response of the PAGAT was non-linear in the range of 0-8.5 Gy, and its sensitivity was low (figure 5(a)). Contrarily, the sensitivity of the AQUAJOINT®-based VIPET was nearly twice that of the PAGAT, and the AQUAJOINT®-based VIPET exhibited linear dose responsiveness (figure 5(b)). Clinically, phantoms in the range of 500–2000 mL can be used, and it is desirable to use smaller samples to acquire a characteristic curve. The AQUAJOINT®-based VIPET has the effect of relatively reducing the error of R2 values.
4. Conclusions

The fundamental characteristics of a gel dosimeter prepared using AQUAJOINT® hydrogel as a gelling agent were examined. The AQUAJOINT®-based VIPET polymer gel dosimeter exhibited good responsiveness to the irradiation dose. In addition, the dose response due to the change in gel volume was smaller than that of PAGAT.

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Figure 5. Dose-$\Delta R_2$ response curve of different volume samples: (a) PAGAT and (b) AQUAJOINT®-based VIPET. Each value is the average of three samples.