Spatial dose distribution analysis of Co-60 HDR brachytherapy of cervical cancer using an AQUAJOINT®-based VIPET polymer gel dosimeter

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Abstract. High-dose rate brachytherapy treatment has become more complicated with the use of three-dimensional image-guided brachytherapy (3D-IGBT) to prepare treatment plans using 3D images, such as those obtained from computed tomography (CT). In planning a 3D-IGBT, spatial measurement of dose distribution verification is recommended. In this study, the spatial dose distribution of intrauterine cavity irradiation by a Co-60 sealed brachytherapy source was acquired using an AQUAJOINT® polymer gel dosimeter. A CT/magnetic resonance imaging (MRI) compatible applicator was inserted into the gel in a bottle. It was irradiated and visualized using MRI. The image was converted to an R2 image using a DD-System (R-TECH INC, Japan), and dose distribution was evaluated using the dose–R2 response curve. The obtained dose distribution, dose profile of the radiotherapy treatment planning system, isodose curve, and gradient passing were calculated. In the dose profile, the dose difference was large near the applicator (high-dose region) and was less than ±2% in the middle-dose region. The isodose curves showed good agreement in the region of 2–6 Gy near the prescription point. The gamma analysis was 87.594% on the sagittal cross-section and 93.711% on the coronal cross-section based on the dose difference (DD)/distance to agreement (DTA) of 3%/3 mm.

1. Introduction

For external radiation therapy, dose distribution verification is performed using various film and semiconductor detectors, and the use of three-dimensional (3D) detectors is also increasing [1-3]. In contrast, verifying the spatial dose distribution in brachytherapy is difficult, and verification by point measurement is a realistic method. In clinical practice, we are moving to 3D-image-guided brachytherapy (IGBT), which plans and treats three-dimensionally, using computed tomography (CT) and magnetic resonance imaging (MRI) for the treatment of cervical cancer. 3D-IGBT leads not only to general intraluminal irradiation but also hybrid irradiation combined with interstitial irradiation that...
needs to be performed in complicated treatment plans. Shifting to 3D-IGBT, spatial measurement of dose distribution verification is recommended. However, no practical individual measurement devices exist, and the validation of individual patient’s plans has not yet been conducted. A previous study using Fricke gel dosimeter for Ir-192 intracavitary brachytherapy for cervical cancer has been reported [4]. To our best knowledge, there is no measurement report of Co-60 using a polymer gel dosimeter, and gradient passing rate similar to external irradiation has not been evaluated.

In this study, an AQUAJOINT®-based polymer gel dosimeter developed by RIKEN and Nissan Chemical Corporation was used [5-7]. AQUAJOINT® is a physical hydrogel formed by mixing two liquids at room temperature. The gel is stretchable, and the elastic property enables an applicator to be inserted into the gel. We aimed to obtain and analyze spatial dose distribution of Co-60 sealed brachytherapy for cervical therapy using an AQUAJOINT®-based VIPET polymer gel dosimeter.

2. Materials and Methods

2.1. Gel dosimeter fabrication
We prepared a dosimeter mixture by first dissolving N-vinyl-2-pyrrolidone (NVP), N,N’-methylene-bis-acrylamide (BIS), 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 yields a homogeneous system comprising of 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 gel precursor was poured into eleven 50 mL PET vials to prepare the response curves for the dose–R2. One 2-L gel dosimeter was prepared to insert an applicator. The bottle was a fluorine-treated polypropylene cylindrical container. Three holes adjusted to the applicator were drilled in the lid of the bottle and the CT/MRI compatible applicator was inserted and fixed. After preparation, it was sealed in a nitrogen-purged aluminum laminated bag.

2.2. Irradiation Planning
In order to prepare the response curve of the dose–R2, a radiation treatment planning system (RTCP, SagiPlan®, Eckert & Ziegler BEBIG, Germany) calculation was performed to irradiate stepwise from 0 Gy to 56 Gy on a slice plane 3.5 mm from the center of the radiation source. We planned to shoot the sample with CT (Optima 580 W, GE, imaging conditions: 120 kV, 335 mA, slice thickness 2.5 mm) and irradiate point A, which is the prescription reference point for intrauterine cavity irradiation, at 4 Gy.

2.3. Irradiation
Vials to prepare the response curve were placed in water with the plastic applicator fixed with adhesive (Figure 1 (a)). Then, irradiation was performed with a small source irradiation apparatus, MultiSource® (Eckert & Ziegler BEBIG, Germany). A 2-L gel sample was connected to the CT/MRI compatible applicator and irradiated based on the treatment plan (Figure 1 (b)).

2.4 MRI scan and analysis
Imaging was performed using MRI (MAGNETOM Avant, Siemens Healthcare) 24 h after irradiation. The imaging conditions were TR = 4000 ms, TE 1 = 30 ms, TE 2 = 136 ms, slice thickness = 3 mm, and FOV = 256 × 256 pixels using multi-SE sequence.

Depending on the direction of frequency and phase, whether metal artifacts appeared were examined in advance. A CT/MRI compatible applicator was placed in the water, and images were compared by changing the direction of frequency and phase parallel or perpendicular to the applicator.
2.5 Profile analysis
Using Image J, the R2 (R2 = 1/T2, s⁻¹) image was created from the MRI image. A region of interest (ROI) was set on the R2 image of the vial, and the R2 value was read to create a response curve (Figure 2). In the DD-System (R-TECH INC, Japan), the R2 image of the sample (Figure 3) was converted into a dose-distribution map. In addition, the dose profile was created by converting the R2 value of the sample using the response curve. We obtained the planned dose distribution from RTPS and compared and analyzed the same section and profile of the AQUAJOINT®-based VIPET polymer gel dosimeter. The profile to be analyzed was the axial section including point A, which was defined as the prescription point. Since the value was saturated in the high dose range after 30 Gy of the response curve, the analysis that results up to a 1 cm distance from the center of the radiation source was excluded because the R2 value has no dose dependency.

2.6 Gradient and gamma analyses
The data were transferred from RTPS to the DD-System through the radiation treatment planning support device, MIM Maestro™ (MIM Software, USA). MIM Maestro™ extracts the dose distribution of an arbitrary cross-sectional data. Sagittal and coronal cross-sections, which are characteristic for intrauterine cavity irradiation, were prepared with the same cross-section as the MRI image. The isodose curve and gradient analysis [8] were calculated for the dose distribution of RTPS and gels as converted by the DD-System.
3. Results and Discussion

3.1 MRI artifacts

Despite a CT/MRI compatible applicator, metal artifacts were apparent (Figure 4). The image with the phase direction set in the axial direction (AP) of the applicator indicated an influence of artifacts of 10-15 mm. By contrast, the artifact was within 10 mm in the orthogonal direction (RL) (Figure 5). In the RL, the metal area of the applicator was thought to be small. In both directions, an increase in the R2 value was observed due to artifacts up to a distance of 10 - 15 mm.

![Figure 4. Influence of metal artifacts due to differences in frequency and phase direction: (a) The AP phase direction, (b) The RL phase direction.](image)

![Figure 5. Profile of metal artifacts due to differences in the frequency and phase direction. (a) The AP phase direction. (b) The RL phase direction.](image)

3.2 Profile analysis

The R2 image was converted to a dose distribution of Co-60 (Figure 6). Measurement and planned dose profile on the cross-section passing through point A of the sagittal image is shown in Figure 7. When the treatment plan data and profile of the AQUAJOINT®-based VIPET polymer gel dosimeter were normalized at point A and compared with RTPS, the dose difference tended to be large in the region within approximately 1.5 cm from the center of the applicator (high-dose range). On the contrary, the dose difference in the middle-dose range was less than ± 2%.
Figure 6. Image converted to dose distribution: (a) Coronal, (b) Sagittal.

Figure 7. Comparison of measurement and planned dose profile at axial slice of point A. Because the position at the distance of 0 mm was as high as ≥1,000 Gy, the value is converted to zero.

At the high-dose range, the large dose difference in the vicinity of the applicator (within 5 mm) was due to the inability of the AQUAJOINT®-based VIPET polymer gel dosimeter dose to exhibit dose dependency over 30 Gy. In the dose range of ≥20 Gy, the response curve tends to gently saturate; therefore, the planned dose of RTPS in the vicinity of the applicator is underestimated. In order to measure this range, improving the dynamic range of the AQUAJOINT®-based VIPET polymer gel dosimeter in high-dose range is required.

In contrast, within 5–15 mm of the applicator, the AQUAJOINT®-based VIPET polymer gel dosimeter showed higher doses than that of RTPS. The range in which this dose difference occurred was close to the region of the metal artifact. Imaging was performed to minimize the artifacts as much as possible; however, it was difficult to completely remove them even with CT/MRI compatible applicators. In order to improve the measurement accuracy, an applicator made of a material, such as plastic, that does not generate artifacts should be used.

3.3 Gradient and gamma analyses

In order to compare the spatial dose distribution, the isodose curves and calculation of the gradient analysis are shown (Figure 8). Good agreements were confirmed in the region of 2 to 6 Gy near the prescription point.

As a result of the gradient analysis excluding the pixel data of ≥20 Gy, the gradient passing rate was 62.38% in the sagittal plane and 67.81% in the coronal plane (Figure 9). In the brachytherapy source, the 3%/3 mm of dose difference (DD)/distance to agreement (DTA) generally used for IMRT (intensity-modulated radiation therapy) was adopted because no evaluation condition acts as a reference for the gradient analysis.
Figure 8. Calculation result of isodose curves comparing RTPS and gel. Solid line: RTPS, dotted line: gel. (a) Coronal plane. (b) Sagittal plane.

Figure 9. Calculation result of gradient analysis. (a) Coronal plane. (b) Sagittal plane.

Furthermore, we improved the DD-System and evaluated by gamma analysis. The result of gamma analysis was 87.594% in the sagittal plane and 93.711% in the coronal plane (Figure 10). Similarly, the evaluation condition was 3%/3mm of DD/DTA. However, since the DD-System used in this study is in the development stage of the program, no reference coordinates were available to match the MRI and dose distribution. The accuracy of the spatial position of MRI images remains uncertain [9]. The decrease in pass rate was mainly due to the uncertain accuracy of this spatial position. Moreover, a
phenomenon with an overestimated dose distribution due to the strong occurrence of MRI artifacts was found in the vicinity of the uterus mouth, near each applicator, especially the connecting parts.

In this study, analyzing the gradient was possible because the MRI slices were 3 mm thick at 256 pixels. In order to improve the measurement accuracy, the following improvements should be considered: (1) expansion of the dynamic range of gel dosimeters to be sensitive at high doses of ≥30 Gy, (2) improvement of spatial position accuracy, and (3) removal of artifacts by changing the applicator.

![Figure 10. Calculation result of gamma analysis. (a) Coronal plane. (b) Sagittal plane.](image)

4. Conclusions
We were able to obtain and evaluate 3D dose distribution with pass rate of the intracavitary brachytherapy by Co-60 radiation source using an AQUAJOINT®-based VIPET polymer gel dosimeter.

5. References
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