Dosimetric characteristics of intensity-modulated radiation therapy and RapidArc® therapy using a 3D *N*-isopropylacrylamide gel dosimeter

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This study aimed to investigate the dosimetric characteristics of intensity-modulated radiation therapy (IMRT) and RapidArc therapy by using 3D *N*-isopropylacrylamide (NIPAM) polymer gel. Optical computed tomography, specifically OCTOPUSTM-10X fast optical computed tomography scanner, was used as a readout tool. Two cylindrical acrylic phantoms (10 cm in diameter, 10 cm in height, and 3 mm in thickness) were filled with NIPAM gel and used for IMRT and RapidArc irradiation by using the Clinac iX treatment machine. The irradiation energies for

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IMRT and RapidArc® were set as 6 MV photons, but their irradiation angles and dose rates differed during irradiation. The irradiation angles of IMRT were 120°, 155°, 180°, 215°, and 245°, and the dose rate was fixed at 400 cGy/min. RapidArc® rotated continuously during irradiation, and the dose rate varied from 330 cGy/min to 400 cGy/min. The pass rates were 98.02% and 97.48% for IMRT and RapidArc®, respectively, and the rejected area appeared at the edge of the irradiated region. The isodose lines of IMRT and RapidArc® were consistent with those of TPS in most regions. Scattering and edge enhancement effects are main factors that cause dose inaccuracy in the edge region and reduced pass rates. Considering dose rate dependence, we used variable dose rates during irradiation with RapidArc®. Results showed that the dose distribution of NIPAM gel was consistent with that of TPS. The pass rates were also the same for IMRT and RapidArc® irradiation. This study proposes a preliminary profile of dosimetric characteristics of IMRT and RapidArc® by using a NIPAM gel dosimeter.

Keywords: NIPAM gel dosimeter; Optical CT; IMRT; RapidArc.

1. Introduction

Intensity-modulated radiation therapy (IMRT) has been widely adopted for clinical use because it can generate dose distributions that precisely conform to the tumor target while minimizing the dose delivered to the surrounding healthy tissues.¹ However, IMRT requires high monitoring units and long treatment times. RapidArc® (Varian Medical Systems), a novel radiation treatment technique, is based on volumetric-modulated arc delivery and differs from intensity modulation, which uses fixed gantry beams. The treatment time of RapidArc® is four to eight times faster than IMRT.² The complex 3D dose distribution generated by RapidArc® is difficult to verify using conventional techniques, such as a 1D ion chamber or 2D detector. Therefore, a true 3D dosimeter must be developed to verify the dose distribution.

Polymer gel dosimeters show great potential for verification of dose distribution because of their ability to record true 3D dose distribution in the entire volume.³ Although the first gel dosimeter, which used radiation-induced color change, was first proposed in 1950,⁴ it only began to attract attention in the 1990s. Many gel formulations have been developed, including polyacrylamide gel, methacrylic and ascorbic acid in gelatin initiated by copper, BANG®, and *N*-isopropylacrylamide (NIPAM).^{5–10} NIPAM gel dosimeters exhibit low toxicity, high linearity, high sensitivity, and easy benchtop preparation without requiring a glove box.^{11–13} In addition, NIPAM gel dosimeters present high spatial stability and can retain the dose distribution between 24 and 72 h post-irradiation.

Previous studies found that an edge enhancement effect was observed around a 4 cm × 4 cm irradiation region at 72 h post-irradiation.¹⁴ Dose overestimates at the high-dose gradient region may result in higher deviation at 72 h post-irradiation. Dose deviation increased with increasing post-irradiation time. A 3D polymer gel dosimeter has been employed to verify the dose distribution of RapidArc®. The results showed that within isodose volumes of 80% and 95%, the dose deviation was less than 5% for 90% of the voxels between the calculated and measured dose distributions.¹⁵ In 2014, Hayashi *et al.* used three types of dosimeters, namely, MapCHECK® diode array detector, radiochromic EBT2 films, and BANG3 RPGD, to verify RapidArc® TPS for irradiation of patients with prostate cancer.¹⁶ The results indicated that the BANG3 RPGD dosimeter

showed discrepancies between calculated and measured doses, particularly in low regions outside the target volume. Further improvement of the BANG3 RPGD dosimeter is thus needed.

In this study, IMRT with constant dose rate and RapidArc® with variable dose rate were used to verify the dose deviation between the calculated and measured dose distribution.

2. Materials and Methods

2.1. NIPAM polymer gel preparation

NIPAM polymer gel is comprised of 5% gelatin, 5% NIPAM, 3% *N,N'*-methylene bisacrylamide, and 5 mm Tetrakis (hydroxymethyl) phosphonium chloride.¹⁰ Two cylindrical acrylic phantoms (10 cm in diameter, 10 cm in height, and 3 mm in thickness) filled with NIPAM gel were used for IMRT and RapidArc® irradiation. The gel was placed in a water bath and cooled in a refrigerator for at least 6 h until solidification to reduce deviation in dose distribution.¹¹ NIPAM gel polymerization required 24 h to achieve dose stability after irradiation.¹⁴

2.2. Treatment planning and irradiation

Two irradiation treatment plans of IMRT and RapidArc® were generated using the Eclipse planning system (Varian Corporation, Palo Alto, CA, USA). The irradiation energies for IMRT and RapidArc® were set as 6 MV photons, but their irradiation angles and dose rates differed during irradiation. The irradiation angles of IMRT were 120°, 155°, 180°, 215°, and 245°, and the dose rate was fixed at 400 cGy/min. RapidArc® rotated continuously during irradiation, and the dose rate varied from 330 cGy/min to 400 cGy/min. The irradiation conditions for IMRT and RapidArc® were as follows: source surface distance = 96 cm, irradiation depth = 4 cm, and prescribed dose = 5 Gy.

2.3. Dose-reading tool and data analysis

After irradiation, polymerization occurred in the NIPAM gel and required 24 h to achieve dose stability.¹⁴ A post-scan was performed through optical computed tomography (CT) using an OCTOPUSTM-10X fast optical CT scanner.¹⁷ After scanning, images were reconstructed using the filtered back-projection algorithm with the program reconQexp.m integrated in MATLAB. Multiple slices were stacked to generate a three-dimensional image of dose distribution. A quantitative evaluation was performed using a gamma analysis technique, as proposed by Low *et al.*¹⁸ Gamma index and pass rate were calculated point by point by comparing the dose distribution between TPS and measured data from the gel dosimeter. The criterion for gamma evaluation was 3% dose difference and 3 mm dose-to-agreement. Pass rate was calculated from the percentage of points with $\gamma < 1.00$.¹⁸

3. Results and Discussion

Reconstructed images of both gel phantoms at the same depth are presented in Fig. 1. The images on the top row are the results of IMRT, and the images on the bottom row are the results of RapidArc®. The images from left to right are non-irradiated gel, irradiated gel, TPS image, and subtraction of irradiated gel and non-irradiated gel. Based on the reconstruction image, consistent dose distribution was achieved by RapidArc® (Fig. 1). However, RapidArc® with various dose rates during irradiation exhibited certain challenges to the gel dosimeter, especially at the high-dose gradient area.

Fig. 1. Reconstructed images of both gel phantoms. The images on the top row are the results of IMRT, whereas the images on the bottom row are the results of RapidArc®. Left to Right: non-irradiated gel, irradiated gel, TPS image, and subtraction of irradiated gel and non-irradiated gel.

3.1. Non-irradiated gel spatial uniformity

Prior to irradiation, the NIPAM gel was scanned to obtain a reference 3D image. The spatial uniformity of the gel phantom indicates the quality of gel preparation and the stability of the measurement system. Seven different depths of transverse slices (10, 20, 30, 40, 50, 60, and 70 mm) were used to evaluate spatial uniformity. We used standard deviation (SD) to estimate the dispersion of optical density at each location between different depths.¹⁹ Low SD values were observed at every location, and the average SD of spatial uniformity for two non-irradiated NIPAM gels were as low as 0.14% and 0.12%. Therefore, both NIPAM gel phantoms were considered homogeneous between different depths and exhibited spatial uniformity. These results are similar to previously reported values.²⁰

3.2. Gamma evaluation

After scanning, gamma evaluation was performed between TPS and the measured dose map by using optical CT. Figure 2 presents the comparison of the measured NIPAM gel

dose distribution and TPS. The gamma index was calculated using a 3% dose difference and 3 mm distance-to-agreement, which are the most frequently used criteria in published comparisons of treatment plans.

The gamma pass rate was calculated in the area percentage with $\gamma < 1$. Table 1 shows the gamma pass rate for IMRT radiation at different depths and post-irradiation times. The maximum pass rate is 98.02%, and the minimum pass rate is 91.8%. Table 2 shows the gamma pass rate for RapidArc® radiation at different depths and post-irradiation times. The maximum pass rate is 97.48%, and the minimum pass rate is 89.02%. The dose distribution is stable from 24 h to 96 h post-irradiation, as indicated by the same level of gamma pass rates at different depths. The gamma pass rates of IMRT and RapidArc® radiation are also on the same level. Nevertheless, the gamma pass rate of RapidArc® radiation is lower than that of IMRT radiation at a depth of 40 mm. For further investigation, a gamma map of the rejected area ($\gamma > 1$) at a depth of 40 mm for 24 h to 96 h post-irradiation time is shown in Fig. 2. The most rejected area ($\gamma > 1$) is evidently located at the edge of the irradiated field. Apparently, the rejected area in RapidArc® is larger than that in IMRT radiation, which explains the lower gamma pass rate of RapidArc® radiation than that of IMRT radiation. The regions at the edge of the radiation field are generally high-dose gradient regions, which may probably induce the edge enhancement effect.¹⁴ A dose is considered to be overestimated if edge enhancement phenomenon occurred, resulting in reduced gamma pass rate. Additionally, from Fig. 1 we found that the PTV shape of RapidArc® radiation is more complex than that of IMRT radiation. It may probably cause the lower gamma pass rate for RapidArc® radiation. More experiments will be conducted on the same PTV shape of RapidArc® radiation and IMRT radiation.

Table 1. IMRT gamma pass rate under 3%/3 mm criteria.

Depth (mm)	30	35	40	45	50
24 h	94.13%	93.60%	92.14%	93.28%	95.29%
48 h	94.29%	92.13%	94.05%	97.95%	95.27%
72 h	92.35%	94.22%	93.18%	97.36%	97.74%
96 h	93.39%	93.27%	91.80%	98.02%	97.45%

Table 2. RapidArc® gamma pass rate under 3%/3 mm criteria.

Depth (mm)	30	35	40	45	50
24 h	93.83%	93.09%	89.02%	94.73%	96.44%
48 h	91.63%	90.46%	89.77%	93.43%	97.48%
72 h	92.87%	91.65%	89.41%	93.91%	96.99%
96 h	91.67%	89.94%	89.73%	93.33%	94.82%

Depth = 40 mm

Post-irradiation time = 24 h

IMRT

40 mm

RapidArc®

40 mm

Fig. 2. Gamma map of the NIPAM gel dosimeter at a depth of 40 mm for 24 h post-irradiation time.

3.3. Isodose line

The superimposed dose distributions at prescribed doses of 50%, 60%, 70%, 80%, 90%, and 100% are shown in Fig. 3 to determine differences in the dose distribution of the treatment planning system and measured data from NIPAM gel. The solid line indicates the treatment planning calculation, and the dotted line represents the measured data from the gel dosimeter. The results show good agreement between treatment planning and measured data. Xu *et al.* claimed that for a gel dosimeter, the dose distribution is only valid in the central region with 75% of the diameter of the gel container^{21,22} because the

optical density is affected by the reflection and refraction of the laser beams between the gel and the container wall. Similar phenomena can be found in the current work. We observed higher differences between treatment planning and measured data in the region at the 50% isodose line. Furthermore, the mismatch of dose distribution may be caused by the edge enhancement effect from the high-dose gradient (Fig. 3).

Depth = 40 mm

Post-irradiation time = 24 h

IMRT
40 mm

RapidArc®
40 mm

Fig. 3. Superimposed dose distributions at the 50%, 60%, 70%, 80%, 90%, and 100% isodose lines at depth = 40 mm. Solid line: Treatment planning calculation, Dotted line: measured data from gel dosimeter.

3.4. Temporal stability

The pass rate of NIPAM gel slightly fluctuates from 24 h to 96 h (Table 1). The NIPAM (5-5-3-5) gel of RapidArc® presents temporal stability despite minimal variations in dose rate. The current results are consistent with those in previous studies.¹⁴

3.5. Projection image profile

The reconstructed image of the NIPAM gel in the axial direction and projection data were processed using ImageJ (version 1.43, developed by the National Institutes of Health). Figure 4 shows the reconstructed image of the radiated gel phantom at 24 h post-irradiation and the central line profiles. The reconstructed images of IMRT and RapidArc® represent the subtractions of the irradiated gel and the reference gel images. Both gel phantoms exhibit the same maximum optical density, but from the line profiles, we could observe small peaks at the edge of the radiation region for RapidArc® irradiation. Therefore, the effects of scattering and edge enhancement are more serious on the gel phantom with RapidArc® irradiation than that on IMRT. These effects may be caused by the variable dose rate for RapidArc® irradiation, considering the problem of dose rate dependence. However, more experiments are needed to confirm this finding.

Fig. 4. Reconstructed image of the NIPAM gel dosimeter and central line profile. (a) IMRT; (b) RapidArc®.

4. Conclusion

A NIPAM gel dosimeter combined with an optical CT scanner was applied on IMRT (dose rate fixed at 400 cGy/min) and RapidArc® therapy (various dose rates ranging

from 330 cGy/min to 400 cGy/min) to investigate the dosimetric characteristics. The NIPAM gel dosimeter exhibited spatial uniformity for different batch preparations. The gamma pass rates were on the same level for both IMRT and RapidArc® irradiation. Moreover, the isodose line showed good agreement between TPS and measured data from the gel dosimeter. When the central line profile between IMRT and RapidArc® was compared, a small peak can be observed at the edge of the irradiated region for RapidArc®. This small peak was caused by the scattering and edge enhancement effect and could be the main reason for the reduction of the gamma pass rate.

NIPAM gel under a small variable dose rate irradiation would not significantly affect the performance of a NIPAM gel dosimeter. Further experiments using larger dose rate variations must be performed to verify the effects of dose rate dependence on NIPAM gel dosimeters.

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