A Characteristic Study on NIPAM Gel Dosimetry Using Optical-CT Scanner

Chun-Hsu Yao1,2,3 Wang-Ting Hsu3,4 Jia-Jung Lee5 Shin-Ming Hsu6
Patrick Yuk-lun Ma4 Bor-Tsung Hsieh7 Yuan-Jen Chang5,8,*

1School of Chinese Medicine, China Medical University, Taichung 404, Taiwan, ROC
2Department of Biomedical Imaging and Radiological Science, China Medical University, Taichung 404, Taiwan, ROC
3Department of Biomedical Informatics, Asia University, Taichung 413, Taiwan, ROC
4Department of Radiation Oncology, Puli Christian Hospital, Nantou 545, Taiwan, ROC
5Institute of Biomedical Engineering and Material Science, Central Taiwan University of Science and Technology, Taichung 406, Taiwan, ROC
6Department of Biomedical Imaging and Radiological Science, National Yang-Ming University, Taipei 112, Taiwan, ROC
7Department of Medical Imaging and Radiological Science, Central Taiwan University of Science and Technology, Taichung 406, Taiwan, ROC
8Department of Management Information Systems, Central Taiwan University of Science and Technology, Taichung 406, Taiwan, ROC

Received 11 Jun 2012; Accepted 28 Dec 2012; doi: 10.5405/jmbe.1212

Abstract

This study investigated the dose characteristics of N-isopropylacrylamide (NIPAM) polymer gel dosimetry in intensity-modulated radiation therapy (IMRT). The NIPAM gel was composed of 5% gelatin, 5% NIPAM, 5% Bis, and 5 mM tetakis (hydroxymethyl) phosphonium chloride (THPC). The gel was poured into a cylindrical acrylic phantom with a diameter of 10 cm, a height of 10, and a wall thickness of 3 mm. The gel phantom was irradiated with IMRT. The phantom energy was 6 MV and the dose rate was 250 MU. The NIPAM gel was scanned using an optical computed tomography (CT) scanning system. In terms of uniformity, the intra-dosimeter showed a consistent dose profile at different depths and a deviation of less than 1.8%. The scanning results showed a consistent dose distribution for each scanning experiment. The percentage isodose lines from the measured data agreed well with those from the treatment planning system (TPS) at 60% to 100% dose level region which is acceptable for clinical applications. Gamma index analysis was performed for representative gamma comparison between the TPS and the measurement results. The acceptance pass rate was calculated for various criteria. The pass rates were as high as 99.5% and 97.8% with 5%/5 mm and 4%/4 mm gamma acceptance criteria, respectively. The results indicate that a NIPAM polymer gel dosimeter can be used in conjunction with optical CT as a dose verification tool, especially for three-dimensional dose verification.

Keywords: Three-dimensional gel dosimetry, NIPAM polymer gel, Optical computed tomography (CT), Intensity-modulated radiation therapy (IMRT)

1. Introduction

Intensity-modulated radiation therapy (IMRT) is often adopted in modern radiation therapy. Before radiation is applied, IMRT requires inverse treatment planning to establish the dose delivery parameters to control the linear accelerator (LINAC). Various techniques have been proposed to improve the treatment planning precision of IMRT in terms of three-dimensional (3-D) dose distribution. Gel dosimetry is one of the best technologies for validating 3-D dose distribution [1,2]. Gel dosimetry has high spatial resolution and precision, especially in areas with high dose gradients. There are two main types of gel, namely Fricke and polymer. Fricke gel was proposed by Gore [3]. It is based on the Fricke chemical reaction after irradiation, in which ferrous ions (Fe2+) are converted to ferric ions (Fe3+). However, due to the ion diffusion effect, the spatial dose distribution changes with time and thus spatial dose information is not retained [4,5]. Polyacrylamide (PAG) gel was introduced in 1993 to avoid the diffusion problem with acrylic monomers and crosslinker N,N'-methylenebisacrylamide [6]. The formation of acrylic polymer chains overcomes the problem of Fricke gel because the long polymer chains are large enough to prevent the rapid diffusion of ions [7]. Maryanski proposed BANG-1 gel, composed of Bis (N,N-methylene bisacrylamide) (3%), acrylamide (3%), nitrogen, gelatin (5%), and 89% deionized water. MGS Research, Inc. developed and patented improved BANG-2 and
BANG-3 gels to decrease monomer toxicity and increase gel sensitivity [8,9].

However, oxygen contamination inhibits the polymerization and crosslinking reactions in a gel dosimeter [10,11]. Fong proposed MAGIC gel to avoid the oxygen-induced inhibition of polymerization. MAGIC gel is composed of methacrylic and ascorbic acid in gelatin initiated by copper [12]. De Deene proposed an oxygen scavenger, tetraakis (hydroxymethyl) phosphonium chloride (THPC), to prevent excessive polymerization before irradiation [13]. Compared with other oxygen scavenger, THPC has the highest reaction rate and increases the dose sensitivity of the gel. Senden proposed a polymer gel called N-isopropylacrylamide (NIPAM). Compared with monomer acrylamide, NIPAM polymer gel is based on a less toxic monomer and is much safer to operator [14].

In this study, a NIPAM polymer gel dosimeter was adopted due to safety considerations. With the addition of THPC, gel preparation can be performed on a bench top in the laboratory. The performance of the gel with various compositions was studied in detail in a previous work [15-17].

2. Materials and methods

2.1 Gel preparation process

Table 1. Composition of NIPAM polymer gel.

<table>
<thead>
<tr>
<th>Gelatin (%)</th>
<th>NIPAM (%)</th>
<th>Bis (%)</th>
<th>THPC (mM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>5</td>
<td>3</td>
<td>5</td>
</tr>
</tbody>
</table>

The gel was prepared inside a fume hood and under normal atmospheric conditions in the laboratory, following the process described by Senden and De Deene [13,14]. The gel was composed of 5% gelatin, 5% NIPAM, 3% Bis, and 5 mM THPC, as shown in Table 1. Furthermore, 5 wt% gelatin (300 Bloom Type A, Sigma-Aldrich Co., LLC, USA) was added to 87 wt% deionized water and stirred for 10 min at 22 °C. The gelatin solution was then heated to 45 °C by an electric heater and continuously stirred with a rod-type stirrer. After the solution reached 45 °C, 3 wt% Bis (Merck) and 5 wt% NIPAM (97%, Sigma-Aldrich) were poured into the gelatin solution and dissolved together at the same temperature. This process took 10 min. Afterward, 5 mM THPC was added to the solution, which was then continuously stirred for 2 min. Finally, the gel solutions were transferred into Pyrex screw test vials (Pyrex Model No. 9826; outer diameter: 13 mm; length: 100 mm) and cylindrical acrylic phantoms (diameter: 10 cm; height: 10 cm; wall thickness: 3 mm) [16]. The vials and acrylic phantoms were wrapped in aluminum foil to prevent photo-polymerization. The prepared polymer gels were carefully stored in a refrigerator at 22 °C until complete solidification.

2.2 Irradiation process

Irradiation was performed 12 h after the preparation of gels using IMRT (SIEMENS ONCOR Impression), as shown in Fig. 1. Before irradiation, the gel vials were placed in the center of a customized 30 × 30 × 4 cm³ acrylic phantom, into which a 16-mm diameter hole was punctured to help accommodate the position of test vials and provide adequate build up and scattering conditions. The gel vials were irradiated with 0, 1, 2, 5, and 8 Gy. The cylindrical acrylic phantom was placed in a vacuum bag on the treatment couch. The treatment fields were identically sized (3 cm × 3 cm). The setup conditions were: gantry: 90 °; treatment couch: 270 °; and photon energy: 6 MV. The prescribed dose was 5 Gy. The source surface distance (SSD) was equal to 98.5 cm.

2.3 Measurements of attenuation coefficient

The attenuation coefficient was obtained by measuring the irradiated gel vials using an apparatus (CT-s1) developed in our previous study [16]. The laser used in CT-s1 is a Lasiris™ SNF laser with 30-mW power and a 785-nm wavelength (StockerYale, New Hampshire, USA). Each sample was placed in the laser scan room for 1 d, with the temperature maintained at 22 °C ± 1 °C. To avoid the effects of temperature [18], the measurement was conducted after the gel samples had attained temperature equilibrium. The light intensity of the reference beam passing through the non-irradiated gel vial was recorded as the initial optical intensity Iₒ. The other beam was used as the object beam by passing it through the irradiated gel. The light intensity of the object beam was recorded as the instantaneous optical intensity I. Non-irradiated and irradiated gel vials were mounted on a stage in a 51 × 75 × 90 mm³ tank. The tank was filled with vegetable oil whose refractive index was similar to that of Pyrex glass to minimize refraction and reflection at the interface. In addition, the gel vials were mounted on a four-axis stage, with three orthogonal linear axes (x, y, z) and a rotational axis (θ), to move the gel to a given scanning location and angle. The attenuation coefficient α of the gel can be calculated as:

\[ \alpha = -\frac{1}{x} \ln \left( \frac{I}{I_0} \right) \]  

(1)

where x is the diameter of the gel; Iₒ is the optical intensity of the laser beam passing through the non-irradiated sample; and I is the optical intensity of the laser beam penetrating the irradiated sample [14].

2.4 Optical computed tomography scanner

A 3-D laser optical computed tomography (CT) scanner (OCTOPUS™ 10 × optical CT scanner, MGS Research, Inc.,...
Madison, CT, USA) was used for the scanning of the cylindrical gel phantoms, as shown in Fig. 2. Since this scanner adopts an oscillating mirror instead of a translation slider to acquire the projections of the gel, its speed is much faster than the previous OCTOPUS model [19]. Scanning a phantom using the scanner takes about 30 minutes, and about 3 hours using the old model. A single laser beam was emitted at a 780-nm wavelength from a 30-mW laser, and reflected by an oscillating mirror located at the focus of the collimating Fresnel lens. All laser beams passing through the collimating Fresnel lens were parallel to each other and to the central axis of the lens. These laser beams scanned the gel mounted on a turntable inside the scanning tank filled with oil. The refractive index of the NIPAM gel was measured using a refractometer (PAL-RL, ATAGO). The refractive index matching reduced light refraction and reflection effects while the light beam was transmitted through the cylindrical gel phantom. All laser beams exited the scanning tank and passed through the second Fresnel lens. The Fresnel lens focused all transmitted laser beams on the light diffuser mounted on the aperture of the photodiode. The transmitted laser beams were collected by a photodiode during each cycle of translational motions as single-projection data. After acquisition, the projection data were transferred to an image reconstruction program written using MATLAB (The MathWorks, Natick, MA, USA). The program reconstructed the image of transverse slice with optical density distribution using a filter back-projection algorithm.

2.5 Quantitative evaluation of dose distributions

A quantitative evaluation of dose distributions was performed using gamma analysis [20,21] implemented using MATLAB (The MathWorks). The calculation of gamma value was based on the composite distribution that presented the dose difference in regions that failed both dose-difference and distance-to-agreement (DTA) comparison criteria. In this study, the measured dose distributions in the NIPAM polymer gel dosimeter were compared with the dose distribution obtained from the treatment planning system (TPS, PROWESS 4.71). Three criteria were adopted for the comparisons, namely 5% dose difference and 5 mm DTA, 4% dose difference and 4 mm DTA, and 3% dose difference and 3 mm DTA.

3. Results and discussion

Figure 3 depicts the dose dependence of the attenuation coefficient for the NIPAM polymer gel composed of 5% gelatin, 5% NIPAM, 3% Bis, and 5 mM THPC. The correlation of the dose and the attenuation coefficient can be expressed by the following equation using linear regression [22]:

\[ y = 0.0276x - 0.005 \]

The curve of Eq. (2) is called the dose-response curve. The sensitivity was 0.0276 mm \(^{-1}\) Gy, and the linearity (R-squared value) for the dose range of 0 to 8 Gy was 0.997. The reconstructed 3-D optical density map from the image reconstruction program only represented the relative dose distribution. The dose-response curve can be used to obtain the absolute dose distribution delivered to the gel dosimeter. In practical applications, a simple linear regression represents the usefulness of a polymer gel dosimeter. The conversion of a relative dose to an absolute dose is more reliable and stable. For different clinical applications, different sensitivities of the NIPAM polymer gel dosimeter can be achieved using different gel recipes [15,17].

![Figure 3. Dose-response curve of NIPAM gel obtained using glass vial approach with 6 MV irradiation (gelatin, 5%; NIPAM, 5%; Bis, 3%; and THPC, 5 mM). Error bars indicate 5% experimental uncertainty.](image)

The line profiles of the non-irradiated gels at different layers were compared to investigate the spatial uniformity of the 3-D NIPAM polymer gel. Figure 4 shows the scanner results of a cylindrical gel phantom filled with non-irradiated gel. Figure 4(a) shows the reconstructed image and Fig. 4(b) shows the line profile along the line in Fig. 4(a) at depths of 1.5, 2.5, 3.5, 4.5, and 5.5 cm. The maximum deviation in the center region (diameter: 6 cm) was only 1.8% for these six slices. The deviation outside this center region has higher due to the light scattering effect from the cylindrical wall. The TPS field in this study was a 3 cm \( \times \) 3 cm square field inside the center region; hence, the scattering effect can be neglected in the results.

Experimental measurement reliability was evaluated to ensure that the measurement deviation was reduced for each measurement. The gel phantom had to be mounted in the
scanning tank in the optical-CT scanner for each experiment. Since re-positioning accuracy affects results, a well designed clamp was used to position the gel phantom in the same place each time. Figure 5 shows a comparison of different scanning results for a given cylindrical gel phantom. The isodose lines matched the dose percentages of 90%, 80%, 70%, 60%, and 50% well. In reality, the verification of measurement reliability should be conducted when the gel phantom size is changed for new experiments.

The dose-response curve (Eq. (2)) of the gel was used to convert the reconstructed image to an absolute dose distribution. Therefore, the dose distributions obtained using the optical CT results (OCT) and the TPS were compared. Figure 6 shows the transverse view of the corresponding isodose lines at a depth of 1.5 cm. The dose distributions of the gel measured by optical CT (dotted lines) agree with those from the planning system (solid lines) within 4% or 4 mm inside the 60% isodose for the isodose lines compared. However, the dose difference along the diagonals of the square field was larger than that in other regions. Moreover, the 50% isodose line of the gel data was a little different from that for the TPS. This discrepancy occurred near the phantom wall and was probably a result of the combined effects of oxygen inhibition and polymerization and the refraction of light on the container wall [23]. Xu [24] indicated that the dose sensitivities determined from the dose-response curve using the glass vial approach are different from those obtained from large gel cylinder experiments. In Xu’s study, the difference was as high as 30% for a given batch of gels. This difference was probably caused by the difference in the temperature inside the two types of phantom during the radiation-induced polymerization process [25,26]. In addition, oxygen inhibition polymerization in the glass vial was more serious than that in the large gel phantom. Gel contaminated by oxygen may be suppressed in the gel-dose response, resulting in smaller optical density readouts for a given delivered dose. The isodose line agreement can be improved further using the sensitivity calibration technique described by Xu [23,24].

In this study, detailed 3-D gamma index analysis was performed on data obtained from TPS and optical CT. Figures 7(a)-(c) show representative gamma comparison maps using three acceptance criteria, namely 5% dose difference and 5 mm DTA, 4% dose difference and 4 mm DTA, and 3% dose difference and 3 mm DTA, respectively. The evaluation is a measure of the standard error between the measured data and the TPS data. As shown in Table 2, the gamma pass rates for the three criteria were 99.5% (5%/5 mm), 97.8% (4%/4 mm), and 92.1% (3%/3 mm). According to Figs. 7(a) and 7(b), the gamma value was less than 1 for the most area of gamma maps with 4%/4 mm and 5%/5 mm, which indicates that the gel dose measurement agreed within the 4%/4 mm and 5%/5 mm criteria. For the 3%/3 mm criteria, the majority of the failure was near the edge of the 3 cm x 3 cm square field, which was the higher-dose gradient area. The error was due to the large dose difference within a short distance. The results can be further improved if a more accurate dose distribution is obtained using sensitivity calibration.
4. Conclusion

This study investigated the dose characteristics of NIPAM polymer gel dosimeter in conjunction with an optical-CT scanner in IMRT. The NIPAM gel dosimeter showed a deviation in uniformity of less than 1.8%. The scanning results showed a consistent dose distribution for each scanning experiment. In addition, the percentage isodose lines from the measured data agreed with that from the TPS at 60% to 100% dose level region, which is acceptable for clinical applications. The pass rates were as high as 99.5% and 97.8% for 5%/5 mm and 4%/4 mm gamma acceptance criteria, respectively. These results show that a NIPAM polymer gel dosimeter is a potential 3-D dose verification tool.

Acknowledgments

This work was supported by the National Science Council of Taiwan under grants NSC 99-2632-B-166-001-MY3 and NSC 101-2314-B-166-005-.

References


