

Accuracy and reproducibility in x-ray computed tomography polymer gel dosimetry

E Maynard¹, M Hiltz^{2,3}, E Heath⁴ and A Jirasek⁵

¹Department of Physics and Astronomy, University of Victoria, Victoria, British Columbia, V8W 2Y2, Canada

²Department of Physics, University of British Columbia - Okanagan Campus, Kelowna, British Columbia V1V 1V7, Canada

³Medical Physics, BC Cancer Agency, Centre for the Southern Interior, Kelowna, BC, V1Y 5L3, Canada

⁴Carleton Laboratory for Radiotherapy Physics, Physics Department, Carleton University, Ottawa, Ontario K1S 5B6, Canada

⁵Department of Physics, I.K. Barber School of Arts and Sciences, University of British Columbia, Kelowna, British Columbia V1V 1V7, Canada

E-mail: andrew.jirasek@ubc.ca

Abstract. This work assesses the overall reproducibility and accuracy of an x-ray computed tomography (CT) polymer gel dosimetry (PGD) system using a N-isopropyl-acrylamide (NIPAM) based polymer gel and investigated what effects the use of generic, inter-batch, and intra-batch gel calibration have on dosimetric and spatial accuracy. Overall excellent spatial and dosimetric accuracy was found with this system for generic, inter-batch calibration methods.

1. Introduction

In polymer gel dosimetry (PGD), a carefully tuned recipe of radiosensitive chemicals is dissolved in gelatin to form a three-dimensional (3D) dosimeter. When irradiated, a gel dosimeter will undergo chemical changes that can be read out and related to the 3D dose absorbed within the gel. Polymer gels have natural advantages in dosimetry as they are inherently 3D, dose integrating, tissue equivalent and deformable. Traditional PGD has been used with MRI as the readout method [1-4], with other read out modalities such as optical CT [5, 6] and x-ray CT [7-11] imaging emerging more recently.

X-ray CT PGD is limited by the small size of the density changes (approximately 1 mg/cm³ per 1 Gy of absorbed dose [12]) that occur due to the polymerization of the gel. X-ray CT PGD is, therefore, hampered by low signal-to-noise ratio and low contrast in its dose resolution. Research has focused on maximizing the signal by increasing the sensitivity of the gel recipe [13, 14], using filtering to decrease noise and remove artifacts [15, 16] and improving calibration techniques [17]. To enable clinical implementation, the reproducibility, dosimetric accuracy and spatial accuracy that can be expected of an x-ray CT PGD system needs to be established.

The aim of this work is to assess the overall reproducibility and accuracy of an x-ray CT polymer gel dosimeter system initially characterized by Johnston *et al* [9]. This study also investigates the effect that calibration across different gel batches has on the accuracy of the system. Specifically, we



investigate the use of inter-batch gel calibration, average or generic calibration curves and intra-gel calibration across different locations within the gel dosimeter.

2. Materials and Methods

2.1. Gel Fabrication

All gel dosimeters consisted of, by weight, 75.5% deionized water, 5% gelatin (Sigma-Aldrich Canada, Oakville, ON), 15% N-isopropyl-acrylamide (NIPAM, TCI Chemicals, OR, USA), 4.5% N,N'-methylenebisacrylamide (BIS, Sigma-Aldrich) and 5 mM tetrakis hydroxymethyl phosphonium chloride (THPC, Sigma-Aldrich) and were fabricated using a procedure initially described by Chain *et al* [13]. Blank gels were also fabricated for background subtraction of CT images. In total, four 1 L gels were fabricated for analysis in this work with all four gels manufactured from a single lot of NIPAM.

2.2. Treatment planning and irradiation

All gels were irradiated with three 3 x 7 cm² fields, at 45°, 270° and 315° in a calibration designed using the ECLIPSE treatment planning system (Varian Medical Systems, Palo Alto, CA) which covered a full range of doses up to a maximum of approximately 27 Gy. This treatment plan was delivered to two separate locations within the gel, at the top and bottom of the gel container. When irradiated each gel was setup using an anthropomorphic head and neck phantom filled with water to ensure complete immobilization of the gel and provide sub-millimeter position reproducibility [18]. The dose for this treatment plan was calculated using the Vancouver Island Monte Carlo (VIMC) system which has been thoroughly validated for the calculation of complex dose deliveries [19]. The VIMC dose calculation was used for calibration of the gel dosimeter and as a comparison to assess the accuracy of the gel dosimeter.

2.3. X-ray CT imaging

Irradiated gels and blank gels were imaged using an Optima CT580 multislice CT scanner (GE Medical Systems, Milwaukee, WI). All CT images were acquired using imaging settings based off previous work by Baxter *et al* [20] and Jonhston *et al* [9] to optimize gel dosimetry scanning protocols. Each gel was set up on the CT scanner bed for imaging using the head and neck phantom to ensure synchronized localization of the gel for imaging and irradiation [18].

2.4. Image processing and calibration

The gel images were processed using image averaging, background subtraction of blank gels, adaptive mean filtering and remnant artifact removal as described by Jirasek *et al* [16]. Calibration of the gels was performed using the techniques described by Johnston *et al* [9] and refined by Jirasek and Hilts [1517].

The gels were calibrated in 4 different ways to assess any changes in accuracy when using different calibration techniques. *Self-Calibration* is where gel image is calibrated using the calibration curve generated by its own image; it is essentially calibrated with itself. This eliminates any error introduced by differences between different gel batches and is a “best case scenario” for the dosimeter. *Intra-gel Calibration* is where the gel image at the bottom of the container is calibrated using the calibration pattern at the top of the gel container. *Average Calibration* is where the gel image is calibrated using the average calibration curve of the four gels in the sample. The results from this type of calibration will determine the plausibility of using a generic calibration curve for this dosimetry system. *Most Divergent Calibration* is where the gel image is calibrated using the single calibration curve from the sample that produces the least accurate dosimetric results. The gel dose generated by each calibration method was compared to the VIMC calculated dose across the sample of four gels using (i) dose difference in low dose gradient region (with a gradient threshold = 0.2), (ii) distance-to-agreement (DTA) in high dose gradient regions, and (iii) gamma distributions and gamma pass rates.

3. Results and Discussion

Figure 1 is an example of the different types of dose analysis used on an individual gel dosimeter. The dose difference map between Monte Carlo and a self-calibrated gel measured dose is shown in figure 1a where good agreement is seen in the low dose gradient regions. The gel dose is lower on average than calculated by Monte Carlo at the highest doses but is more accurate at other dose levels. The gel in figure 1a has an absolute mean dose difference of 0.46 Gy across all points within the low dose gradient region. Figure 1b shows the distance-to-agreement (DTA) between measured gel dose and Monte Carlo calculated dose in the high dose gradient region. In this gel, more than 90% of points in the high dose gradient region have a DTA of less than 1 mm and more than 99% of points have a DTA of less than 2 mm. Figure 1c combines both the high and low gradient regions together and a gamma analysis gives a sense of the dosimetric and spatial accuracy through the entire gel dosimeter. In this gel fewer than 2% of points fail the gamma metric when using a 3%/3mm criterion.

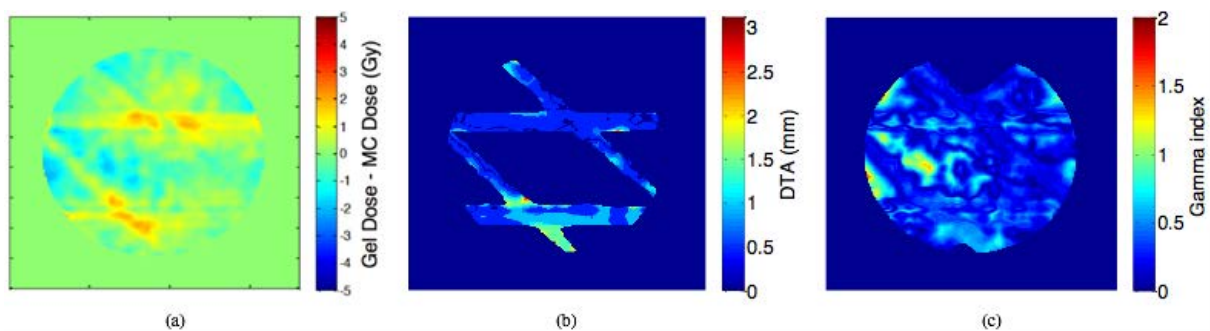


Figure 1. (a) Measured gel dose – Monte Carlo calculated dose for an individual self-calibrated gel dosimeter, (b) DTA map of the high dose gradient regions comparing gel dose to Monte Carlo dose and (c) gamma index map with a 3%/3mm criterion and 10% dose threshold.

Table 1 summarizes the results across all gel dosimeters used in the sample for each of the described calibration methods. The average calibration method produces a mean dose error similar to the “best case” self-calibration method which demonstrates the effectiveness of using an average calibration. Even when using the most divergent calibration the average dose error remains below 3%. The intra-gel calibration method produces an average dose error of approximately 5% due to differences in the dose response at the top and bottom of the gel container. A dose dependent correction was calculated using an average of this difference in response and with this correction, the accuracy of the intra-gel calibration method improved to within 2%.

Table 1. Summary of results in the reproducibility study. Dose error values are measured in the low dose gradient region and relative to the maximum dose. Distance-to-agreement (DTA) values are measured in the high dose gradient region. Gamma analysis is performed across the entire gel with a 10% dose threshold and a 3%/3mm dose criterion.

Calibration method	Mean dose error	Mean DTA (mm)	Mean pass rate DTA < 2 mm	Mean pass rate $\gamma < 1$ (3%/3mm)	Mean gamma value
Self-calibration	$1.62\% \pm 0.05\%$	0.608 ± 0.03	$99.8\% \pm 0.2\%$	$98.2\% \pm 0.4\%$	0.320 ± 0.005
Average calibration	$1.82\% \pm 0.25\%$	0.628 ± 0.07	$99.6\% \pm 0.3\%$	$96.8\% \pm 3.6\%$	0.348 ± 0.040
Most divergent calibration	$2.57\% \pm 0.50\%$	0.718 ± 0.17	$97.2\% \pm 2.6\%$	$90.9\% \pm 7.0\%$	0.454 ± 0.074
Intra-gel calibration	$4.83\% \pm 1.10\%$	1.340 ± 0.21	$83.3\% \pm 5.9\%$	$76.6\% \pm 11.7\%$	0.706 ± 0.145
Intra-gel calibration (corrected)	$1.82\% \pm 0.26\%$	0.628 ± 0.07	$99.6\% \pm 0.3\%$	$96.8\% \pm 3.7\%$	0.348 ± 0.041

DTA analysis in the high dose gradient regions complements the dose difference values measured in the low gradient regions. Overall the spatial accuracy is excellent for the self, average, and corrected intra-gel calibration methods. The average calibration results again indicate good reproducibility within the sample set and even when using the most divergent calibration within the sample, more than 97% of points in the high gradient region have a DTA of less than 2 mm.

Average passing rates ($\gamma < 1$) at the 3%/3mm criterion across the sample gels are greater than 95% for the average calibration and intra-gel calibration when corrected. Again we see the effectiveness of using an average calibration curve when compared to self-calibration and the effectiveness of the dose dependent correction for intra-gel calibration.

4. Conclusion

Comparison of gel measurements with Monte Carlo dose calculations found excellent dosimetric accuracy when using an average (or generic) calibration and minimal accuracy was lost when compared to a “best case scenario” self-calibration method. An intra-gel calibration method was also investigated but required a dose dependent correction to avoid large dose discrepancies. Spatial accuracy was also found to be excellent for the average calibration method and little accuracy was lost when compared to the self-calibration method. Gamma analysis using a 3%/3mm criterion also found good agreement between the gel measurement and Monte Carlo dose calculation when using either the average calibration or self-calibration methods (96.8% and 98.2%, respectively).

Overall, this work has established the accuracy and reproducibility of an x-ray CT PGD dosimetry system and demonstrated the effectiveness of inter-batch calibration and the use of a generic calibration method.

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