Isopropanol-based polymer gel dosimeters for use with x-ray CT imaging

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Abstract. We report on investigations aimed at increasing the dose response sensitivity and resolution in x-ray CT imaging of polymer gel dosimeters (PGD). We incorporate isopropanol as co-solvent into the gel formulation and show that this incorporation increases dose sensitivity and dose resolution of x-ray CT imaged gel dosimeters. These gels are reproducible in response and stable post-irradiation. We apply the system to a simple 1L gel test case where 2 separate irradiations are used to generate a dose response calibration curve. A third irradiation (3-field) is then calibrated and compared to treatment planning predictions. Results indicate that isopropanol-based PGDs are promising formulations for x-ray CT gel dosimetry and that this current system outperforms previous attempts at dose reconstruction using x-ray CT imaging of PGDs.

1. Introduction
A persistent limitation of x-ray CT polymer gel dosimetry is the low dose sensitivity and resolution of the system. This limitation has precluded applications of x-ray CT polymer gel dosimetry to clinically relevant problems. Nonetheless, the system is an attractive possibility for 3D dosimetry as CT scanners are readily available in clinical settings, the system is robust and not highly sensitive to imaging temperature, and CT imaging of polymer gel dosimeters can be accomplished in a reasonably short amount of time.

Recent efforts in increasing polymer gel dosimeter radiation sensitivity have concentrated on (i) investigating alternative crosslinkers in the gel, and (ii) incorporating a co-solvent to improve the crosslinker solubility within the gel solution [1,2]. Suitable alternative crosslinkers have not, to date, been identified [1]. In terms of increasing crosslinker solubility, two co-solvents have been investigated and have produced promising results. The first, glycerol, has shown to increase resultant dose response sensitivity. However, the net increase of dose response sensitivity was shown to be limited and, furthermore, the shape of the dose response curves were shown to vary depending on the amount of co-solvent, hence making calibration of the system problematic.

We here report on using a isopropanol as co-solvent in x-ray polymer gel dosimetry. We show that isopropanol based gels (i) can significantly improve the dose sensitivity and resolution of the x-ray CT imaged gels, (ii) are stable over time, and (iii) are an attractive possibility for x-ray CT polymer gel
dosimetry. We illustrate the application of isopropanol based x-ray CT polymer gel dosimetry to a simple 3 field irradiation.

2. Materials and Methods

2.1 Gel manufacture

Polymer gels were manufactured using 5% gelatin (Sigma-Aldrich, Oakville, Ontario, Canada), 30% isopropanol, 5mM tetrakis hydroxymethyl phosphonium chloride as antioxidant. The total amount of monomer (N-isopropylacrylamide, NIPAM, TCI Chemicals, OR, USA) and crosslinker (N,N' bis-acrylamide, Sigma-Aldrich) were varied as needed (6% - 20%T) while maintaining equal weights (i.e. 50%C) of monomer and crosslinker in each gel. The total amount of gel manufactured depended on the study (0.25 - 1L).

To begin manufacture of isopropanol based normoxic gels, water and isopropanol were heated to 30°C at which point gelatin was added. The solution was further heated to 34 °C at which point the bis-acrylamide crosslinker was added. The solution was heated and stirred to 45 °C, then cooled to 37 °C and the NIPAM was added. Once all monomer was dissolved, THPC was added. Prepared gel was transferred to 20 mL scintillation vials (Wheaton Scientific, Millville NJ, USA) or 1L jars (Modus Medical, London, Ontario, Canada).

2.2 Gel irradiation

Gels were irradiated using a Varian Clinac linear accelerator (Varian Inc, Palo Alto, CA, USA) using 6MV x-rays, a 15x20 cm² field size, and a dose rate of 400 cGy/min at 1.5 cm depth in water [2]. For dose response studies, gels were irradiated in a customized phantom to between 2 - 50 Gy. For the imaging application, gels were irradiated in an immobilization device with 3 separate irradiations: (i) a single PDD with 4 Gy at d_max, (ii) a two-field cross (~25 Gy at d_max), and (iii) a 3-field irradiation. The single and 2-field irradiations were used to generate a calibration curve for the polymer gel dosimeters. This calibration was then applied to the 3-field irradiation in order to convert relative response to dose. All treatment planning was performed using Eclipse (Varian Medical, Palo Alto, CA, USA).

2.3 Gel imaging

Gels were imaged using a GE HiSpeed X/i scanner (GE Medical Systems, Milwaukee WI, USA) operating at 140 kVp and 200 mAs. Image averaging (16 averages) and blank (i.e. unirradiated gel) background subtraction was utilized for each final image. For dose response studies, gel vials were placed in a customized holder, as described previously [3]. For imaging of the 1L gel phantom, a customized mask assembly was used for precise placement of irradiated and background samples.

2.4 Data processing

All images were smoothed using a 5x5 Weiner filter with 2 iterations [4].

3. Results and Discussion

3.1 Dosimeter optimization

Figure 1 illustrates the dose response curves (figure 1a) and subsequent dose resolution (figure 1b) for isopropanol-based polymer gel dosimeters with varying total monomer/crosslinker (%T) content. Also shown, for comparative purposes, is the dose response curve for an anoxic-manufactured acrylamide-based polymer gel with no co-solvent. Figure 1b illustrates that high %T gels provide dose resolutions (1σ) on the order of 0.2-0.3 H/Gy at doses up to 20 Gy. From these results, 16%T gels were chosen for all future studies.

Figure 2 illustrates the dose response reproducibility for 3 separate batches of 16%T gel (figure 2a) and imaging session reproducibility (figure 2b) 1 - 8 days post manufacture. Results indicate that isopropanol based gels are reproducible and stable in their response.
Figure 1: (Left panel) Dose response curves and (right panel) dose resolution of 30% isopropanol-based polymer gel dosimeters with varying %T. Also shown, for comparative purposes, is an anoxic (acrylamide based, 6%T) polymer gel response.

Figure 2: Dose response reproducibility for (left panel) three batches of gel and (right panel) multiple imaging sessions of a given gel (days post irradiation).

3.2 Dosimeters Imaging

Figure 3 illustrates the dose response calibration curve generated by mapping select corresponding treatment plan / gel image points in the single field and 2-field irradiations. The calibration curve of figure 3 was then applied to the single field, 2-field, and 3-field gel images in order to convert relative gel response to dose.

Figure 3: Calibration curve for polymer gel imaging. Curve generated by mapping select points in single field and 2-field gel images to treatment plan. (see figure 4).
Figure 4 illustrates an isodose overlay (gel image with treatment plan isodoses) and representative profiles for the single and 2-field calibration images. It can be seen that calibrated images are capable of reproducing treatment plan doses.

Figure 5(a) illustrates the gel image and treatment plan isodose overlay for the 3 field "test" irradiation. Figure 5(b,c) illustrate representative profiles for the gel and treatment plan. Figure 5(d) illustrates a dose difference map (gel image - treatment plan) for the 3-field irradiation. Results indicate that the use of a single and 2-field calibration irradiation is capable of being applied to a test irradiation. Furthermore, low-doses (<4 Gy) are accurately imaged with the CT polymer gel system, with polymer gel images capturing low-dose isodoses. This is a significant improvement over previously reported applications of x-ray CT polymer gel dosimetry [5].

Figure 4: Gel images and treatment plan isodose overlays for PDD (4 Gy at $d_{max}$, top left) and 2-field (top right) calibration irradiations. Bottom left: Representative PDD profile through row 256 of PDD gel image and treatment plan. Bottom right: Representative profile through row 250 of square-field gel image and treatment plan.

4. Conclusions

These results, while preliminary, indicate that incorporating isopropanol-based polymer gel dosimeters in to x-ray CT polymer gel dosimetry increases the dose sensitivity and resolution of the system. While the dose resolution is still lower than that of, for example, MRI systems, these results indicate that x-ray CT imaging can be used to reconstruct high and low-dose information from irradiated polymer gel dosimeters. This is a significant step forward in x-ray CT polymer gel dosimetry, in that previous applications of the technique were only capable of high-dose reconstruction.
Figure 5: Top left: Gel image and treatment plan isodose overlay of 3-field irradiation. Gel image calibrated with calibration curve of figure 3. Top right: Representative profile through row 240 of gel image and treatment plan. Bottom left: Representative profile through column 200 of gel image and treatment plan. Bottom right: Dose difference map (gel image - treatment plan). Colour axis in Gy.

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