Revealing the impact of radiation-induced refractive index changes in polymer gel dosimeters

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Abstract. This study examines effects of radiation-induced refractive index (RI) changes in polymer gel dosimeters. A prototype fan-beam optical computed tomography scanner was used to image a normoxic polymer gel dosimeter that was irradiated with two simple irradiation patterns— one single beam, one cross beam. A combed fan-beam was used for rayline tracing. Scans revealed that notable rayline errors occur when a steep, side-to-side dose gradient (i.e. RI gradient) is encountered. When the gradient occurs in the plane of the detector system, distinctive streaks in images are observed. When the gradient occurs perpendicular to the plane of the detector system, much more severe image errors are observed.

1. Introduction
The optical properties of gelatin dosimeters (both absorption-based and scatter-based) continue to be researched for 3D radiation dosimetry [1, 2]. Due to their pliability, they could potentially fill a multifaceted role as a deformable 3D dosimeter [2]. Such dosimeters would be clinically attractive, as a number of tumour sites change position and shape on inter-fraction and intra-fraction timescales (e.g. prostate and lung, respectively). If effective methods to accommodate tumour motion and tumour deformation are to be prudently developed, a deformable 3D dosimeter would be an appealing tool to verify these methods.

It has long been known that polymer gel dosimeters can exhibit slight changes in refractive index (RI) when irradiated [3]. The potential for geometric distortion in optical computed tomography (CT) caused by radiation-induced RI changes has been tested previously [4]. However, those tests used the positions of completely opaque needles to evaluate geometric distortion. The work here will show that, in certain cases, radiation-induced RI changes can lead to readout errors caused by rayline bending that only occurs from certain projection angles; these would have little effect on the positions of needles in a needle-phantom. This work will contend that rayline errors occurring over a short range of projection angles can result in distinctive streaking artefacts near steep, side-to-side dose gradients. In other cases, radiation-induced RI changes can cause errors that are far more severe, particularly for the fan-beam optical CT geometry.

2. Material and Methods
A normoxic polymer gel dosimeter (cylindrical, 1 L, 95 mm diameter) was irradiated with two simple dose-distributions (see figure 1a, 1b). The gel (w/w%: 91.8% deionized water, 4.0% gelatin, 2.0% acrylamide, 2.0% bisacrylamide, 0.2% (9mM) tetrakis (hydroxymethyl) phosphonium chloride (all chemicals from Sigma-Aldrich; Oakville, ON, Canada)) was mixed and allowed to set in a room...
temperature bath for 24 hours prior to a pre-irradiation scan with a prototype fan-beam optical CT scanner [5]. Then, the dosimeter was immediately irradiated and given 24 hours to polymerize before a post-irradiation scan was acquired. Pre-irradiation and post-irradiation scans were compared ray-by-ray to calculate transmission data. Two artefact removal techniques were performed in sinogram space to remove ring artefacts that are distinct to the prototype and streaking artefacts attributable to a pair of seams that run down the sides of the flask housing the gel. These artefact removal techniques are described in more detail in an accompanying submission.

A simple line-pair pattern was printed on a piece of transparency plastic (1.5 lp/mm, see figure 1c) to allow rayline tracing to be easily performed. To do so, one light sinogram was acquired with the plain fan-beam. Then, the line-pattern (“comb”) was taped in place on the inside of the entry window to create a combed fan-beam. Next, a combed light sinogram was acquired. A rayline sinogram was then calculated by dividing the plain sinogram by the combed sinogram.

Figure 1: Square photon beams (18 MV, 3x3 cm², Clinac 21EX linear accelerator; Varian Medical Systems; Palo Alto, CA, USA) were used for simple (a) single-beam, and (b) cross-beam irradiation patterns with isocenter doses of 8.7 Gy and 10.0 Gy, respectively. Distributions shown were calculated by treatment planning software (Eclipse™; Varian Medical Systems). The comb pattern used for rayline tracing is shown in (c) with a ruler for scale.

3. Results and Discussion
Figure 2 displays scanner reconstructions of slices located in the middle of the single-beam and cross-beam irradiated regions of the dosimeter. It is contended that the streaking artefacts that follow along the sides of each beam (approximately -30% in magnitude) are caused by radiation-induced RI errors. In order to initially assess this interpretation, rayline tracing was used for each irradiated slice, as well as an unirradiated slice. Light sinograms and rayline sinograms for each slice are shown in figure 3.

Figure 2: The dosimeter is shown in (a). Opacity reconstructions for slices in the middle of the single-beam and cross-beam irradiated regions are shown in (b) and (c), respectively.
Rayline tracing indicates two different errors in these slices. First, tracing in all three slices elucidates the errors that are caused by the pair of seams that run vertically down the sides of the flask. These seams bend rays off of their initial trajectory, which causes errors that must be removed in order to avoid streaks in reconstructions. Second, raylines around projections 250 and 600 in figure 3e show ray bending that corresponds to steep dose gradients, as can be seen in figure 3b. These errors occur each time the scanner faces down the irradiated beam. Similar errors occur four times in the sinogram in figure 3f near projections 75, 260, 430, and 615. Again, the locations of these errors correspond to steep dose gradients in projections in figure 3c.

To further investigate the ramifications of radiation-induced RI changes, two additional slices of the dosimeter were scanned. Figures 4a and 4b display reconstructions of slices located in the penumbrae of the single-beam and cross-beam irradiated regions of the dosimeter. The locations of these slices, as well as those from figures 2b and 2c, are indicated in figure 4c. As is evident, severe errors result. Here, rather than dose gradients occurring side-to-side in the plane of the detector system, dose gradients occur vertically, perpendicular to the detector system. In these cases, rays are redirected out of the plane and away from the detector system. This results in an overestimation of opacity. It should be noted that identical window and level values have been used for all reconstructions. Despite these slices being in the penumbral region of the irradiation patterns, maximum optical density values in figures 4a and 4b are more than double the maximum values in figures 2b and 2c.

Correction methods are being considered for these artefacts. Ray tracing could be used to pinpoint rayline errors that result from RI gradients that occur side-to-side in the detector plane. In these instances, one could replace values of bad raylines using interpolation of nearby pixels in sinogram space. However, RI gradients that occur perpendicularly to the detector plane cause three main problems in the fan-beam geometry: 1) rayline tracing with a combed beam cannot denote raylines that bend vertically out of the detector plane, 2) many more rays of the sinogram are affected, and 3) the magnitude of these errors are much greater. Theoretically, one could determine a value for the maximum dose gradient that would still allow for proper raylines. This could then be taken into consideration when comparing measured dose distributions with planned dose distributions.
Figure 4: Opacity reconstructions for slices near the edges of the (a) single-beam, and (b) cross-beam irradiated regions. The slice locations of all four reconstructions are indicated in (c) in the sagittal plane of the dose distribution calculated by treatment planning software.

4. Conclusions
New image artefacts have been observed in a normoxic polymer gel dosimeter. It is believed that these are the first artefacts that are clearly attributable to radiation-induced refractive index changes. This attribution has been demonstrated in two ways. Rayline tracing was used to illustrate the bending of rays caused by dose gradients that occur side-to-side in the detector plane; this results in distinctive streaking artefacts. Dose gradients that occur perpendicular to the detector plane result in more problematic errors due to multiple raylines being redirected off of the detector system; this results in severe errors in reconstructions.

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