Recent developments with a prototype fan-beam optical CT scanner

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Abstract. The latest design of a prototype fan-beam optical computed tomography scanner is presented. A new beam creation system consists of a 635 nm laser diode module with variable, DC voltage-controlled beam intensity. A change in scanner alignment allows for the elimination of ring artefacts caused by data corruption that is spaced symmetrically across the detector array. These artefacts, as well as a pair of streaking artefacts caused by flask seams, are removed in sinogram space. A flask registration technique has been developed that allows for accurate, reproducible dosimeter placement. Protocol investigations with gel dosimeters have indicated the importance of: i) proper cooling techniques during gel manufacture, and ii) scanning the dosimeter while it is at room temperature. Latest reconstructions of a normoxic polymer gel dosimeter are presented as an indicator of current system performance.

1. Introduction

A variety of near tissue-equivalent materials have been developed that increase in opacity when exposed to radiation. Relationships can be established between their optical density (OD) and absorbed dose to allow for their use in radiation therapy dosimetry investigations. Notable examples currently under evaluation for 3D dosimetry [1] include polymer gels, dye-based polyurethane (PRESAGE™), and dye-based gels [2-6]. For readout of optical density, many optical computed tomography (CT) systems have been proposed. The first system used a translating pencil-beam analogous to first generation x-ray CT scanners [7]. More recent designs have opted for broad-beam geometries that are capable of faster scans by simultaneously illuminating the entire dosimeter [6, 7]. However, these systems find themselves restricted to using absorption-based dosimeters due to errors associated with imaging scatter-based dosimeters [10-12].

This work gives an update to a previously presented prototype fan-beam optical CT scanner [13, 14]. Its design intends to strike a balance between speed and versatility. Its beam simultaneously illuminates an entire slice of the dosimeter and its multi-hole collimator ensures accurate readout of highly attenuating dye-based and scatter-based samples [13]. Changes to its design are described. Two new artefact removal techniques are performed in sinogram space. A flask registration technique has been devised to finely reproduce the placement of dosimeters. Tests with gel dosimeters indicate the importance of proper cooling techniques during gel manufacture and scanning dosimeters while they are at room temperature. Finally, latest results with a normoxic polymer gel dosimeter are presented.
2. Materials & Methods

Two main changes have been made to the prototype since it was last presented [13]. First, the green HeNe laser, pair of linear polarizers, and line generating lens have all been replaced by a red laser diode module (LDM) with 60° line-creating head ($\lambda = 635$ nm, 3 mW, Edmund Optics; Boulder, CO, USA); the beam intensity of the LDM is modulated by a DC voltage input. The second change in design was a slight shift in alignment. The axis of rotation of the dosimeter mount was moved slightly off-center (10.4 mm) to allow for a new artefact removal technique to be implemented.

The system has suffered from ring artefacts caused by data corruption that affects specific detector elements. The detector array is an approximate arc consisting of 5 linear photodiode arrays. Data was found to be unreliable in the first few detector elements of each array, resulting in unreliable data that is located roughly symmetrically across the 5 arrays. Shifting the scanner’s axis of rotation off-center allows for the collection of an asymmetrical 360° sinogram that consists of two 180° sinograms containing redundant information. However, due to the shift in alignment, the locations of unreliable data no longer overlap when the second sinogram is flipped. This allows the two sinograms to be combined into a complete sinogram of reliable data. The values of the first 8 pixels in each 64-element linear array are ignored. Currently, to avoid residual ringing caused by their removal, values for these pixels are replaced using linear interpolation within each projection of both sinograms. Then, the two 180° sinograms are averaged, ray-by-ray.

Another artefact the system has been afflicted by is caused by two seams that run down the sides of the flasks being used. These seams are suspected to cause refractive errors that result in multiple streaking artefacts. The removal of these artefacts is also performed in sinogram space. Upon re-binning fan data into a parallel geometry, the locations of these seams follow easy-to-trace sinogram curves. These curves are traced and their values are replaced using interpolation of nearby pixels.

Early tests indicated that comparing “before” and “after” scans (i.e. pre-irradiation and post-irradiation scans, respectively) ray-by-ray lowered image noise considerably, and that even slight positional mismatches of these scans would reintroduce this noise. In order to finely reproduce the placement of dosimeters in the scanner, a flask registration technique was devised. To start, the central ray of the fan-beam is roughly aligned with a fiducial mark on the outside of the flask. Then, the flask is shifted a known amount so that the beam is targeting a blank region of the flask. This position is considered the “zero” position. Here, a light profile is acquired and saved, and the “before” scan can proceed. When the dosimeter is ready for its “after” scan, the fiducial mark is used again for rough alignment and the flask is shifted by the known amount to be roughly in the vicinity of the zero position. Next, a survey of many light profiles with positions slightly shifted vertically and angularly is acquired. Each light profile in the survey is then divided ray-by-ray by the light profile that was saved at the zero position during the “before” scan. Thus, a perfect alignment would give a homogenous profile with a value of 1 (noise aside), and any mismatches in position would introduce noise to the profile. Ergo, the zero position is located by locating the least noisy profile in the survey.

Tests were performed on normoxic polymer gel dosimeters housed in cylindrical flasks (1 L, 95 mm diameter). Gels consisted of (w/w%): 91.8% deionized water, 4.0% gelatin, 2.0% acrylamide, 2.0% bisacrylamide, and 0.2% (9 mM) tetrakis (hydroxymethyl) phosphonium chloride (all chemicals from Sigma-Aldrich; Oakville, ON, Canada). Two different protocols have been used for fabricating and imaging these dosimeters. Protocol #1 used the original green HeNe laser setup [13]. In this case, the flask was placed into a cold bath immediately after pouring the mixture into the flask. Six hours later, the dosimeter was removed from the fridge and scanned with the optical CT. Scanning occurs in a room temperature matching solution and takes ~45 minutes. The dosimeter was then irradiated, returned to the cold bath, and allowed to react overnight. Roughly 24 hours after irradiation, the dosimeter was removed from the cold bath and its “after” scan was acquired. Protocol #2 used the red LDM setup. In this case, after pouring the mixture into the flask, it was allowed to cool overnight in a room temperature bath. Roughly 24 hours later, the dosimeter was scanned in the room temperature matching solution. It was then irradiated, returned to the room temperature bath, and allowed to react overnight. Roughly 24 hours after irradiation, its “after” scan was acquired.
Simple 3×3 cm² square fields were used for irradiations (Clinac 21EX linear accelerator; Varian Medical Systems; Palo Alto, CA, USA). In protocol #1, 6 MV photons were used to create single-beam and cross-beam patterns (doses to isocenter: 3.7 Gy and 4.4 Gy, respectively). In protocol #2, 18 MV photons were used to also create single-beam and cross-beam patterns (doses to isocenter: 8.7 Gy and 10.0 Gy, respectively). Switching from green light to red light resulted in decreased beam attenuation by the polymers in the gel. Therefore, dose levels in protocol #2 were increased to achieve absorbance profiles of roughly equal magnitudes between the two protocols.

3. Results & Discussion
The effectiveness of both artefact removal techniques is shown in Figure 1. Images are of a synthetic polymer (Duramax B-1000; Rohm and Haas; Philadelphia, PA, USA) uniformly dispersed in water. Reconstructions are from the same data with and without the artefact removal techniques being implemented. As is apparent, the techniques effectively eliminate both artefacts. While removal of the streaking artefacts is more qualitatively evident in the images, profiles through the center of the flask show that ring errors with magnitudes of up to ~40% the uniform value are suppressed.

Figure 1: Images of a uniform scatterer (a) without and (b) with artefact removal implemented; (c) central profiles through (a) in red, and (b) in blue.

Figure 2: Images illustrating the performance of the flask registration technique: (a) flask left unmoved between I₀ and I scans, (b) data deliberately mismatched 1 mm vertically, (c) data deliberately mismatched 1° angularly, and (d) flask fully removed and registered using the technique.

Figure 3: Reconstructions of irradiated dosimeters manufactured and scanned using protocol #1 (a & b) and protocol #2 (c & d).
Figure 2 illustrates the effectiveness of the flask registration technique. Figure 2a shows an image that was reconstructed by acquiring both scan data and reference data without disturbing the placement of the flask. Figures 2b and 2c show images where positional shifts were deliberately introduced. Figure 2d shows a reconstruction where the flask was fully removed from the scanner before acquisitions of scan data and reference data and the registration technique was implemented. The technique effectively reproduces the positioning of the flask well enough to avoid excess noise. Although this technique could overlook positional errors caused by axial tilt that might occur when the dosimeter is inserted into its mount, such errors have not yet shown themselves to be significant.

The importance of temperature concerns are demonstrated in Figure 3. Images in Figure 3a and 3b are from protocol #1 and images in Figure 3c and 3d are from protocol #2. Images obtained using protocol #1 suffer from increased schlieren errors caused by refractive index inhomogeneities in the dosimeter. Two factors are suspected to cause the errors seen in protocol #1. First, it is believed that, by placing the flask containing a warm mixture (~43 °C) into a cold bath (~5 °C), convection currents were caused in the dosimeter as it set. Second, after placing the cold dosimeter in a room temperature matching bath to be scanned, the dosimeter begins warming. Hence, the gel may be gradually morphing while the flask is being registered and the dosimeter is being scanned. Both of these issues are avoided by giving the gel more time to set and by scanning it while it is at room temperature.

Images of the dosimeter manufactured under protocol #2 are compared with dose data provided by a commercial treatment planning system (TPS) (Eclipse™; Varian Medical Systems) in Figure 4. A linear relationship between OD and dose was assumed, so a single conversion factor was used to convert reconstructions to dose distributions. Methods of filtering and binning are now being considered to reduce noise that remains in images. For example, images in Figures 4b and 4d are the same data from Figures 3c and 3d, only binned into larger pixels (from ~0.25×0.25 mm² to ~2×2 mm²). Preliminary tests indicate that best results would be obtained by filtering in sinogram space.

It is worth noting the streaking artefacts that occur along the sides of each beam in Figures 3c and 3d. These artefacts are believed to be caused by radiation-induced refractive index changes, which are known to occur in polymer gel dosimeters [2]. This theory is the subject of a separate submission.

Figure 4: Dose reconstructions from a polymer gel dosimeter compared with calculated dose distributions. Images in (a) and (c) are from TPS, (b) and (d) were reconstructed from the dosimeter. Also indicated in (a) and (c) are the positions of the profiles compared in (e-h).

4. Conclusions
An update to a prototype fan-beam optical CT scanner has been provided. Artefact removal techniques that remove ring and streaking artefacts in sinogram space were described and their results presented. A flask registration technique was introduced and its performance was shown. Scans acquired using two different dosimetry protocols have indicated the need to be mindful of temperature during gel
manufacture and scanning. Most recent results indicate that data filtering and binning will be necessary to reduce remaining image noise. Finally, a streaking artefact was shown that is believed to be caused by radiation-induced RI changes.

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6. References
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