A prototype fan-beam optical CT scanner for polymer gel dosimetry

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Abstract. A prototype optical CT scanner has been developed for scanning polymer gel dosimeters used in 3D radiation therapy dose verification. The scanner is based on a 3rd generation, fan-beam CT design and employs a 543 nm laser fanned through a 60° line-generating lens. A series of 5 detector arrays or 64 elements each collects light on the distal side of the water tank. Pre-detector collimators are employed to reject light scattered away from incident ray trajectory. Results of scanner characterisation studies, as well as preliminary data acquired on irradiated polymer gels, are discussed.

1. Introduction

Optical computed tomography (OptCT) has been employed by a number of groups in the imaging of polymer gel dosimeters for radiation dosimetry. Two basic OptCT designs have emerged in recent years. The first is based on a 1st generation translate-rotate CT design, employing, typically a single detector and laser beam, scanned in parallel across the dosimeter. While potentially a very accurate method for imaging dosimeters, the systems can be slow [1]. The second category of designs employ a cone beam of light and, typically, a CCD detector to simultaneously image multiple “slices” of the dosimeter [2]. While offering rapid imaging times, scatter rejection and collimation are still outstanding issues in these systems.

This study reports on the use of a 3rd generation CT design to image polymer gel dosimeters. The system utilizes a fan beam of 543 nm laser light. Light emerging from the distal end of the scanning tank is collected using an array of 320 photodetectors arranged concentric with the focal point of the fan beam. Custom manufactured scatter-rejection collimators are positioned in front of each detector element. The system thus offers possibilities for rapid imaging (~1 min/slice) and scatter rejection. The OptCT scanner is still in a prototype phase and currently ring artefacts in the resultant images limit the overall dose accuracy attainable with the system.

2. Methods

2.1. Instrument Design

A schematic and image of the OptCT scanner are shown in figure 1. A 2mW, 0.8 mm beam diameter, 543 nm laser (Research Electro-Optics, Boulder CO) is incident on a 60° line generating lens (Edmunds Optics, Barrington, NJ). Fanned laser light is incident through a semi-circular matching
medium tank, designed such that light is incident normal to the tank faces. The matching medium consists of water and glycerol for index matching to gel refractive index, as well as blue dye used for attenuation matching. Polymer gels are rotated and translated utilizing computed controlled rotation and translation stages (Newport, Irvine, CA). Gels are housed in 1L cylindrical containers (Modus Medical, London, ON). Laser light is collected on the distal side of the tank using five concentrically arranged photodetector arrays (Hamamatsu, Japan), with each detector array housing 64 photodetector elements of 0.7 x 0.8 mm. Detector pitch is 0.8 mm. A collimator array, designed such that each collimator element is concentric with the fan beam focal spot, is positioned in front of the detector array. A custom-built microcontroller interfaces detector output and synchronization to a PC. Data collection and reconstruction is performed using Matlab (The Mathworks, Natick, MA).

![Figure 1](image)

**Figure 1**: (a) Schematic and (b) image of OptCT scanner.

2.2. Instrument characterisation and data post processing
A series of instrument characterization tests were performed. The uniformity of detector intensities when subject to the light fan beam was measured. System temporal stability, slice acquisition time, system noise, spatial resolution, and spatial distortion were characterized.

Image reconstruction was performed using the filtered backprojection algorithm built in to Matlab. Further postprocessing was performed to optimize image quality. Specifically, image filtering in the image domain, the FFT domain (FFT of image), and filtering of the sinogram (pre-reconstruction) were all tested using a range of image filters. Window sizes in the image filters were also tested.

2.3. Polymer gel imaging
Two cases utilizing NIPAM polymer gel (3% NIPAM, 3% bis-acrylamide, 5% gelatin, 5mM THPC) irradiated with a 6MV photon beam were used to test the imaging capabilities of the system. In the first case, a square 3x3 cm$^2$ field (maximum dose ~5 Gy) was used to irradiate polymer gel along the length of the 1L cylinder container. In the second case a 7 field IMRT irradiation was performed on a 1L cylindrical gel phantom (6 Gy at isocentre). Isodose overlays, profile plots, and dose difference maps between planned and imaged dose distributions were used to test the ability of the system to image irradiated polymer gel dosimeters.

3. Results and Discussion

3.1. Instrument characterisation
Figure 2a illustrates the uniformity of detector intensities when a fan beam is passed through the tank full of matching medium solution and with no polymer gel in place. Figure 2b illustrates laser/detector temporal stability. Typically, stability is within 0.8% of the mean detector intensity.

Table 1 shows the effects of index of refraction mismatch on image distortion (magnification). With optimized index matching solution, magnification distortions are reduced to within 0.01 cm.

Spatial resolution was determined by utilizing profiles through a needle phantom. The needle line function was deconvolved from the image and the 30% value of the MTF of the resultant profile was used as a determination of the system spatial resolution. Using this method, a spatial resolution of 0.25 mm/pixel was obtained, matching well the grid size of the reconstructed image (0.22 mm/pixel).

Figure 2: (a) Signal intensity variation over the full detector array. (b) Laser/detector temporal stability as a function of acquisition number (i.e. time).

Table 1: Effects of index of refraction mismatch on image distortion (magnification). True physical distance was measured utilizing x-ray CT imaging.

| True Physical Distance | Gel Cylinder Diameter(cm) | Needle Separation(cm) |
|------------------------|---------------------------|-----------------------|
| True Physical Distance | 9.64±0.01                 | 3.00±0.01             |
| Image Distance(n=1.33) | 9.51±0.01                 | 2.94±0.01             |
| Image Distance(n=1.35) | 9.64±0.01                 | 3.00±0.01             |

Figure 3a illustrates the effects of multiple averages per angle on the resultant standard error on the mean detector signal. As illustrated in figure 3b, the decreasing standard error as a function of increasing the number of averages comes at the expense of increased integration time. Figure 3b was calculated using 1° per angular increment. It is anticipated that large improvements to the results in figure 3b can be realized with improved data transfer speeds between the microcontroller and PC.
3.2. Polymer gel imaging

Figure 4 illustrates an OptCT image of the 3x3cm$^2$ square field irradiated gel. Shown are results for a raw image (figure 4a), a Gaussian filtered image (figure 4b) and a sinogram median filtered image (figure 4c). Figure 4d illustrates plan contours overlayed over the OptCT sinogram-filtered image and shows the ability of the system to accurately reconstruct the overall position and shape of the irradiation. Figure 4e illustrates a dose difference map between the OptCT image (sinogram filtered) and treatment plan. Figure 4f illustrates profile plots through OptCT images and the treatment plan. Figures 4 shows that, in general, filtering in the sinogram domain (i.e. prior to image reconstruction) offers the greatest improvements in image quality. Still, ring artefacts can be observed in the images and remain an outstanding issue for future work.
Figure 4: (a) Raw OptCT image of 3x3 cm² irradiated polymer gel, (b) Gaussian filtered image, (c) sinogram median filtered image, (d) plan contour overlay, (e) dose difference map between OptCT image and treatment plan, (f) profile plot through OptCT images and plan.

Figure 5 illustrates the results for OptCT imaging of polymer gel irradiated with a 7 field IMRT plan. Figure 5a illustrates the raw image. Figure 5b illustrates the treatment plan. Figure 5c illustrates the sinogram median filtered image, while figure 5d illustrates the planning contour overlay. The dose difference map between the sinogram filtered OptCT image and the treatment plan is shown in figure 5e. Figure 5f shows representative profile plots through the gel cylinder. While the general shape of the dose distribution is well captured in the OptCT images, ring artefacts still complicate more detailed quantitative analysis.
Figure 5: (a) Raw OptCT image of 7-field IMRT irradiated polymer gel, (b) treatment plan, (c) sinogram median filtered image, (d) plan contour overlay on OptCT image, (e) dose difference map between treatment plan and sinogram filtered image, and (f) representative profile plots through images.

4. Conclusions
A prototype fan beam optical CT scanner based on a 3rd generation CT design has been developed. The system utilizes a semi-circular design, pre-detector collimation, and photodetector array to acquire projection data from irradiated polymer gel dosimeters. While in the prototype stage, the system can reconstruct dose distributions delivered to the polymer gel. However, ring artefacts remain an outstanding issue for future work. Suppression of ring artefacts will enable further quantitative analysis on OptCT images of irradiated polymer gel.

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