Preliminary investigations with a photodiode-based fan-beam optical CT scanner

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Abstract. An updated version of a prototype fan-beam optical computed tomography scanner is presented. The scanner uses a 0.83 mm diameter 543 nm HeNe laser beam with a 60° line-generating lens for fan creation. A pair of linear polarizers is used for light intensity control. A set of five 64-element photodiode arrays forms the detector arc. Extended dynamic range is achieved by adjusting light intensity and photodiode integration time. Two detector collimators (one single-slot, one multi-hole) are employed for comparative purposes. Highly attenuating solutions of scatter-based and absorption-based agents are examined using both types of collimation. Comparison of the results provides useful information about the persistent presence of scatter in optical CT.

1. Introduction
For more than a decade, the effects of radiation on the optical densities of polymer gels have been investigated [1]. While initial gel dosimeters utilized scatter as a mechanism for light attenuation, polyurethanes utilizing absorption for light attenuation were later composed [2]. In order to promote the use of 3D dosimeters, a relatively small number of researchers worldwide continue development in optical CT systems.

Currently, two commercial systems are available. The first—the OCTOPUS\textsuperscript{TM} from MGS Research Inc. (Madison, CT, USA)—uses a pencil-beam scanning geometry. Although scan times using pencil-beam geometry are long, scatter contamination is avoided by only illuminating a small volume of the dosimeter at a time and by detector collimation. The second commercial system—the Vista\textsuperscript{TM} from Modus Medical Devices Inc. (London, ON, Canada)—uses a cone-beam geometry. With a cone-beam geometry, scan times are vastly improved by acquiring full projections for multiple slices simultaneously. However, this simultaneous illumination can lead to multiple scattering, which may compromise the use of scatter-based dosimeters. Cupping artefacts are observed with the Vista\textsuperscript{TM} scanner when examining polymer-based dosimeters that have been treated with uniform high doses [3]. A similar effect has also been observed in highly attenuating absorption-based phantoms [4]. The existence of similar phenomena for both scatter-based and absorption-based samples brings the cause of the cupping artefact into question.

This work presents the updated design of a fan-beam optical CT scanner that is currently under development [5]. Preliminary results examining highly attenuating scatter-based solutions and absorption-based solutions are presented.
2. Materials and methods

2.1. Fan-beam optical CT scanner

A schematic and photograph of our system are shown in Figure 1. The light source is a 543 nm HeNe laser with 0.83 mm beam diameter and 2 mW output (Research Electro Optics, Inc.; Boulder, CO, USA). Light intensity control is performed using a pair of linear polarizers (Edmund Optics; Barrington, NJ, USA). Tests show that the polarization sensitivity of our detectors is minimal. Still, to minimize effects seen due to beam polarization, the second polarizer remains stationary while the first (closest to laser) is adjusted. Fan creation is achieved using a 60° line-generating lens (Edmunds Optics). A scanning medium is housed in a semi-circular tank designed with concentric walls so that light enters and exits the medium with normal incidence. Phantoms are contained in 1L cylindrical PET flasks (Modus Medical Devices Inc.). Flasks are suspended overhead and moved using a rotational stage and a translational stage, both of which are instructed via a Universal Motion Controller (Newport; Irvine, CA, USA). Light is detected by five 64-element photodiode arrays (Hamamatsu; Hamamatsu City, Japan). Detector elements have 0.8 mm pitch, 0.7 mm active width and 0.8 mm active height. Detectors are mounted concentrically onto one of two collimators. The first, a single-slot, provides no scatter-rejection collimation (slot h: 0.8 mm, d: 12-14 mm). The second, a multi-hole collimator, has holes cut for each individual element (w: 0.7 mm, h: 0.8 mm, d: 15 mm).

![Figure 1: (a) Schematic of current setup, and (b) a photograph.](image)

Data acquisition and collection was performed via a custom-built circuit board and five daughter boards, which were developed at the University of Victoria. Operating at the fastest speeds specified by our detectors (2 MHz clock rate), the circuit board stores scan data to onboard memory. Current research does not focus on minimizing acquisition time. At the moment, data collected from elements near array edges are compromised, which leads to ring artefacts at consistent radii in our reconstructed images (see Figure 2a). This issue has a hardware-based solution that requires modifying the current circuit board. Nevertheless, the system is capable of acquiring 6500 full-profile views in ~35 seconds before onboard memory fills and data must be output to the PC (upload time ~100 seconds).

Uniform scatter-based phantoms of diluted Duramax B-1000 polymer (Rohm and Haas; Philadelphia, PA, USA) were examined using water as the scanning medium. In order to investigate scanning protocols and their effects on image noise, a disc region of interest was selected to lie just outside of the inner rings and within the outer rings (N.B. the outermost rings in Figure 2a are the walls of the flask). The ROI sampled 46192 pixels, and relative noise ($\sigma/\mu$) was used to quantify image quality. Full 360° sinograms (acquired at 1° increments) of water-filled flasks were acquired for $I_o$ before scatterer was added through a porthole in the upper portion of the flask. Adding scatterer through the porthole allowed the same slice to be examined for I and $I_o$ sinograms. Absorbance profiles were calculated respectively for each projection angle ($A = -\log_{10}(I/I_o)$). Data collection and image reconstruction were orchestrated using MATLAB (The Mathworks™; Natick, MA, USA).
Figure 2: (a) Unprocessed image examining a dilution of Duramax B-1000 polymer (ROI radii indicated), (b) relative noise acquiring multiple samples per projection, (c) relative noise when delaying scans, and (d) relative noise comparing different slices of the flask.

The stability of both our detectors and our light source is demonstrated in Figure 2b. Multiple samples were acquired and averaged for each projection angle. Image noise showed no significant gain achieved by obtaining multiple samples. Examining the length of time between acquisitions of the \( I_0 \) and \( I \) sinograms, Figure 2c indicates that although noise is at its lowest with the shortest delay, there are only minor penalties for lengthening the time between acquisitions. The largest source of noise in our imaging investigations came in comparing different slices of the flask. Multiple slices of a water-filled flask were scanned to serve as \( I_0 \) sinograms for a final scan. As can be seen in Figure 2d, images suffer greatly when comparing different surfaces of the flask. We attribute these differences to surface imperfections, and while they vary dramatically from slice to slice, their variations are consistent. This indicates that registering the surface of the flask may provide huge reductions in image noise. Future work aims to address this task.

2.2. Extending dynamic range

In order to interrogate samples of high absorbance (\( A > 1.25 \)), the dynamic range of the scanner must be extended. Using the light intensity control allowed by our polarizer pair, a method of DR extension is implemented which is similar to methods used by other investigators [4, 6]. For transmission profiles containing ‘dark’ readings, light intensity is increased to obtain valid data, which is then normalized to fill in for missing values. The characterization curve of our polarizer pair is used for normalization. Shifting to longer photodiode integration times can further extend our DR. In this case, integration times are used to normalize the data obtained. The linearity of each method was tested before being used for these investigations. By employing a combination of the two techniques, absorbance values slightly greater than 4 are measurable.
2.3. Examining highly attenuating solutions
Concentrated solutions of scatter-based and absorption-based agents (Duramax B-1000 polymer and blue food colouring, respectively) were prepared. In order to evaluate the absorbances of these solutions, 9 dilutions of each solution were prepared. Absorbance values of these dilutions were obtained using a Cary 500 UV-VIS-NIR Spectrophotometer (Varian, Inc.; Palo Alto, CA, USA) with cuvettes of 1 mm pathlength. By considering the absorbance for a given concentration over 1 mm pathlength, theoretical absorbance values for longer pathlengths were calculated. A flask 95 mm in diameter with ~1 mm thick walls was used to contain samples of increasing concentration. Precise concentrations for each solution were scanned using the single-slot collimator. These tests were then repeated using the multi-hole collimator. For comparison between measured and theoretical absorbance values, the center three pixels of the measured absorbance sinograms were averaged (3 pixels × 360 projections) and compared against theoretical values for a 93 mm pathlength.

3. Results and discussion
Absorbances up to ~2 were accurately measured for both solution types using both collimators (see Figure 3a,b). For the highest concentration of dye, measurements using the single-slot collimator understated absorbance values ($A_{th} = 4.09$, $A_{mSS} = 3.71$), while measurements using the multi-hole collimator maintained linearity ($A_{mMH} = 4.09$). For scattering solutions, similar results were observed for the highest concentration that provided readings for both collimators ($A_{th} = 3.84$, $A_{mSS} = 3.32$, $A_{mMH} = 3.91$). Two higher concentrations provided measurements with the single-slot collimator, although these values were severely nonlinear ($A_{th} = 7.55, 14.54$; $A_{mSS} = 3.72, 3.87$).

![Figure 3: Measured vs theoretical absorbances for (a) dye, and (b) scatterer (blue dotted line indicates expected values). Absorbance sinogram profile comparisons for (c) dye, and (d) scatterer. Multi-hole collimator results are plotted in solid-black, single-slot collimator results in dashed-red.](image-url)
Figure 4: Profiles through reconstructed images for (a) dye, and (b) scatterer. Multi-hole collimator results are plotted in solid-black, single-slot collimator results in dashed-red.

Absorbance profiles are shown in Figure 3 and profiles through reconstructed images are shown in Figure 4. Flattening of absorbance profiles is especially apparent with the highest two concentrations of scatterer that were examined with the single-slot collimator (Figure 3d). Cupping of reconstructed images is also apparent for these concentrations (Figure 4b). The magnitude of ringing caused by array-edge data corruption is evident in the image profiles. An additional “spiking” artefact is seen in reconstructions of high absorbances with the single-slot collimator. The cause of this effect is currently unclear, though it may be due to the redistribution of light reflected off of the elements of our detectors. The multi-hole collimator limits detection of such stray light.

4. Conclusions
The current version of a fan-beam optical CT scanner has been presented. System stability has been discussed and our most recent imaging issues have been indicated. Scanning of highly attenuating phantoms using two types of collimation has provided useful information regarding the effects of scatter in optical CT. Results indicate that the understatement of absorbances for highly attenuating scatter-based and absorption-based phantoms is due to signal contamination by scattered light.

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