

Fan-beam scanning laser optical computed tomography for large volume dosimetry

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Abstract. A prototype scanning-laser fan beam optical CT scanner is reported which is capable of high resolution, large volume dosimetry with reasonable scan time. An acylindrical, asymmetric aquarium design is presented which serves to 1) generate parallel-beam scan geometry, 2) focus light towards a small acceptance angle detector, and 3) avoid interference fringe-related artifacts. Preliminary experiments with uniform solution phantoms (11 and 15 cm diameter) and finger phantoms (13.5 mm diameter FEP tubing) demonstrate that the design allows accurate optical CT imaging, with optical CT measurements agreeing within 3% of independent Beer-Lambert law calculations.

1. Introduction

Optical computed tomography (CT) has been developed for three-dimensional (3D) radiation dosimetry via scanning of volumetric gels or solids that undergo either radiation-induced colour change (radiochromic materials) or radiation-induced polymerization reactions (polymer gel dosimeters) [1]. Optical CT evolved similarly to x-ray CT, starting from “translate-rotate” scanners, and culminating in broad-beam CCD-based systems operating in either cone-beam [2, 3] or telecentric geometry [4, 5]. The accuracy of broad-beam scanners is perturbed by scatter [6]. It is therefore desirable to make use of single-ray, single-detector geometry, so that transmission measurements within a projection are independent and are only polluted by the scatter associated with a single pencil beam. This motivates a return to scanning-laser systems. Scanning laser geometries have been reported [7-12], but many were too slow for practical applications. Here, we describe a prototype fan-beam scanning laser system which is capable of acquiring 3D imaging of a 15cm diameter, 12cm height cylinder at high resolution (<0.5 mm voxels) in a reasonable scan time (~45 minutes).

2. Methods

Figure 1 shows a schematic of the prototype system. A laser beam is directed to a vertical translation stage, upon which a turning mirror and a fast galvanometer (“galvo”) mirror are mounted. The galvo mirror is swept back and forth across the scanned object in a fan-beam pattern. It is driven by a triangular-wave voltage at a rate of 100Hz. The translational stage moves at constant speed during data acquisition, set by the desired slice thickness. The beam falls upon a small area diffuser in front of a vertically translating photomultiplier tube (Hamamatsu). This allows additional collimation to reject stray light, improving upon the previous cone-beam design [12]. The voltage output from the PMT module is sampled by a DAQ device (National Instruments) at a rate of 1 MHz and downsampled as



desired. 2D transmission images are generated by assigning the measured voltage at a sampling time to the known ray position at that time.

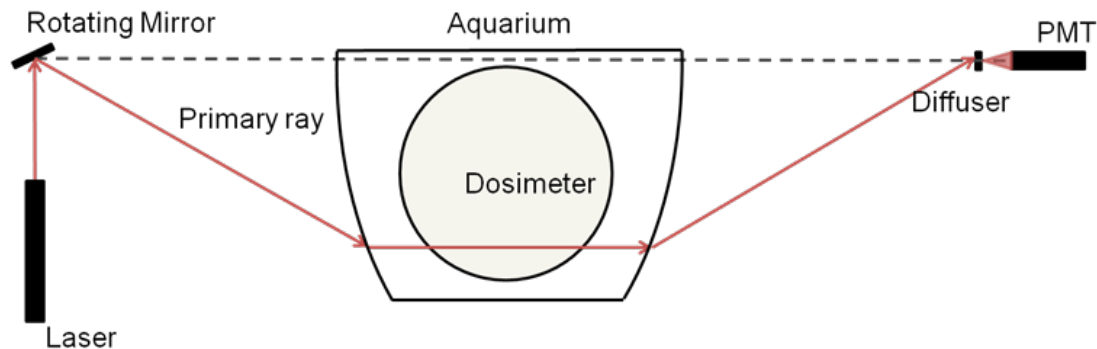


Figure 1. Schematic (top view) of the fan beam scanning laser system.

The shape of the aquarium was generated through ray-tracing simulation to achieve parallel-beam geometry through the scanned volume as well as to focus the light rays down towards a small detector for improved scatter rejection. The asymmetrical design avoids the overlap of regions of important projection data with perpendicular interfaces between the laser beam and the aquarium wall, which result in interference fringes that create rings in reconstructed images (Figure 2).

2.1 Experiments

To illustrate the effect of interference fringes in projection images, optical CT scans of an 11cm diameter uniform solution phantom were obtained using both a symmetric and asymmetric aquarium design. To demonstrate the scanner's ability to image large volumes, a 14.8 cm diameter uniform solution phantom was scanned. Finally, a finger phantom consisting of four FEP tubes (13.5mm outer diameter, 12.5mm inner diameter) [13] was imaged to simulate a small-field dosimetry problem. Carbon black solutions [14] were used as the attenuating liquids in the phantoms. In these preliminary experiments the photomultiplier was stationary. A large area diffuser was used at the detector end with no additional collimation / scatter rejection.

2.2 CT scanning and reconstruction

The data acquisition card samples at a constant temporal frequency, which corresponds to uniform *angular* spacing of rays in this system. However, due to the acylindrical aquarium, this results in *non-uniformly* sampled parallel beam projections. Images of transparent rulers were used to measure this effect. This information was used to re-sample the projections onto a uniformly spaced grid, with spacing equal to the *maximum* inter-sample spacing. In this way, interpolation artifacts from the image re-gridding are avoided. Once this was done, filtered backprojection was performed using a Hamming filter. In all experiments, 1024 projections, spanning 360° of rotation, were acquired (20cm x 12cm FOV, 0.25mm “pixels”). Reconstructions were performed with 0.33 mm isotropic voxels. All reconstruction slices are displayed with 150 mm FOV.

3. Results and Discussion

Figure 2 shows reconstruction slices of a uniformly attenuating solution imaged within the symmetric and the asymmetric aquarium. The ring artifacts near the center of the image in the symmetric case have been avoided by the use of the asymmetric design.

Figure 3 shows the results of the large-volume (15 cm diameter) solution phantom scan as well as the finger phantom. The uniform solution phantom is reconstructed flat (mean value within 1%) over its entire diameter and height. The attenuation coefficient was 0.105 ± 0.003 , which agreed within 2%

with a Beer-Lambert law calculation (0.107 ± 0.005) made along the central axis of the cylinder with a small aperture (0.5 cm diameter) placed in front of the diffuser.

The finger phantom mean values were measured within 5 mm diameter, 5 mm height ROIs at the center. These were again compared against Beer-Lambert law calculations made by taking the transmission value with the 0.5 cm diameter aperture in place. Excellent linearity between CT and Beer-Lambert law calculations was observed, with a linear regression resulting in $r^2 = 0.9998$ and a slope of 0.983. Note that there is approximately 2-3% underestimation of attenuation in the CT reconstruction compared to the central axis calculation. This may be due to the relatively high scatter of the FEP walls of the phantom, as a large acceptance angle detector was used in this preliminary experiment. However, the fingers were reconstructed circularly and have the correct radius (within 1 pixel), demonstrating the geometric fidelity of the scanner in spite of the complex geometry.

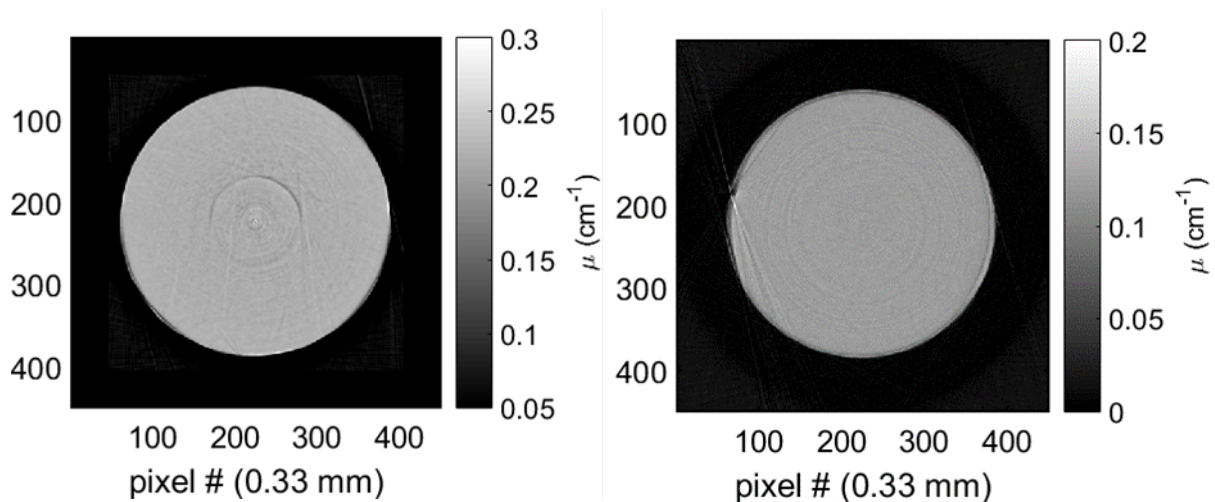


Figure 2. Reconstruction slices of 11cm diameter uniform solution phantoms scanned using: a) symmetric aquarium design. b) asymmetric design. The strong ring in a) is related to interference fringes which have been avoided in the asymmetric design.

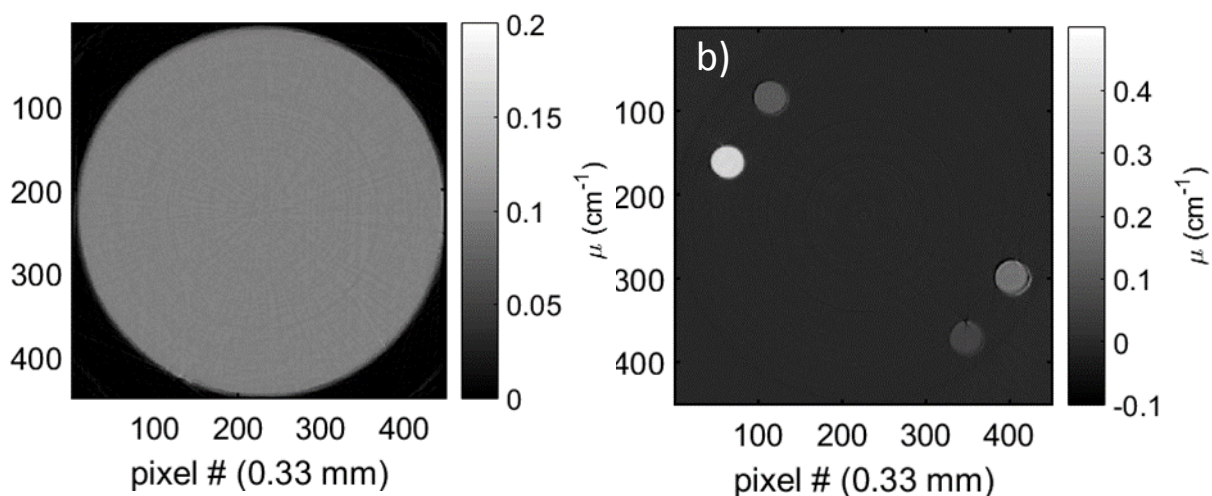


Figure 3. a) Uniform solution phantom (15cm diameter) reconstruction slice. b) FEP finger phantom (13.5mm outer diameter, 12.5mm inner diameter) reconstruction slice.

Table 1. CT and Beer-Lambert law attenuation coefficients in finger phantom.

Finger	μ_{CT} (cm ⁻¹)	$\mu_{Beer-Lambert}$ (cm ⁻¹)
1	0.064 ± 0.001	0.066 ± 0.001
2	0.115 ± 0.002	0.118 ± 0.001
3	0.175 ± 0.005	0.179 ± 0.004
4	0.400 ± 0.005	0.408 ± 0.008
Linear Regression	$\mu_{CT} = 0.983(\mu_{Beer-Lambert}) - 0.0009$ $r^2 = 0.9998$	

4. Conclusion

We have presented preliminary results from a fan beam scanning laser system making use of a galvo mirror for the fast (horizontal) scan direction and a translational stage for the vertical direction. The system is capable of scanning large volume dosimeters (15cm diameter). The geometric fidelity of the system has been demonstrated here. Currently, it takes about 45 minutes to acquire a 1024 projection dataset (20x20x12 cm³ imaging volume, 0.25mm voxel resolution). It should be feasible to double the galvo mirror frequency, which will reduce scan time to about 25 minutes. Finally, implementation of detector-side collimation will result in a fast, highly accurate, large volume dosimetry scanner.

5. Acknowledgments

The original version of the ray-tracing code used to generate acylindrical aquarium designs was written by Paul Gallivan. KHD acknowledges scholarship and funding support from NSERC, Western University, and the Ontario Research Fund (OCAIRO project). The authors also acknowledge a grant from the Plunkett Foundation. Disclosure: The authors have a research agreement with Modus Medical Devices Inc. concerning optical CT applications.

6. References

- [1] Baldock C *et al* 2010 *Phys. Med. Biol.* **55** R1-63
- [2] Wolodzko J G *et al* *Med. Phys.* **26** 2508
- [3] Olding T *et al* 2010 *Phys. Med. Biol.* **55** 2819-40
- [4] Sakhalkar H S and Oldham M 2008 *Med. Phys.* **35** 101-11
- [5] Krstajić N and Doran S J 2007 *Phys. Med. Biol.* **52** 3693
- [6] Granton P V *et al* 2016 *Phys. Med. Biol.* **61** 2893
- [7] Gore J C *et al* 1996 *Phys. Med. Biol.* **41** 2695
- [8] Kelly R G *et al* 1998 *Med. Phys.* **25** 1741
- [9] Maryanski M J and Ranade M K 2001 *SPIE Medical Imaging 2001* pp 764-74
- [10] Oldham M *et al* 2003 *Med. Phys.* **30** 623-34
- [11] Krstajić N and Doran S J 2007 *Phys. Med. Biol.* **52** N257
- [12] Jordan K J *et al* 2013 *J. Phys.: Conf. Ser.* **444** 12062
- [13] Jordan K 2013 *J. Phys.: Conf. Ser.* **444** 12076
- [14] Jordan K and Battista J 2009 *J. Phys.: Conf. Ser.* **164** 12045