Simulated design optimization of a prototype solid tank optical CT scanner for 3D radiation dosimetry

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Abstract. Optical computed tomography (CT) is one of the leading modalities for imaging gel dosimeters. There exist many prototype designs, as well as some commercial optical CT scanners that have showcased the value that gel dosimeters can provide to improve 3D dose verification for radiation treatments. However, due to factors including image accuracy, scan time, or demanding setup and maintenance there is currently no single scanner that has become a ubiquitous staple in a clinical setting. In this work, a prototype solid tank optical CT scanner is proposed that minimizes the need for a refractive index bath commonly found in optical CT systems. In addition to the design proposal, a ray-path simulator was created to optimize the design such that the solid tank geometry improves light collection across the detector array, maximizes the volume of the dosimeter scanned, and maximizes the dynamic range of the scanner.

1. Introduction

Gel dosimeters offer great potential as tools used to advance radiation treatment capabilities through three-dimensional dose verification [1]. By some criteria they are currently viewed as the only true 3D dosimetric tool [2]. A gel dosimeter is a composition of radio-sensitive chemicals that are fixed in place by a material matrix, most commonly gelatin, agarose, or plastic. The radio-sensitive chemicals respond in a measurable way to absorbed dose, and can then be read out at a later time [3]. Gel dosimeters can be imaged using MRI, x-ray CT, or optical CT [4]. The current state of gel dosimetry is quite open. Many varieties of gel dosimeters exist, and in optical CT, many gel dosimetry scanner designs. There is no obvious gold standard for a gel dosimeter or an imaging modality.

Optical CT is a high-resolution candidate for scanning gel dosimeters [5]. The imaging modality has good contrast, and a wide range of customizability for a relatively low-cost. Customization comes by way of optical instruments such as polarizing lenses, varied light sources, mirrors, and beam spreaders. However, optical CT relies on visible light which is subject to Snell’s Law and the Fresnel Equations as it transmits a material interface. The resulting reflections increase noise via scatter, and refraction is a source of artifacts during image reconstruction, particularly filtered back projection.

Filtered back projection takes advantage of the reverse radon transform which assumes a direct path is taken from the signal source to the detector. However, in optical CT systems, when a photon transmits an interface of two media with differing refractive indices at an oblique angle, the photon will...
refract. As a means to minimize refractive artifacts, nearly all optical CT designs contain some sort of index matching fluid contained in a bath to reduce refractive deviations [6, 7, 8, 9, 10]. Refractive baths typically have a significant volume of index matched fluid in them (1-15L). The fluid can evaporate or separate over long scanning periods, changing the remaining fluid’s refractive index. If a matching fluid becomes inhomogeneous from separation, Schlieren patterns may appear in the viewing area naturally or as the result of motion in the fluid [11].

The goal of this research was to find a verifiably ideal design for a solid tank optical CT scanner. Such as design would maximize light collection, minimize artifacts, reduce the need for index matching, and have a uniform beam profile. An optical ray simulator was created using Matlab (MathWorks Natick, MA), was subsequently used to simulate hundreds of thousands of potential geometries with variations across five geometric variables. In this work, a specific scanner type was being tested which featured a solid acrylic "tank" allowing for a significant reduction in index matching fluid to between 5-15mL, and features the inclusion of iterative reconstruction techniques that account for refraction allowing for accurate image reconstructions regardless of refractive index mismatches. This work creates a framework for identifying ideal geometries for such a prototype fan-beam optical CT scanner, and optimizes for beam uniformity, spatial resolution, detector efficiency, and artifact minimization.

2. Materials and methods
The proposed fan-beam scanner design features a solid acrylic (PMMA) block with a hole bored through it. A gel dosimeter can then be placed through the bored hole, and moved using rotational and translational motors. An O-ring is fitted into the bore such that when pressed against a gel dosimeter it creates a seal. Within the gap between the bore and the dosimeter, a very small volume of refractive matching fluid is held in place by the O-ring. On the rear wall of the block is an array of uncollimated photodiode detectors, which have been their detecting surface pressed directly against the acrylic.

The primary tunable geometric properties that influence the quality of an optimal geometry were: the length of the block \(x_{bl}\), the position of the bore translated from the center of the block \(x_{bc}\), the distance from the focal point of the laser to front face of the block \(x_{fp}\), and two properties tied to the elliptical front face of the block, the semi-major axis length \(x_{ma}\) and eccentricity \(x_{be}\) (Fig. 1).

**Figure 1:** Shown is a schematic representation of the proposed solid tank optical CT scanner. Each of the five tunable parameters highlighted: block length \(x_{bl}\), bore position from the block center \(x_{bc}\), laser position from the block face \(x_{fp}\), semi-major axis length \(x_{ma}\) and block eccentricity \(x_{be}\).

**Figure 2:** An example showing how ray path and intensity are simulated through a geometry. At refractive interfaces the ray-path is altered (Snell’s). An incident ray suffers an intensity loss from reflection upon the entry and exit from an object (Fresnel) with a different refractive index, as well as suffering intensity losses from attenuation (Beer-Lamber).
The ray-path simulator that was constructed has full customizability including: the five tunable parameters, laser polarity, material refractive index, attenuation coefficients, laser fan angle, etc. During each simulation, 400,000 rays are generated and uniformly distributed in a 60° fan, approximating the optical fan-beam created by our laser. In this research the virtual gel was comparable to a FlexyDOS3D dosimeter with a refractive index of 1.4225, and a uniform linear attenuation of 0.166 cm⁻¹ [12].

When a ray a material interface, the refraction induced changes to ray path is calculated using Snell's Law. The relative intensity of each ray is tracked as it passes through the system, measuring losses from reflection using the reflectance Fresnel equations, as well as intensity losses from attenuating objects which can be placed in the system (Fig. 2).

The purpose of simulating many geometries is to find a best geometry. A best geometry would maximize spatial resolution, minimize spatial artifacts, and maximize dynamic range of detector profiles. In order to score geometries three relevant quantities were identified: effective radius (Fig. 3), magnification (Fig. 4), and beam uniformity (Fig. 5). Effective radius evaluates how much of the bore area is imaged, and highlights any reductions in the field-of-view (FOV) is due to ray refractions. The magnification quantifies the fraction of the available detectors that are used to image the gel volume. Beam uniformity is the root-mean-square error (RMSE) of each simulated signal profile. Each of the three properties was weighted equally and scored from 0 to 1. The sum of the scores for each property was the final metric used to identify ideal geometries (Fig. 6).

Figure 3: Schematic showing ray paths that result in different effective radii \( r_{\text{eff}} \). Top panel: ray paths resulting in high \( r_{\text{eff}} \). Bottom panel: ray paths resulting in low \( r_{\text{eff}} \).

Figure 4: Schematic showing ray paths that result in varied magnifications. Top panel: ray paths leading to high magnification. Bottom panel: ray paths leading to low magnification.

Figure 5: A sample diagram showing intensity profiles that would result in different beam uniformity (RMSE) values. Top panel: a signal profile with good beam uniformity. Bottom panel: a signal profile with poor beam uniformity.

3. Results and discussion
During simulation, virtual detectors are used as bins to collect rays refracted through the solid tank. The number of rays passed through the system was tuned in order to ensure that a statistically significant number of rays are collected in each detector element. Increasing the number of rays results in a more
accurate profile, but increases the time required for each simulation, and 400,000 rays was found to be a balance between computation time, and profile smoothness.

Each simulation dataset returns a 5 dimensional matrix of scores corresponding to the permutations of the 5 variables: $x_{bl}$, $x_{bc}$, $x_{lp}$, $x_{ma}$, and $x_{be}$. During simulation a challenge was sampling resolution. The nature of 5D computation means that to go from 10 points of resolution to 11 would be a 61% increase in the number simulations for a 9% increase in resolution. Ultimately, trial and error was the method used to find regions of high-scoring geometries. Once one such area was found, another "zoomed-in" simulation was performed to get a higher sampling resolution in the region-of-interest.

The ideal values for the 5 variables were found to be: $x_{bl} = 290$ mm, $x_{bc} = 5$ mm, $x_{lp} = 41$ mm, $x_{ma} = 61$ mm, and $x_{be} = 0$. The beam profile of this geometry can be seen in Fig. 7, and to show how quickly beam uniformity degrades Fig. 8 shows a profile with $x_{bc} = 18$ mm.

**Figure 6:** A Laser position ($x_{lp}$) vs. Bore Center ($x_{bc}$) 2D contour of 5D data which shows a local maxima. Fixed variables are: $x_{bl}$, $x_{ma}$, and $x_{be}$.

**Figure 7:** A simulated profile with decent beam uniformity ($x_{bc} = 5$ mm).

**Figure 8:** A simulated profile with poor beam uniformity ($x_{bc} = 18$ mm).

### 4. Conclusion

Using a ray path simulator, an ideal design for the proposed solid tank fan-beam optical CT scanner was found. Hundreds of thousands of geometries were simulated by varying 5 variables corresponding to the block geometry. The simulated geometries were compared by scoring three properties of interest: effective radius, magnification, and beam uniformity. The ideal values for each of the variables were found to be: $x_{bl} = 290$ mm, $x_{bc} = 5$ mm, $x_{lp} = 41$ mm, $x_{ma} = 61$ mm, and $x_{be} = 0$ for this specific design. This simulator can be used in the future to find the optimal design of a new block that would be used to test gels other than FlexyDos3D.

### 5. References

[1] Jackson J et al 2015 *Phys. Med. Biol.* **60** 2217-30
[2] Schreiner L J 2015 *J. Phys. Conf. Ser.* **573** 012003
[3] Hoecker F E et al 1958 *Int. J. of Appl. Radiation and Isotopes* **31** 35
[4] Baldock C et al 2010 *Phys. Med. Biol.* **55** R1-63
[5] Oldham M 2006 *J. Phys. Conf. Ser.* **56** 58-71
[6] Gore J C et al 1996 *Phys. Med. Biol.* **41** 2695
[7] Wolodzko J G et al 1999 *Med. Phys.* **26** 2508-13
[8] Krstajić N et al 2007 *Phys. Med. Biol.* **52** 3693-13
[9] Xu Y et al 2004 *Med. Phys.* **31** 3024-33
[10] Campbell W G et al 2013 *Med. Phys.* **40** 061712
[11] Settles G S 2001 *Schlieren and Shadowgraph Techniques Visualizing Phenomena in Transparent Media*. SpringerLink eBooks
[12] Deene Y D et al 2015 *Phys. Med. Biol.* **60** 1543-63