

Investigation of a low-cost optical-CT system with minimal refractive index-matching fluid

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Abstract. Optical computed tomography (optical-CT) is a method for visualizing 3-dimensional dose distributions in radiochromic dosimeters. Projection images are acquired by collimating a visible light point source into parallel-beam geometry and imaging differential absorption through the sample dosimeter. Practical challenges involved in optical-CT imaging were addressed through the investigation of an in-house Fresnel-based optical-CT system with considerably less refractive index-matching fluid. The “DFOS” (Duke Fresnel-based Optical-CT System) system differed from current optical-CT systems by replacing cumbersome convex telecentric lenses with a lighter and much less expensive Fresnel system. A second major modification was the replacement of the refractive index-matching fluid bath with a solid polyurethane tank. PRESAGE radiochromic dosimeters were irradiated with orthogonal parallel-opposed treatments and dose distributions were readout by the DFOS system and compared to both treatment planning software prediction and two other in-house optical-CT systems. Gamma index passing rate at the 3%/3mm threshold in relation to Eclipse treatment planning software for the treatment was 92.2%, compared to 96.8% and 95.6% for two other systems featuring a traditional setup. The DFOS system showed promise for 3D dosimetry, but the performance is still substantially inferior at present to the gold-standard systems.

1. Introduction

Optical computed tomography (optical-CT) is a method for reconstructing linear attenuation coefficients of visible light, the visible light analogue of X-ray CT [1]. Optical-CT is used in the imaging of 3D dose distributions [2] given by radiotherapy treatment machines to radiochromic plastic dosimeters such as PRESAGE (Hueris Pharma, Skillman, NJ). In order to image and reconstruct distributions using optical-CT, planar projections must be made of incident visible light attenuation in a sample both before and after irradiation.

One of the distinct challenges in optical-CT is the method for directing incident light through a sample and into a detector or CCD array in a straight path with minimal deviation due to refraction at the air/dosimeter interfaces. Telecentric lenses may be used to achieve parallel-beam geometry for the incident light, while immersing the dosimeter in a fluid of similar refractive index minimizes refraction.



For this work, two questions were addressed: (1) Can the bulky, expensive, telecentric lenses be replaced by a more manageable Fresnel lens system? And (2) can the cumbersome refractive index-matching fluid be minimized utilizing a solid tank concept [3, 4]? This work introduces the Duke Fresnel dry Optical-CT System (DFOS) system that attempts to address both these questions.

2. Methods and Materials

2.1. *Modification of traditional Optical-CT systems*

The setup and operation of the DLOS optical-CT system (Duke Large Optical-CT Scanner) has been well documented [5, 6]. Here we present a new derivative system called DFOS (Duke Fresnel Optical-CT Scanner). This system has two major differences. First, the convex telecentric lenses are replaced with Fresnel lenses (Light Works, Toledo, OH), resulting in a cost savings of over 90% (~thousands of dollars to hundreds), and a lens weight reduction from ~7kg to 500g. Fresnel lenses have inherent non-uniformity due to the Fresnel grooves, and a moiré effect is noticeable when imaging with a pair of lenses in a telecentric setup. Our rationale was that it may be possible to correct for Fresnel imperfections through the pre and post-irradiation scan information [6]. The second key modification is the replacement of the fluid bath with a solid tank bath which enables a reduction of >90% of the amount of refractive matching fluid. Refractive index matching fluid is used in optical-CT to allow incident light to pass through the dosimeter in a parallel path without refraction at the interface between two media. For the DFOS system, the glass aquarium was replaced with a 17x17x17cm³ polyurethane cube with a cylindrical bore of diameter 11.5cm and height, allowing for placement of an 11cm diameter x 10cm dosimeter. The 2.5mm air gap surrounding the dosimeter requires just ~90 cm³ of fluid of match the refractive index between the polyurethane tank (RI = 1.5) to PRESAGE dosimeters (RI = 1.47-1.51), compared to ~13500 cm³ of fluid for the DLOS system.

For all DFOS image acquisitions shown here, an incident light image or “flood” field was purposefully omitted. This assumes that the LED output, and therefore incident light, remains constant between pre- and post-irradiation scans. In the absence of a dosimeter, the “dry” polyurethane tank essentially becomes an air-gap, refracting all incident light out of the CCD field-of-view and making flood field acquisition impossible. Further investigation into the LED consistency and the validity of flood field omission is required.

2.2. *PRESAGE dosimeters and Treatment Plans*

To evaluate the DFOS system, a rectangular parallel-opposed treatment was delivered to a cylindrical PRESAGE radiochromic dosimeter (diameter 11cm). The dose distribution was then imaged in the gold standard DLOS, DMOS and prototype DFOS systems immediately sequentially, at 24h post irradiation. Prior in-house work indicated that the optimal dose-readout time for the DEA PRESAGE formulation to be 3-24 hours post-irradiation – this formulation has been found to be stable within 2% over this time period. To generate the treatment plan, CT scans were taken of the dosimeter and imported to the Eclipse Treatment Planning Software (Varian Medical Systems, Palo Alto, CA) for dose prediction. The treatment consisted of two orthogonal sets of parallel-opposed 4cm x 10cm beams, delivered to a cylindrical 11cm diameter x 10cm PRESAGE dosimeter. Dose was configured in order to have 3 distinct dose regions by delivering 200 monitor units each for the right/left lateral and left/right lateral beams (low dose) and 300 monitor units each for the anterior/posterior and posterior/anterior beams (medium dose), leaving a high dose cube in the center of the distribution. Projection images were taken over 360-degrees at 1-degree increments with the Fresnel-lens system (DFOS) as well as two conventional systems (DLOS and DMOS) both before and after irradiation and reconstructed at 2mm resolution with a custom MATLAB GUI (figure 1). For this preliminary study, relative dose was converted to absolute dose by making a point measurement in the Eclipse predicted dose distribution and scaling the DFOS reconstructed dose accordingly. This step was justified as PRESAGE has been shown to exhibit a strong linear optical density change with absorbed dose [7, 8].

DFOS reconstructed dose was compared against Eclipse dose prediction by calculating the gamma index with 3%/3mm criteria.

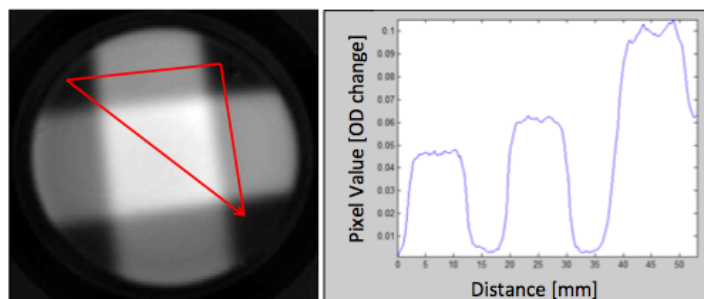


Figure 1. Axial slice from 3D reconstruction of optical density change in treated dosimeter with 2mm resolution (left), with line profiles through the 3 dose regions (right). The dosimeter is 11cm in diameter, and the radiation fields are 4x10cm.

3. Results

The 3D gamma pass rates for the DFOS, DLOS, and DMOS systems, when evaluated against the known Eclipse distribution, were 92.2%, 95.6%, and 96.8%, respectively (figure 2). The DLOS and DMOS distributions were highly consistent (99.0% gamma passing rate when compared to each other). This result is an important demonstration of the reproducibility and reliability of our gold-standard scanning systems. Figure 3 shows comparative line profiles through the dose distributions of each system. The DFOS distribution was observed to be significantly noisier, and contain substantial artifacts that were not fully removed by the pre and post-irradiation correction. A surprise observation was a rounding of the penumbral dose gradients that was observed in all three systems (figure 3). This effect has not been seen at this magnitude in scans of other Presage dosimeters, and may be specific to this experimental formulation. The cause is unknown at this point, and is under investigation. Similarly both DLOS and DMOS distributions showed elevated dose regions at very low dose levels, as seen in the tails of the profiles in figure 3. This effect has also not been seen in other dosimeters, and is possibly another feature of this formulation.

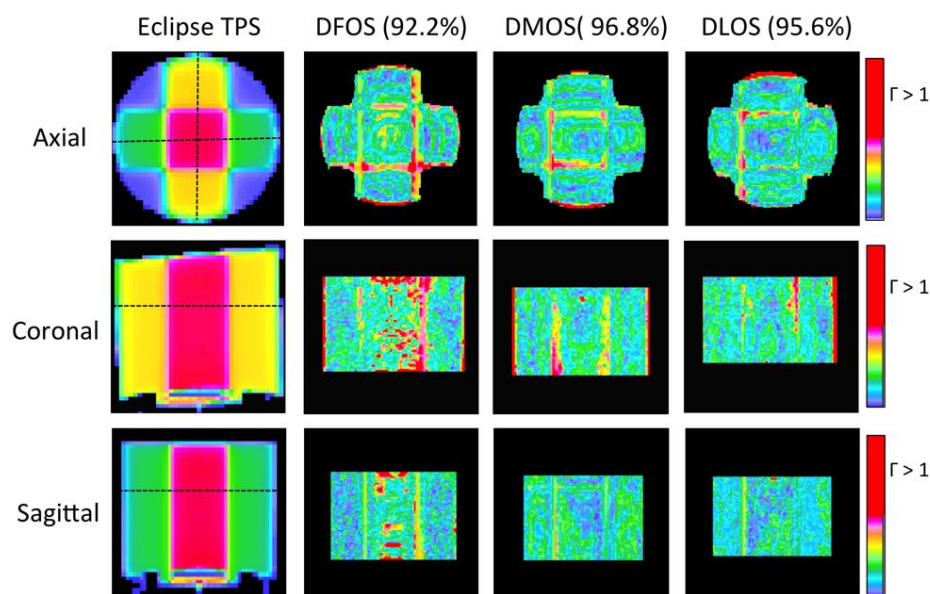


Figure 2. Orthogonal views through 3%/3mm gamma maps evaluated between measured and calculated dose distributions of the same dosimeter scanned by different scanners: DFOS (column 2), DMOS (column 3), and DLOS (right). 3D passing rates are given atop the columns. The eclipse dose is show in 1st column.

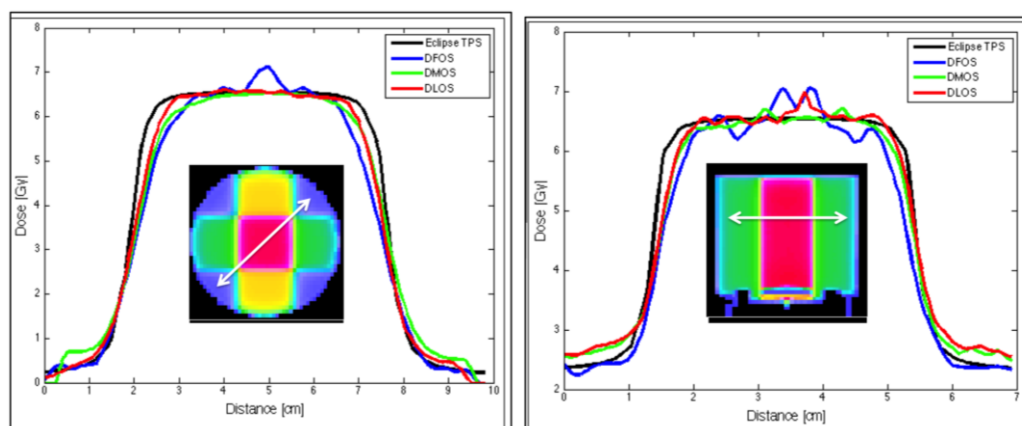


Figure 3. Dose line profiles comparing Eclipse (black), DFOS (blue), DMOS (green), DLOS (red) through the dose distribution of figure 1 and 2.

4. Conclusion

The DFOS scanner incorporates two major design changes from our prior scanners: low-cost Fresnel lenses, and a fluid saving solid tank. Both have dramatic implications for the cost and efficiency of optical-CT 3D dosimetry, provided no significant loss of accuracy is incurred. The Fresnel lenses introduced substantial ring and other flood field artifacts when compared to the DLOS systems. Some correction was possible using pre and post-irradiation correction strategies, but extremely robust apparatus is required to avoid any change in alignment between the two. The huge reduction (>90%) in the amount of required RI fluid associated with the solid-tank, makes fluid matching and general scanning much easier. It may also (in some cases) reduce noise in the floods.

Overall, first attempts for imaging 3D dose distribution with an optical-CT system with minimal fluid and Fresnel lenses is reasonably promising. A 92.6% gamma pass rate was achieved with a simple 4 field irradiation. This value was notably lower than either DLOS or DMOS (both >95%). The reduced agreement is attributed to increased noise of the DFOS and also the presence of other artifacts (e.g. more significant penumbral rounding). Further investigation is warranted to see how close DFOS can approach to DLOS and DMOS.

5. References

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