A prototype optical-CT system for PRESAGE 3D dosimeter readout

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Abstract. This work introduces the Duke Integrated-lens Optical Scanner (DIOS), a prototype optical-CT system designed for convenient and low-cost readout of PRESAGE 3D dosimeters. A key novelty of the DIOS is the incorporation of a multi-purpose light-collimating tank (the LC-tank). The LC-tank collimates light from a point source, maintains parallel ray geometry through a dosimeter mounted inside the tank, and refocuses emergent light onto a CCD detector. A second purpose is to dramatically reduce the amount of refractive matched fluid required in prior optical-CT scanners. This is achieved by substituting large quantities of refractive-matched fluid with solid RI-matched polyurethane. The advantages of DIOS include eliminating the need for expensive telecentric lenses, and eliminating the impracticality of large volumes of RI matched fluid. The DIOS is potentially more susceptible to stray-light artifacts. Preliminary phantom testing shows promising agreement between PRESAGE/DIOS readout and prior commissioned optical-CT scanners, as well as with Eclipse dose calculations.

1. Introduction
Prior works have demonstrated state-of-the-art 3D dosimetry [1] can be achieved with PRESAGE radiochromic plastic dosimeters and optical-CT readout [2-6]. The high transparency of Presage (low stray and scattered light contamination) enables compatibility with very fast broad-beam scanning approaches [7-9]. Given the high accuracy requirements for quantitative dosimetry, current broad beam scanners in our lab utilize expensive stray-light reducing telecentric lenses and substantial volumes of refractive matching fluid in order to attain best accuracy and results [10]. In an effort to develop a simpler, more practical, and less expensive optical-CT readout system, compatible with non-specialised clinics, we developed the Duke Integrated-lens Optical Scanner (DIOS). The DIOS is an economical alternative to our current systems (Duke Large-FOV Optical Scanner, DLOS). Here we present an evaluation of a prototype DIOS system.

2. Methods
The DIOS design consists of a filtered 3W red LED (633nm ± 10) incident on a solid light-collimating (LC) tank of refractive-index (RI) matched polyurethane, and a 12-bit monochromatic CCD camera (Figure 1). At a specific radius of curvature, the scanning tank is able to collimate the diverging LED light field into parallel-CT geometry as it transmits through a dosimeter sample. Any light that has not been absorbed or scattered within the system is re-converged onto the CCD for data acquisition. This system allows instantaneous acquisition of a large field-of-view optical projections through a sample. A dosimeter can be mounted onto a computer-controlled rotation stage to allow projections at varying angles, enabling tomographic imaging of measured optical density information. The addition of a
diffusing film increases the uniformity of the incident light field, and a focusing lens with an aperture on the CCD is included to reject scattered light and reduce edge blurring.

Figure 1. Basic DIOS schematic.

DIOS operation is functionally equivalent to the Duke systems (e.g. DLOS). However, unlike prior scanners, the DIOS design is able to omit costly telecentric lenses and large volumes of RI fluid (>10 L) by relying on the new RI-matched light-collimating polyurethane tank. A small amount of RI fluid is still required to limit heavy light scatter at interfaces, but this is typically less than 100 mL.

2.1. Light-collimating tank prototyping

To determine the optimal system parameters to attain parallel-ray CT geometry within the LC-tank, a Monte Carlo study was performed in ScanSim, an in-house optical-CT ray tracing software [11]. A diverging light source was modeled by a series of light rays originating from a single point, and their paths were tracked as each ray travels through different media at varying RI. Simulations show that a 25cm radius of curvature achieves sufficiently parallel-ray geometry for a typical 1kg PRESAGE dosimeter (10cm diameter, 10cm height cylinder), with focal distances at approximately 50cm.

Using ScanSim parameters, a positive mould of the LC-tank was modeled in AutoCAD (Autodesk, Inc., San Rafael, CA, USA) and 3D printed on a nominal fused-deposition modeling 3D printer. The light-incident surfaces were capped with a thin layer of stainless steel to minimize the impact of striation artifacts from 3D printing on scan quality. The finished positive mould was used to create a rubber negative mould and cast in transparent polyurethane (Figure 2).

Figure 2. Finished positive mould (left) and cast polyurethane LC-tank (right).

2.2. Benchmarking

A series of custom optical phantoms were produced to assess the imaging capabilities of the DIOS system. The modulation transfer function and resolution were measured by acquiring optical projection images featuring an attenuating edge phantom. A 3D ‘spiral’ phantom (1kg polyurethane cylinder, with 5mm channels drilled at varying radial distances) was used to verify geometric accuracy in tomographic reconstruction via comparison between DIOS optical-CT and conventional x-ray CT.

A 3D dosimetry study was performed to assess the DIOS’s ability to accurately measure optical density. A 4-field box plan was chosen as a benchmarking test, to deliver regions of highly-uniform dose as well as sharp dose gradients. The treatment plan was created in Eclipse (Varian Medical Systems, Palo Alto, CA, USA).
Systems, Palo Alto, CA) to deliver a maximum dose of 1 Gy onto a 1kg PRESAGE dosimeter. The dosimeter was irradiated using a Varian 600CD linac at 6MV, and OD was immediately read out using the DIOS. Accuracy was assessed using comparison between DIOS and the Eclipse treatment simulation, as well as readout from a separate commissioned optical-CT system (DLOS).

3. Results

MTF measurement shows the approximate cut-off frequency in the DIOS to be 4.5 mm\(^{-1}\), implying maximum image resolutions of 0.22 mm can be achieved. Tomographic reconstruction of the spiral phantom shows great spatial agreement between optical-CT and x-ray CT (both reconstructed at 1mm isotropic voxel resolution).

Dose comparison between Eclipse, DIOS, and the standard DLOS optical-CT system can be seen in figure 4. DIOS dose measurement shows good agreement between Eclipse and DLOS doses, only suffering from minor concentric ring artifacts and some speckling from slight movement of the diffuser. 3D gamma comparison between DIOS readout and Eclipse calculation shows 95.6% of voxels passing 3%/3mm criteria (Figure 5).
4. Conclusions
The first prototype of the DIOS has demonstrated promising performance as an economical and practical optical-CT system for 3D dosimetry. By incorporating a solid LC-tank of RI-matched polyurethane, the DIOS is able to remove the need for costly and difficult components from prior systems, such as telecentric lenses and large volumes of refractive matching fluids. This system aims to enable comprehensive 3D dosimetry techniques more accessible to general clinical use. However, omission of telecentric lenses has the potential to introduce unwanted scattered light in data acquisition, resulting in possible feature blurring and overall reduction in spatial resolution. Future work will aim to commission the DIOS through more stringent dosimetry tests, and further prototypes will incorporate larger fields of view and more robust mechanisms of scatter rejection.

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