

Preliminary characterization of the Duke Integrated-Lens Optical-CT scanner (DIOS)

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Abstract. The present study investigates a cost effective and practical non-telecentric optical-CT scanner developed for 3D dosimetry, the Duke Integrated-Lens Optical-CT scanner (DIOS). The DIOS system includes an upgraded light-collimating tank (the LC-tank) made of solid polyurethane with precision curved ends (with lensing functionality) and a precision cylindrical central hollow for the dosimeter. The LC-tank thus collimates light from a small area light source (~2cm diameter) into parallel rays through the dosimeter, with refocusing of emergent light onto a CCD camera with a focusing lens with an aperture. The solid nature of the LC-Tank dramatically reduces the amount of required refractive matching fluid compared to earlier scanning systems. The aim of this work was to perform preliminary characterization studies of DIOS in comparison to earlier systems, particularly telecentric systems. The preliminary results indicate promising performance for the DIOS approach.

1. Introduction

In recent years there has been a push to develop commercial optical-CT readout 3D dosimetry systems for BANG gels, polymer gels, radiochromic gels, and radiochromic plastics [1-7]. A standard optical-CT scanner model, the Duke Large-FOV Optical Scanner (DLOS), achieved high-accuracy, high-resolution 3D dosimetry using large telecentric lenses and a large refractive matching fluid tank [7-9]. While high in image quality, this model was (1) prone to mess and hassle due to the excessive amount of refractive matching fluid needed to immerse the dosimeter, and (2) presented a significant expense exceeding \$20,000 per scanner. The Duke Integrated-Lens Optical Scanner (DIOS) is a significantly cost-effective (<\$2,000) and mass-producible model that seeks to match DLOS image quality standards, using a curved light-collimating tank (LC-tank). Previous works have introduced a prototype for the DIOS system [10], presenting preliminary construction and testing of the dry tank and scanner setup. The DIOS system design is illustrated in Fig. 1, which includes a 3W red LED ($633\text{nm} \pm 10$), a solid polyurethane light collimating tank on a rotating stage, a Presage 3D dosimeter, and a 12-bit monochromatic CCD camera. A focusing lens with an aperture on the camera is included to help to reject scattered light and reduce depth-of-field blurring. The tank and Presage are both made from clear polyurethane, so that if a thin layer of RI-matched fluid is present, light passes through the tank unimpeded. The rotating stage allows a full 360° rotation so that projections can be collected at various angles for 3D reconstruction. The current work has improved the manufacturing and performance of the original DIOS scanner, mitigating spatial resolution loss and image distortions that plagued the initial version. The most significant change from the original to the upgraded system is the light source, where a small, uniform opal diffuser replaced the film diffuser. The second change is the streamlined fabrication of the spherical surfaces of the LC-tank using spherical Teflon molds of precisely known

radius of curvature. The source is placed at the focal point calculated from the radius of curvature of the spherical LC-tank surface so that the tank is able to collimate the diverging LED light field into the desired parallel-CT geometry as it transmits through the Presage dosimeter. We present a comparison of the new DIOS to DLOS and demonstrate that the upgraded LC-tank has an improved flood field and improved modulation transfer function (MTF). We also discuss a method to compensate for image deformation stemming from LC-tank imperfections using grids. Preliminary findings indicate that the upgraded DIOS system has resolution and image quality sufficient for clinical implementation, while making improvements in cost and practicality compared to DLOS.

2. Methods

Evaluations focused on characterizing the improved MTF, the spatial consistency of the point-spread function, the accuracy of geometrical reconstruction, and the stray-light effects of this upgraded system.

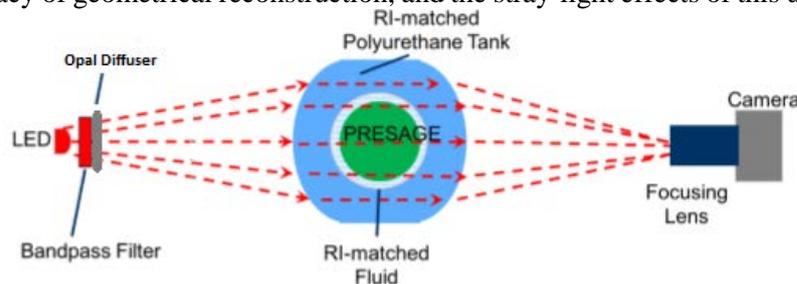


Figure 1: Upgraded DIOS system schematic. Novel features include the more precise tank and the large-area source with opal diffuser.

2.1 Upgraded LC-Tank

A new light collimating (LC) tank has been developed with significantly less distortion and high throughput via improved manufacturing procedures, involving two spherical cap Teflon molds that “sandwich” the LC-tank from both sides. Previous methods required destruction of the mold after casting the LC-tank to extract the tank from the mold. The current method allows the Teflon molds to be separated from the LC-tank easily and reused for another tank. In addition, the process to mount the tank onto the rotating stage has been significantly simplified, requiring only drilling a single hole and pouring in slow-curing adhesives to attach the tank to the rotating stage.

2.2 Light Field and Flood Field Uniformity

In addition to the new tank, a small and uniform area light source, created using an LED source and an opal diffuser, replaced the large and heterogeneous diffuser used in the previous DIOS system. This allowed for a more uniform flood field and improved the MTF. To test uniformity of the upgraded tank compared to the previous version, a flood field image was collected. A blank dosimeter was placed in the tank on the center rotating stage. Refractive matching fluid was pipetted into the tank to fill the air gap surrounding the blank dosimeter so that the field appeared uniform. A single image was taken of the field to produce a flood field image. Coefficient of variation (COV) was determined from this flood image by taking a small central area from old and new DIOS flood images and then dividing the pixel-by-pixel standard deviation by mean flood value (adjusted for dark background from thermal noise).

2.3 Edge and Pin-hole Image Resolution

An optical edge and pin-hole were used to evaluate the resolution of the system. A thick piece of black aluminum foil with a straight edge was placed at the center of the tank, immersed in refractive index fluid. The foil covered half of the light field. An image of the edge was used to calculate the MTF using the built in ImageJ MTF calculator. Resolution of the system was estimated from the MTF using the 10% threshold.

A pin-hole was created using an iris immersed in refractive index fluid. This pin-hole was moved to various points around the tank for acquisition. The acquired pin-hole images were used to test the spatial

invariance of the point spread function (PSF) of the system. Line profiles were collected through the center of each pinhole and the PSFs were compared.

2.4 Tank Distortion

The extent of tank deformation was estimated from a 3D-printed grid with 3.5 mm wide holes and 2.35 mm wide gridlines immersed within the LC-tank. This grid was placed 3.5 cm from the center of the tank towards the camera, the closest location to the camera within the tank. This was the 0 degree rotation stage position. A single image taken at this point was compared with an image taken at 3.5cm from the center of the tank *away* from the camera, the 180 degree rotation stage position. The two images were registered and compared. Two horizontal line profiles taken through the same grid position on each of the two images were compared as were two vertical line profiles. The profiles were analyzed to determine whether there was any position dependent distortion.

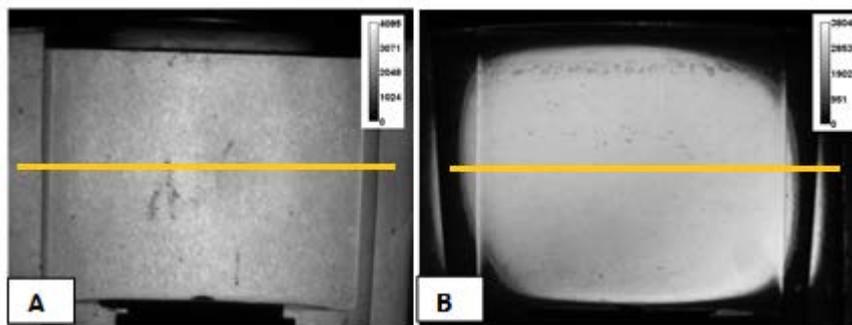
2.5 Stray Light Comparison with DLOS System

Light may reach the camera via multiple scattering events, called the stray light effect. A thick piece of light-blocking metal was placed at the center of the tank on the rotation stage. A single projection image was acquired of the partially blocked field. An additional projection was acquired of a completely blocked field, with a sheet of metal blocking the entire camera lens. The photon counts of the blocked field and the partially blocked field were compared to determine the amount of stray light present in the system. The stray light analysis for DIOS was compared with the data collected for the same experiment with the DLOS system. The DLOS system version of the experiment used a slightly wider metal piece. The line profile of the intensity of the two images compared with the dark image was analyzed to characterize the stray light.

3. Results and Discussion

3.1 Light Field and Flood Field Uniformity

The purpose of the diffuser is to compensate for the deformation of the LC-tank causing the focal point of the lens to shift and to blur. A uniform area-source is thus preferred to compensate for this imperfection. The original DIOS flood used a coarse diffuser film and consequently suffered from a textured flood field causing a high coefficient of variation. The upgraded DIOS flood field has significantly improved uniformity in the central area owing to the uniform opal diffuser ($COV_{\text{FloodUpgraded}} = 0.0082$ compared to $COV_{\text{FloodOriginal}} = 0.151$). This is demonstrated in the consistent image field in figure 2. In the upgraded DIOS image in figure 2B, the two vertical light-colored lines in the image represent the edges of the dosimeter in the tank. Several imperfections remain such as the uneven field in the bottom left side of the image in 2B where the image field is dimmer and appears to curve in at the corner. Several small speckled imperfections remain on the lens face and a thin strip of bubbles where the polyurethane set imperfectly remains at the top of the lens. The image quality is a clear step up from the previous DIOS version that lacked a uniform diffuser.



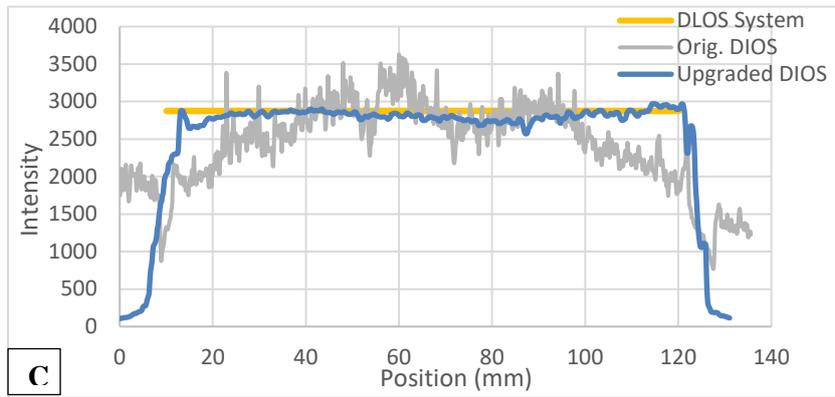


Figure 2: Flood field image comparison between the upgraded and the original DIOS systems and the DLOS system. (A) Flood field image from original DIOS system. (B) Flood field image from the upgraded DIOS system. (C) Center horizontal line profile comparison between the original DIOS, upgraded DIOS, and DLOS imaging systems.

3.2 Edge and Pin-hole Image Resolution

Figure 3 is a comparison between the MTF measured with the original DIOS scanner and the current paper's upgraded DIOS scanner. When the MTF is 0.1, the original scanner's cut-off frequency was 1.4 mm^{-1} , and able to resolve 0.71 mm . The upgraded DIOS system's cut-off is 3.7 mm^{-1} , and able to resolve 0.27 mm . This leads to significantly improved image resolution.

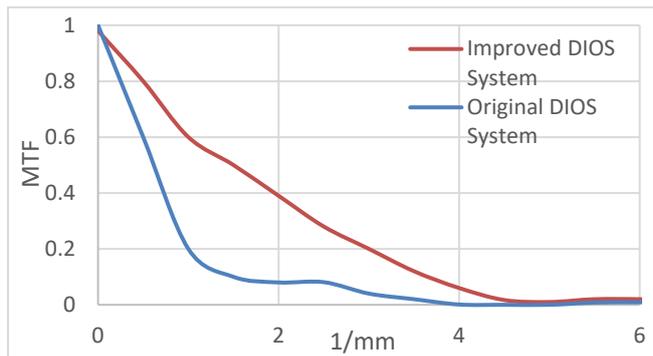


Figure 3: MTF comparison between the original DIOS system and the current upgraded DIOS system.

Additionally, through the collection and line profile analysis of a variety of pinhole measurements scattered throughout the tank, consistent profiles were found at various different locations in the field. This indicates that this system has the capability for deconvolution, which would allow for a full-field deconvolution correction for the PSF.

3.3 Tank Distortion

The images in figures 4 indicate that spatial deformation is minimal with respect to position on the tank. The image of the grid placed at $+3.5 \text{ cm}$ from the center of the LC-tank (rotation stage 0° position) does not deviate significantly when compared to image of the grid placed at -3.5 cm (rotation stage 180° position), meaning light is traveling relatively collimated within the $\pm 3.5 \text{ cm}$ with respect to the scanner center of rotation. However, qualitatively, we note there is a systemic barrel distortion causing a bulged appearance of the grids in figure 4A and B. This is likely due to the spherical surface of the lens where our flat-lens approximations fail. A deformation field correction could be applied to the images before reconstruction. Methods to correct deformation of the images will be explored in future works.

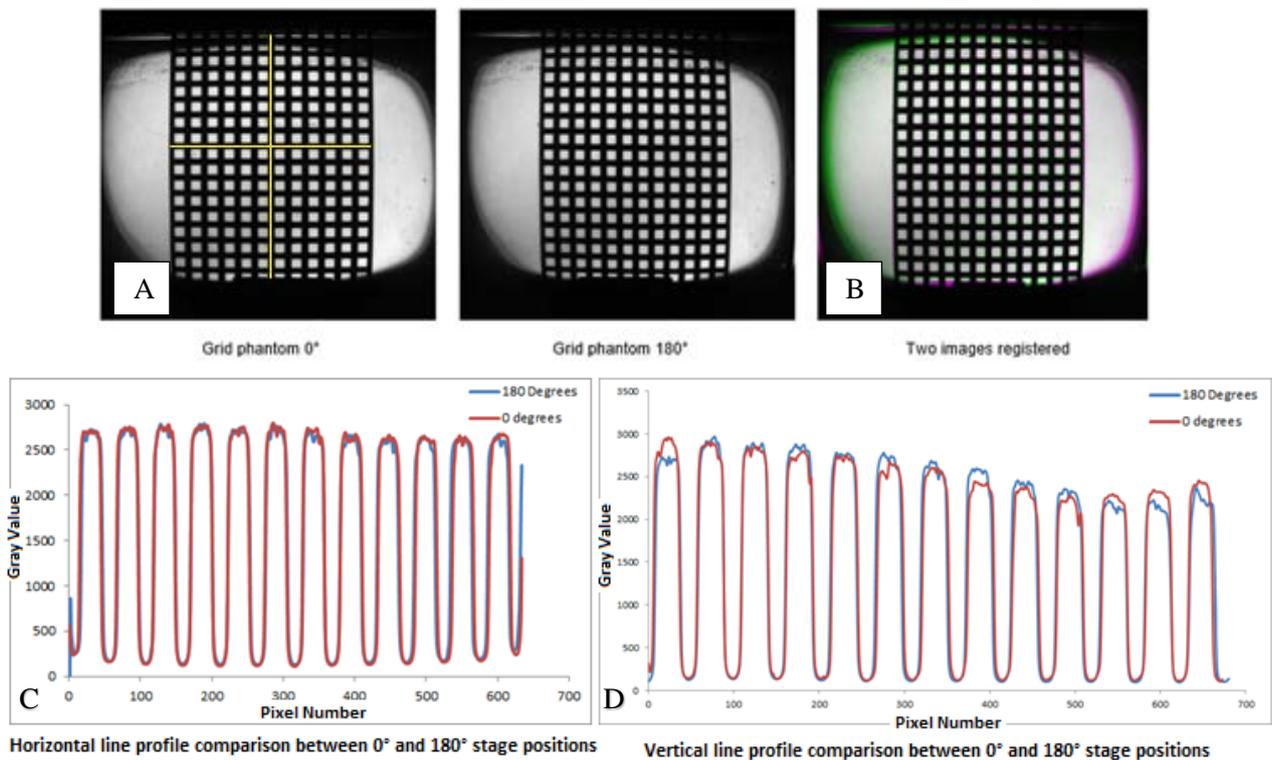


Figure 4: Depth of focus analysis using a grid phantom attached to the rotating stage. (A) Images taken with the grid phantom at the 0 degree rotating stage position and the 180 degree position. This test was to determine if there are any depth of focus distortions depending on location of the object in the tank. (B) The two images in A were registered for comparison. (C) Horizontal line profile depth of focus comparison, according to the yellow profile drawn in (A), between a grid phantom positioned at 0 degrees and a grid phantom positioned at 180 degrees in the tank. (D) Vertical line profile depth of focus comparison according to the vertical yellow profile drawn in (A).

3.4 Stray Light Comparison with DLOS System

The stray light analysis concluded that due to the telecentric lenses used in the DLOS system, the elimination of stray light is still superior in the DLOS system compared with the DIOS system. However, both systems reduced the stray light by at least 2 orders of magnitude. Deconvolution by a PSF for the DIOS system could eliminate the stray light [4].

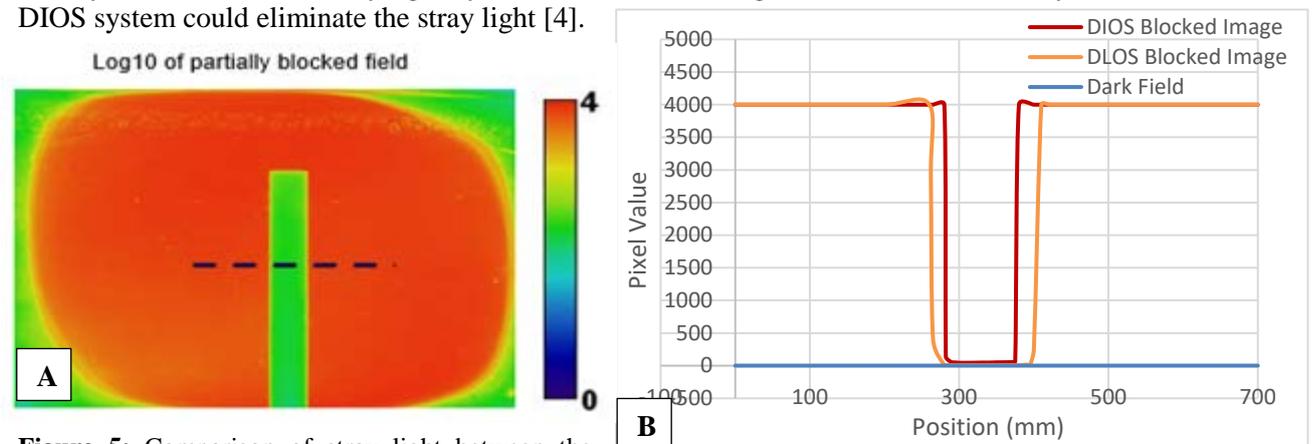


Figure 5: Comparison of stray light between the DLOS and DIOS systems. (A) DIOS flood projection image of an opaque light block placed in the center of the field of view. (B) Line profile, the black line shown in (A), through the DIOS system compared with the same experiment and line projection on the DLOS system and compared with a line profile through a dark field image.

4. Conclusions

The basic characterizations presented here demonstrate that the DIOS system establishes a parallel ray geometry with good geometric accuracy approaching that of a telecentric system (i.e. DLOS). A notable increase in stray-light under a light block was observed in the DIOS when compared to DLOS. This is to be expected as a result of the price paid for the lack of telecentricity. The exact implications of this increased scatter are unclear at this point, and will need further study in the context of 3D dosimetry verification measurements. However, the fact that the point spread function was observed to be largely spatially invariant may offer an approach to partially correct for any loss of accuracy through point-spread-deconvolution scatter correction.

5. Acknowledgement

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6. References

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