ScanSim: A tool for simulating optical-CT imaging

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Abstract. A software tool has been developed that can simulate image formation in a variety of optical-CT scanning configurations. The formalism of the simulation is introduced, including two main modes: a diverging point source mode, and a converging broad beam mode. Preliminary results are presented for scanning Presage dosimeters in both modes and immersed in refractive media of widely varying refractive index (RI), including air, water, and a fully matched medium. Pronounced differences in the edge artifacts and accuracy of reconstructed coefficients is observed. The ScanSim software is shown to be a useful tool to investigate and quantify many aspects of optical-CT image formation, including reducing dependence on matching fluids.

1. Introduction
The first optical-CT scanner for radiation dosimetry was proposed by Gore et al. [1]. This 1st generation scanning laser system has now been evaluated by several groups and found to be an accurate and reliable system with the facility to minimize artifacts from scattered and stray light [2-4]. More recently, other approaches to optical-CT scanning system have been proposed, including broad-beam scanning systems [5-9]. These systems have potential for very high spatial resolution and much faster scanning times (minutes), at the potential expense of higher susceptibility to scatter and stray light and associated artifacts. In general the scanning laser systems are used for dosimeters where the primary contrast mechanism is light scattering (e.g. polymer gels). Broad-beam systems have been explored in conditions of low-light-scatter, and dosimeters where the primary contrast mechanism is light-absorption (e.g. Presage, FBX gels). Despite the significant diversity in scanner design and approach, a common feature of all current systems is the requirement for the dosimeter to be immersed in a refractively matched fluid. This fluid minimizes the refraction of light incident on the curved surfaces of the dosimeter, and facilitates the measurement of line-integrals of attenuation which is critical input for reconstruction. Effective refractive matching between the dosimeter and fluid is known to be critical to reducing edge artifacts in optical-CT. Good matching also facilitates accurate dosimetry particularly in broad-beam scanning systems, which are more sensitive to this aspect. Despite the advantages to immersing the dosimeters in a refractively matched fluid-bath, this procedure is one of the most challenging, laborious and messy aspects of optical-CT scanning. The purpose of the present work was to create a software tool ‘ScanSim’ which could simulate the optical-CT imaging process under a wide variety of conditions both with and without a refractive matched fluid. The aim is to explore new scanning arrangements that might reduce or eliminate the need for refractively matched fluid (convenience and cost), and to reduce artefacts (improve accuracy).

2. Methods
Two basic modes of the software were implemented (figure 1a and b) corresponding to a converging or diverging incident beam respectively. The software parameters include the refractive indices of the dosimeter and surrounding fluid, the attenuation coefficients of medium and fluid, wavelength of incident light, the radius of the cylindrical dosimeter, the divergence or convergence of the incident beam, and the position of the dosimeter. In addition rays that deflect from the optical-axis by more than a given tolerance angle (degrees) are shown as dashed, enabling visualization of the scatter rejection of a telecentric system.

Figure 1a: Convergent broad-beam geometry. The ‘ScanSim’ software models the attenuation and refraction of light rays that originate at an extended source (located at x=0), and converge at the point X (large red X) in the absence of the dosimeter. The attenuation and refraction of the ray as it passes through the dosimeter (shown as the green cylinder outline) are modeled through to the imaging plane. A single example ray is shown in this figure.

Figure 1b: Divergent broad-beam geometry. The ‘ScanSim’ software models the attenuation and refraction of light rays that originate at a point source (located to the left of x=0), and diverge at an angle $\beta$. The attenuation and refraction of the ray as it passes through the dosimeter (shown as the green cylinder outline) are modeled through to the imaging plane (xend,yend). A single example ray is shown.
At present ScanSim can simulate optical-CT imaging of uniformly attenuating cylindrical non-scattering. Ray paths and associated intensity loss (caused by both attenuation within the dosimeter, and Fresnel transmission losses at interfaces) for a single projection are first simulated. Due to symmetry, all other projections corresponding to an optical-CT data set will be the same. A full acquisition data set for reconstruction is generated by re-sorting rays according to the angle of the trajectory through the dosimeter. Each ray is thus assigned to the projection in which it would be normal to the detecting plane, and thus a parallel ray reconstruction algorithm can be used to reconstruct the ensemble of generated projections. Simulations assume an ideal detector which assigns a detected pixel intensity to the corresponding line integral of attenuation. This can be achieved in the real world if the dimensions of the dosimeter are known, and the trajectory of ray-paths can be calculated a-priori, both of which are easily feasible for cylindrical dosimeters.

ScanSim simulations have been run to investigate the correlation between refraction matching, edge artefacts, and the accuracy of reconstructed attenuation coefficients. Also to investigate the potential for new in-air scanning configurations, and configurations which might use lower RI matched fluids.

3. Results and discussion

3.1 An illustrative ScanSim simulation.

In-air optical-CT imaging of a 50mm radius Presage cylinder (uniform attenuation 0.115/cm, and RI=1.501), using the divergent geometry mode (a point light source positioned 200mm away) is shown in figure 2. The user defined parameters of the simulation are shown in the left panel). The upper right figure shows ray-paths from the point source (x=0) through the Presage cylinder shown as black circle. Ray colors are artificial, and just facilitate discerning different ray-paths. The lower left panel shows both the accumulated transmitted power coefficients (green line) of each ray, and the total intensity of each ray (blue), compared to un-attenuated light. The lower middle 2 images show the sinogram data of the ensemble of generated projections, and the lower right image shows the final reconstructed image.
Figure 2: A ScanSim simulation in divergent mode (or point light source at x=0 upper right image). This figure illustrates the challenges of in-air scanning of Presage due to a strong lensing effect. A substantial edge artifact is observed (~20mm wide), and greatly depressed attenuation coefficients are reconstructed compared to the known input attenuation.

3.2. ScanSim investigation of the effect of variable RI matching.
A sequence of divergent beam simulations were run to investigate the correlation between refraction matching, edge artifacts, and the accuracy of reconstructed attenuation coefficients (figure 3). All parameters (except the RI of the surrounding fluid) were kept constant for all simulations, including: RI dosimeter=1.501, source-distance=400mm, ray-spacing=1mm, dosimeter-radius=50mm.

Figure 3: Results from 3 simulations. All parameters were constant except for the refractive-index of the surrounding medium, which was 1.0 (air), 1.3 (water), and 1.5 (Presage), in the upper, middle and lower rows respectively.

The simulations of figure 3 illustrate the significant effect of refractive matching on both the edge artifacts, and the accuracy of the reconstructed attenuation coefficient.
4. Conclusions

The ScanSim software is a useful tool for investigating many aspects of the mechanisms and artifacts of optical-CT imaging. Further studies are planned to explore and quantify the relationships between RI matching and edge and reconstruction artifacts, as well as to investigate new scanning configurations that may reduce the requirement for expensive and difficult-to-work with high RI fluids. Simulations assume an ideal detector which assigns a detected pixel intensity to the corresponding line integral of attenuation. This can be achieved in the real world if the dimensions of the dosimeter and ray-paths are known a-priori, as is the case with cylindrical dosimeters.

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References
[1] Gore, J. C., Ranade, M., Maryanski, M. J., and Schulz, R. J., "Radiation dose distributions in three dimensions from tomographic optical density scanning of polymer gels: I. Development of an optical scanner", Phys.Med.Biol., Vol. 41, pp 2695-2704, 1996.
[2] H.S. Sakhalkar, J. Adamovics, G. Ibbott and M. Oldham, “A comprehensive evaluation of the PRESAGE/optical-CT 3D dosimetry system”, Med. Phys. 36 (1), 2009.
[3] Islam KT, Dempsey JF, Ranade MK, Maryanski MJ, Low DA, Initial evaluation of commercial optical CT-based 3D gel dosimeter. Med Phys. 2003 Aug;30(8):2159-68.
[4] Xu Y, Wuu CS, Maryanski MJ., Performance of a commercial optical CT scanner and polymer gel dosimeters for 3-D dose verification. Med Phys. 2004 Nov;31(11):3024-33
[5] Baldock C, De Deene Y, Doran S, Ibbott G, Jirasek A, Lepage M, McAuley KB, Oldham M, Schreiner LJ. Polymer gel dosimetry. Phys Med Biol. 2010 Mar 7;55(5):R1-63. Epub 2010 Feb 11. Review.
[6] Oldham M, 3D dosimetry by optical-CT scanning., J Phys. 2006;56:58-71
[7] Doran SJ, Koerkamp KK, Bero MA, Jenneson P, Morton EJ, Gilboy WB. A CCD-based optical CT scanner for high-resolution 3D imaging of radiation dose distributions: equipment specifications, optical simulations and preliminary results., Phys Med Biol. 2001 Dec;46(12):3191-213.
[8] Olding T, Holmes O, Schreiner LJ., Cone beam optical computed tomography for gel dosimetry I: scanner characterization., Phys Med Biol. 2010 May 21;55(10):2819-40
[9] Clift C, Thomas A, Adamovics J, Chang Z, Das I, Oldham M. Toward acquiring comprehensive radiosurgery field commissioning data using the PRESAGE/optical-CT 3D dosimetry system., Phys Med Biol. 2010 Mar 7;55(5):1279-93