Initial characterization of fast laser scanning optical CT apparatus for 3-D dosimetry

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Abstract. Laser scanning optical computed tomography (optical CT) is potentially a better technique for analyzing 3-D dosimeters than CCD based dosimetry due to the fact that narrow cone of light passing through the sample is not affected by the refractive index inhomogeneities of surrounding structures. We have previously demonstrated fast laser scanning of 3-D dosimeters using an optical arrangement borrowed from confocal microscopy. The main rationale for this design is that it guarantees good telecentricity at high scanning speeds. Here we demonstrate a number of advantages of this arrangement as compared to broadbeam optical CT based around CCD detectors. Additionally, we provide initial characterization of the apparatus in terms of signal-to-noise and dynamic range.

1. Introduction
Optical computed tomography (optical CT) is potentially the cheapest avenue for measuring dose distributions in 3-D [1-5]. Alternatives include Magnetic Resonance Imaging (MRI) [6], X ray CT and ultrasound [7]. All modalities have been discussed in detail in review articles in previous DOSGEL conferences [8-10]. We present here an initial effort in characterizing the fast laser scanning optical CT apparatus first described in [11].

2. Methods
The fast laser scanning setup is shown in Figure 1 (reproduced from [11]). Figure 1(a) shows the diagram of the setup while Figure 1(b) shows the relay optics consisting of two galvanometer mirrors and two paraboloidal mirrors. The arrangement ensures fast raster scanning from a stationary pivot point on the galvo mirror 2. The high quality test target (HQT T) (Edmund Optics, Barrington, NJ, US, part NT54-803) is used to calculate the modulation transfer function (MTF). MTF is calculated from a line profile of the transmission image of the HQT T in air.

A signal-to-noise ratio study was performed applying the same methodology as in [12]. The only difference is that here, the scans done were performed over 400 views rather than 1000 views. The voxel size in the reconstruction domain was set to 1 mm and 0.5 mm. Note that MTF was measured from distortion-corrected projections, while the uniformity study used raw images. Comparisons are
made for MTF versus voxel size and SNR versus voxel size. Linearity in absorbance measurements and projection signal-to-noise ratio (SNR) were shown previously [11].

Lastly, we present a scan of a PRESAGE™ (Heuris Pharma, NJ, USA) sample irradiated with a proton beam. The sample was irradiated four times, using an unmodulated beam, collimated to a 12mm diameter circular cross-section. The beam was applied for different durations (of the order of tens of seconds), such that estimated doses of 1, 2, 16 and 20 Gy were applied at the Bragg peak.

3. Results
Figures 2(a) and 2(b) show modulation transfer functions for the system in two experiments. Figure 2(a) compares the MTF for a 512 × 512 image with the HQTT at or near the focal plane of L₁ (i) with the same configuration but with the HQTT further from or nearer to L₁; and (ii) with the CCD-based scanner operating at a similar field-of-view and nominal pixel resolution. The MTF for the laser-based apparatus is better than the corresponding broadbeam apparatus up to 2 lp/mm. After that, the MTF drops sharply to zero. This is a clear indication of the finite size of the laser focal spot, which blurs out any spatial frequencies above a certain threshold. It might have been expected that (for the planar HQTT, at least) the nominal laser spot size should not have been a limitation, since in the focal plane of L₁, the beam diameter should be extremely small. Although this needs further investigation, a possible reason is that the HQTT was not placed exactly in the focal plane. The numerical apertures (NA) and pixelation of both systems are similar and therefore both should be capable of similar spatial resolution. Figure 2(b) shows the expected sharp decline in MTF for reduced image resolution (i.e. increased voxel size). It should be stressed that one has the possibility of using a laser beam with smaller diameter [17] should this prove necessary.

The uniformity study results are shown in Figures 2(c) and 2(d). In Figure 2(c) the reconstruction SNR for 1mm voxel is better than 90:1 from absorbance range 0.2 to 1.6. Note that for most of the absorbance range (0.5 to 1.6) it is better than 200:1. Therefore the instrument provides a unique
potential for speed, high quality readout and good dose resolution. Figure 2(d) shows a fall in SNR with reduced voxel size. However, SNR for 0.5mm voxel in laser scanning arrangement is similar to 1mm voxel in broad beam arrangement.

The scan of PRESAGE sample is shown in Figure 3. To illustrate the reconstruction process we show the projection as read by photodiodes (Figures 3(a) and 3(b)), the absorbance of that projection which is obtained after calibration using the HQTT [12] (Figures 3(c) and 3(d)) and finally, the reconstruction slice (Figures 3(e) and 3(f)). Notice the high SNR of all the profiles. The profile across the slice (Figure 3(f)) shows that the irradiated circles are not uniform. We are currently investigating whether this is a scanner artifact or whether the dose deposited really had this form.

4. Discussion
Fast laser scanning is an established field [13, 14] and most of the innovations presented here have been borrowed from a confocal microscopy scanning arrangement [15]. The acquisition speed relies on fast galvanometer driven mirrors and appropriate photoreceivers. This has not been exploited to the full in optical CT. For example, the fastest galvanometer mirrors (driven at mechanical resonance, so called resonant galvanometer) can perform up to 10kHz line scanning, which is equivalent to video rate imaging. This suggests that the potential for development of the scanner is great.
Figure 3 - (a) and (b) Projection (transmission values from photodiode readings) and line profile across it, (c) and (d) absorbance projection and line profile across it, (e) and (f) reconstruction slice and line profile across it.
It has been shown that the positioning of the sample plays an important role in determining the MTF of the laser system. The results with the HQTT placed away from the focal plane of L1 are worse than the one done in focus. However, again, one can exploit existing advances in extended depth-of-field techniques which are directly applicable to our arrangement [16].

5. Conclusion
Exhaustive characterization has yet to be done and we present an initial insight into performance of fast laser scanning apparatus. The results are very promising, but need further verification and comparison with other dosimetry techniques such as radiochromic film and ionization chambers.

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