Feasibility of a dual wavelength laser optical CT scanner with in-air gel readout

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Abstract. Net optical attenuation in optical CT scanning is usually determined by pre and post-irradiation scans. Replacement of the pre-irradiation scan by a scan of different wavelength, acquired concurrently with the post irradiation scan is proposed. This would result in greater practicality of gel dosimetry and potentially improved image quality. This study indicates that the approach may be viable, however experimental investigation is required for analysis of the prospective benefits of removing inter-scan variations.

1. Introduction
Contemporary optical CT scanners typically require the use of refractive index matching fluid and pre-irradiation scans [1-3][1-4]. Removing both of these requirements simplifies the scanning process and may help make optical CT scanning a more attractive option for dosimetry in the radiotherapy clinic. In this work, the viability of a dual wavelength scanner is investigated for the case of a previously developed fluid-less optical CT at the Royal Adelaide Hospital (RAH) [4][5]. A laser beam of different wavelength scanned sequentially to the measurement laser could provide more relevant reference data than pre-irradiation scanning as dust, fingerprints and other scattering particles are sampled at the time of readout.

2. Dual wavelength concepts and methods
Differential absorption measurements require two wavelengths, \(\lambda_1\) and \(\lambda_2\) giving significantly different responses to dose. As refractive index is wavelength dependant, the difference in \(\lambda_1\) and \(\lambda_2\) is minimized to mitigate the effects of refractive index change. Therefore the gel dose response absorption spectrum was searched for a steep gradient where \(\lambda_1\) gives near maximum response to dose, while \(\lambda_2\) gives a substantially reduced response. Ferrous, xylene orange gel (FXG) is scanned with the existing RAH scanner using a He-Ne 594 nm laser, providing a suitable \(\lambda_1\). At increased wavelengths the dose response decreases. For example, at 633 nm the response is approx. 1/3 of that at 594 nm, and drops further to 1/6 at 650 nm. A \(\lambda_2\) of 633 nm (He-Ne laser) is considered in this work however laser diodes can provide other wavelength options.

The second laser is directed at the rotating mirror as shown in figure 1, resulting in a \(\lambda_1\) scan across the cylinder followed by \(\lambda_2\). The measured net transmission for each data point of a projection as a
function of dose, \( D \) and mirror angle, \( \theta \) (refer figure 1), is:

\[
T_{(\lambda_1, \lambda_2)} (\theta, D) = \frac{R_1 (\theta, D_1)}{R_2 (\theta, D_2)} \times \frac{R_{1\text{ref}}}{R_{2\text{ref}}} \times \frac{R_{2\text{air}}}{R_{1\text{air}}}
\]  

(1)

where subscripts 1 and 2 correspond to \( \lambda_1 \) and \( \lambda_2 \). \( R \) and \( R_{\text{ref}} \) are the measurement and reference photodiode readings, and \( R_{\text{air}} \) is the measurement photodiode reading with the gel cylinder removed from the beam path. The measured net transmission is converted to attenuation and processed as usual, with conversion to dose via gel cuvette calibration samples, scanned by the optical CT.

Conceptually the net transmission comprises a number of elements that may be significant for this scanner configuration:

\[
T_{(\lambda_1, \lambda_2)} (\theta, D) = \frac{T_{1\text{gel}} (\theta, D_1)}{T_{2\text{gel}} (\theta, D_2)} \times \frac{T_{1\text{eff}} (\theta) \times T_{1\text{contam}} (\theta) \times T_{1\text{defect}} (\theta) \times T_{1\text{int}} (\theta)}{T_{2\text{eff}} (\theta) \times T_{2\text{contam}} (\theta) \times T_{2\text{defect}} (\theta) \times T_{2\text{int}} (\theta)}
\]  

(2)

where there is a dosimetric component, \( T_{\text{gel}} \) for attenuation by the gel sample, and non-dosimetric components, \( T_{\text{eff}} \) for losses due to reflection at material interfaces, \( T_{\text{contam}} \) for losses due to contaminant particles in the gel or on the cylinder surfaces, \( T_{\text{defect}} \) for losses due to defects of gel cylinder, \( T_{\text{int}} \) for losses/gains due to optical interference. Since the intention is that the non-dosimetric terms will cancel, they need to be examined as a function of wavelength.

Change in refractive indices due to wavelength gives altered ray paths, which may affect all components of equation (2). \( T_{\text{gel}} \) changes if rays traverse gel differently. \( T_{\text{eff}} \) depends on ray angle and refractive indices. \( T_{\text{contam}} \) and \( T_{\text{defect}} \) change if rays do not intersect the particles or defects in the same way. \( T_{\text{int}} \) is affected by ray path change and wavelength. Because of these issues, the intent is to minimize change in ray paths rather than apply corrections. Ray paths and reflection losses were calculated using methods similar to previous [4][5], for \( \lambda_1 = 594 \text{ nm} \) and \( \lambda_2 = 633 \text{ nm} \). Refractive indices used in calculations were \( n_{1\text{gel}} = 1.342, n_{2\text{gel}} = 1.340, n_{1\text{PMMA}} = 1.491 \) and \( n_{2\text{PMMA}} = 1.489 \). The
gel PMMA cylinder dimensions were 76 mm outer diameter and 51 mm inner diameter, according to the existing scanner configuration [4][5].

3. Results and discussion
The existing RAH in-air scanner could incorporate an additional laser of different wavelength, while retaining a scan acquisition speed of 5 sec per slice due to the continuous 360° rotation of the scanning mirror. Alignment of the two lasers would be a fundamental aspect of the experimental setup, together with matching of polarization and spot sizes. Two sets of projection data would be acquired in a volumetric scan, one at the measurement wavelength of 594 nm and another at 633 nm, giving net transmission using equation (1). This has the advantage of removing inter-scan variability that may occur when the dosimeter is scanned on two separate occasions. It may be particularly advantageous where positioning reproducibility is limited. A guaranteed benefit is the convenience and time saving of a single scan.

A disadvantage of the proposed dual wavelength method is the loss of around 1/3 of the FXG dose sensitivity ($T_{gel}$). Some of this loss could be recovered by use of a higher wavelength than 633 nm, at the expense of greater ray deviations.

Calculated ray paths are similar for 594 and 633 nm as shown in figure 2. The differences between red and yellow ray locations at each of the four interfaces of the gel cylinder are given in figure 2(c). As expected, deviations are greater at the exit interfaces, reaching 0.13 mm at the gel-PMMA exit.

**Figure 2.** (a) Ray tracing through the gel cylinder from left to right for 594 nm (black lines) and 633 nm (dashed red lines). (b) Zoomed view of figure 2 (a) in the region of greatest path deviations between 633 and 594 nm (3rd and 4th interfaces). (c) Calculated differences in ray positions at each interface of the PMMA cylinder. Radial distance, $Y$ is effectively proportional to the mirror angle, $\theta$. The deviations are $< 0.1$ mm for the majority of rays and interfaces. Considering a laser beam FWHM of 0.4 mm, the largest deviations while not large, are not completely insignificant. However, their comparison to inter-scan spatial precision may be favourable. If so, both $T_{1}^{contam}/T_{2}^{contam}$ and $T_{1}^{defect}/T_{2}^{defect}$ could be closer to unity than that of pre-irradiation scanning.
Reflection losses ($T_{\text{refl}}$) occurring as the beam scans across the cylinder must be accounted for as there is variation of at least several percent. A 633 nm beam may be used as a reference since there are small differences compared to 594 nm as shown in figure 3. The difference is 0.1 – 0.2 % at 90 % of the gel radius (where the data is usually truncated during processing). Therefore $T_1^\text{refl}/T_2^\text{refl}$ should be close to unity.

![Graph showing transmission vs radial distance](image)

**Figure 3.** Calculated transmission through the gel cylinder, assuming 100 % transmission for the gel. The differences between 633 nm and 594 nm are given by the right y-axis.

Optical interference must be avoided since $T_1^\text{int}/T_2^\text{int}$ is unlikely to be unity. The gel cylinder hard coating has been previously noted to cause optical interference [5][6]. To avoid this, the cylinder should have a refractive index matched hard coating or be uncoated.

### 4. Conclusions

A dual wavelength optical CT scanner has been proposed, allowing both measurement and reference scans to be obtained in one scan, giving improved practicality for optical CT in gel dosimetry. There is the prospect of improved scan quality by better spatial registration of artifact generating flaws in reference and measurement projection data. The tradeoff between loss of gel measured sensitivity and potential improvement of artefacts is to be examined by experimental investigation. While this proposal is specific to the RAH in-air optical CT, it may also be suitable for other scanner configurations and gels/solids.

### 5. References

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