Quantifying refractive index mismatch effects on cone beam optical CT scanner measurements

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Abstract. A series of experiments are conducted to evaluate the effects of refractive index (RI) mismatch in readout with a Vista cone beam optical CT scanner. The changing optical attenuation in cuvettes of different colours and RI are quantified using a spectrophotometer, which shows decreasing attenuation as RI increases. A small jar of a colourless solution inside a large jar of another colourless solution with different combinations of fluids of varying RI is imaged in the Vista scanner. Large RI solutions surrounding small RI solutions create a converging lens, while small RI solutions surrounding large RI solutions create a diverging lens. The same dual-jar system is used with solutions of varying RI and colour (attenuation) to assess the effect of RI on attenuation coefficient determination.

1. Introduction
Optical computed tomography (CT) has become a popular imaging modality for gel dosimeters [1, 2]. Typically the dosimeter is placed in a tank filled with a solution to minimize refraction as light travels from the source to detector through the dosimeter in the tank. A common issue one encounters in optical CT is refractive index (RI) mismatch between a gel dosimeter and the surrounding substance. A large RI mismatch decreases the usable region of interest (ROI) within a dosimeter [3] caused by a lensing effect [4] which distorts attenuation information near the dosimeter’s edges. To reduce this effect, some match the surrounding solution to the RI of the dosimeter, but for high RI dosimeters, such as PRESAGE [5], this requires a highly viscous liquid that may produce other complications [6]. Dekker et al [4] used a scanning laser optical CT system and large area detector with a rotating fiducial marker to trace refracted rays and perform an accurate reconstruction. However, this requires very precise scanner geometry and a reference ray trace scan, adding to the total scan time. The Vista cone beam CCD-based optical CT scanner (Modus Medical Devices Inc., London, ON, Canada) uses a diffuse light source, rather than a scanning laser, and large area detector [7]. In this paper we present results of experiments to investigate the effects of RI mismatch on measurements with the Vista optical CT scanner. The experiments were designed to examine both the effects at the edge of an RI mismatch and the possible perturbation of attenuation measurements internal to a volume simulating a three dimensional radiochromic dosimeter.
2. Materials and Methods

2.1. Fabrication of solutions
Several solutions (in percent by weight unless otherwise stated with an error of ± 1%) were created for these experiments with varying RI: distilled water, 12% propylene glycol (PG), 30% PG, 50% PG, 50% glycerol, 70% PG, 70% glycerol, 100% PG, and 90% glycerol. These solutions have an RI of 1.3324, 1.3463, 1.3659, 1.3880, 1.3976, 1.4105, 1.4266, 1.4320, and 1.4584 respectively, measured with a Reichert r² mini refractometer (Reichert Technologies, AMETEK, Inc., Buffalo, NY, USA) with an error of ± 0.0002. The RI of 90% glycerol is from [8] with an error of ± 0.0001 as it exceeds the RI limits of the refractometer. RI values were measured with a 589 nm light source at 20°C ± 1°C.

2.2. Varying colour and index of refraction
Each RI fluid prepared was divided into three small containers. Each container was dyed with 0.99% v/v blue, green, or red food colouring to change optical attenuation values due to absorption. These solutions were poured into 3.5 mL cuvettes and were scanned using a SpectroVis Plus spectrophotometer (Vernier, Beaverton, OR, USA). The spectra determined the maximum absorbance for each solution. Since the maximum absorbance differed slightly for solutions of different RI, a best estimate was used to determine the wavelength of maximum absorbance for green (509.5 nm), blue (457.2 nm), and red (630.4 nm) solutions. The optical attenuation at these peak wavelengths were recorded and plotted against the solutions’ RI’s to determine a relationship (see figure 3).

2.3. Double jar test 1: colourless solutions
The next set of experiments used a small polyethylene terephthalate (PETE) jar (diameter = 6.8 ± 0.2 cm) suspended in a large (PETE) jar (diameter = 9.5 ± 0.2 cm) by gluing the small jar’s lid underneath the centre of the large jar’s lid aligning the central axes of the jars. Four non-coloured solutions were initially used: distilled water, 12% PG, 30% PG, and 50% PG. The small inner jar and large outer jar were alternately filled with the various solutions to provide every possible combination of RI. Each combination was scanned with 590 nm diffuse light in the Vista scanner. Three-dimensional (3D) reconstructions of each jar were created with a reference scan of distilled water in both jars. The 3D attenuation information was imported into MATLAB and a horizontal plane midway through the jars was selected for analysis. The attenuation values of a circular region on this plane were averaged to find the mean attenuation in the inner jar for each combination.

2.4. Double jar test 2: coloured solutions
To examine the effects of changing the refractive index on attenuation quantification, a batch of distilled water (RI = 1.3324) and 30% PG (RI = 1.3668) samples were each separated in two; one dyed red and the other green with 0.99% v/v food colouring. Three samples of 12% PG (RI = 1.3461) were prepared: no dye (colourless), dyed red, and dyed green. The red, green, and colourless 12% PG alternated being in the small jar while red and green water and 30% PG alternated surrounding it. Lastly, the colourless
12% PG filled the outer jar, and the inner jar contained red or green water or 30% PG. Each jar combination was imaged in the Vista scanner and reconstructed with a reference scan of colourless distilled water in both jars. The analysis was completed in MATLAB by examining a line profile along a horizontal cross section through the middle of the two jars.

![Figure 2. Reproducibility of the spectrophotometer measurements (70% PG sample).](image)

![Figure 3. Optical attenuation values for cuvettes of different solutions and colours (error bars are smaller than the symbol size).](image)

![Figure 4. Different combinations of fluids in the dual jars. A schematic of the jar configuration is included on the right.](image)

### 3. Results and Conclusions

Figure 1 shows the spectra of all nine solutions in different colours in cuvettes as measured in the spectrophotometer; figure 2 demonstrates the reproducibility of the spectra measurements. The graphs show the absorbance value at each colour’s wavelength of maximum light transmission (as indicated by a vertical line). Figure 3 shows optical attenuation vs. refractive index for each coloured solution in the cuvettes. The data show a negative slope for each colour, indicating that the attenuation coefficient of each coloured solution decreases slightly with RI.

The Vista scanner measured average attenuation in the inner jar for each jar combination (figure 4). Since all solutions are colourless the expected optical attenuation should be zero, however lensing in the double jars perturbs the measurement. When the solution in the outer jar has a larger RI than the fluid in the smaller jar, the combination becomes a converging lens and the measured optical attenuation in the small jar is negative. Conversely if the solution in the outer jar has a smaller RI than the inner jar’s solution, the combination acts as a diverging lens and will produce a positive measured optical attenuation value in the small jar.

The line profiles through both jars containing various coloured liquids are shown in figure 5 with no image averages taken. Figure 5a shows the attenuation profiles for all jar configurations with a red solution in the outer jar. The left and right halves of each figure correspond to a measurement with solutions of different RI surrounding different colours of 12% PG. Observing from left to right in figure
5 a and b follows a change in refractive index, while observing from bottom to top tracks a change in attenuation. Perturbations at the jar walls due to RI mismatch are clearly evident; the position of the outer jar walls in Figure 5 are approximately at 35 and 220 pixels and the inner jar walls are near 60 and 195 pixels. This dramatic change in attenuation at the jar walls solidifies the knowledge that a RI mismatch can lead to false attenuation information near the edges of a dosimeter. Since the Vista scanner’s light source is 590 nm, one expects green to attenuate more light than red, as can be seen in Figure 5. However, the attenuation through green 12% PG is higher when a red solution surrounds it instead of a green solution, a very unexpected result.

![Figure 5](image)

**Figure 5.** Line profiles through the double jar system. Red solutions (a) and green solutions (b) surround red (light and dark red lines), green (light and dark green lines) and clear (black and grey lines) 12% PG. The left half of (a) and (b) represent 30% PG in the outer jar and the right half of (a) and (b) represents water in the outer jar. A small insert shows a top down view of the two jars, where the grey region represents varying colours of 12% PG.

The results from our experiments indicate that index of refraction has a slight effect on the quantification of the optical attenuation coefficient of the samples in the centre of a jar, and a large effect at the jar walls where the RI mismatch occurs. This supports the measurements from cuvettes seen in figure 3. From figure 4 we can clearly see that a jar will act as a converging or diverging lens and alter the measured attenuation values from the truth, depending on whether a jar’s solution has a higher or lower RI than the fluid surrounding it. RI mismatch at the jar walls as shown in figure 5 provides insight into the extent the optical attenuation coefficient can be distorted at the boundary between two materials. This confirms that a RI mismatch will decrease the ROI available for gathering dose information.

4. References

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