Development of a Quality Assurance Scattering Phantom for Cone Beam Optical CT

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Abstract. Standard water-based acrylic emulsion scattering solutions have been developed for use in optical scattering gel phantoms. These solutions display good uniformity and long term stability, and can be index matched to polymer gels through the addition of propylene glycol or molten gelatin. Preliminary quality assurance (QA) performed on the Vista cone beam optical computed tomography (OptCT) scanner (Modus Medical, London, ON) using these standard scattering solutions provides valuable information toward the establishment of protocols for scanner warm-up and dosimeter/bath temperature control. A characterization of Vista scanner response over a range of scattering concentrations indicates that improved dosimeter performance may be realized through lowering the %T concentration of the polymer gel into the linear response range of the scanner. A gel molding process has been developed for these scattering solutions, with promising results obtained for early stage scattering gel phantoms.

1. Introduction
An important step in the qualification of a new optical CT scanner is to separate the evaluation of optical measurement integrity and performance limitations from the uncertainties in dose delivery and gel dosimetry. Independent optical absorption [1,2] and optical scattering [3] phantoms have previously been developed toward this end. A scattering phantom is particularly useful in the characterization of OptCT scanner intended for use in polymer gel dosimetry. In this paper we describe the characterization of novel calibration scattering solutions, initial scattering gel phantom development, and an associated performance evaluation of the VISTA cone beam optical CT scanner (Modus Medical, London, Canada) for use in polymer gel dosimetry.

2. Materials and Methods
A low cost water-based acrylic emulsion has been identified that has a comparable average particle size (~350 nm) to that of polymer gel dosimeters [1], a reasonable index of refraction (~1.5) and which exhibits good solution stability over time. This emulsion (Duramax B-1000, Rohm & Haas) is easily diluted in propylene glycol-water mixtures and maintains uniformity of colloidal distribution in heated gelatin solutions. Acrylic scattering solutions incorporating 12% propylene glycol by weight for refraction matching were prepared in 1 L polyethylene terephthalate (PET) jars (9.2 cm in diameter) and evaluated using the VISTA cone beam OptCT scanner. Reference and data scans were
taken using 633 nm LED illumination and a 1024x768 pixel CCD camera (410 projections over 360°).
Reconstructions were completed via Feldkamp backprojection with a Hamming filter to a 0.5 mm
voxel size. Portions of the scattering solutions were separated and also measured using an Ultrospec
1000 UV-VIS spectrophotometer (Amersham Pharmacia, Uppsala, Sweden).

Heated acrylic scattering solutions containing 5% gelatin by weight and varied amounts of
propylene glycol for refraction matching were cast into both gelatin and machined acrylic molds
forming usefully shaped and sized scattering phantoms for evaluation of scanner performance
capabilities and for comparison to similar structures in polymer gel dosimeters.

N-isopropylacrylamide (NIPAM) based polymer gels were prepared in the manner according to
Senden et al. [4], with 50 %C and total monomer and crosslinker (%T) in the range of 4-6 wt%. Gels
were poured into 1 L polyethylene terephthalate (PET) bottles for imaging and irradiated using a T780
Cobalt-60 tomotherapy benchtop (MDS Nordion, Kanata, Canada) approximately 24 hours post-
manufacture using 1x1cm² pencil beams.

3. Results and Discussion
Varied concentration acrylic scattering solutions containing 12 wt.% propylene glycol (PG) show
good long term stability and uniformity over a period of the seven months to date. Linear regression
fits to mean attenuation coefficient against concentration of scattering solution at 0 months and seven
months agree within error (Figure 1). These acrylic scattering solutions can then be used as standards
for scanner QA and to optimize the dosimetry of polymer gels against scanner performance.

The compatibility of the acrylic emulsions with heated gelatin solutions allows for the development
of scattering gel phantoms that can be used for rapid calibration of the scanner. A five finger scattering
phantom with 0 wt.% propylene glycol-based scattering solutions in the scattering regions (Figure 1
bottom left) provides a single scan assessment of VISTA scanner contrast linearity that could be used
in daily scanner QA. Two additional effects are worthy of mention. First, an obvious difference is
observed between the mean attenuation coefficient of the 0 wt.% and 12 wt.% scattering solutions at
equivalent scattering concentrations. This is primarily sourced from the addition of propylene glycol,
which increases the refractive index of the solution relative to that of the scattering particles, leading

![Figure 1: OptCT-derived mean attenuation coefficients of standard acrylic scattering solutions (top left) measured at 0 months (right, in blue) and 7 months (right, in pink) agree within error. A simple gel phantom (bottom left) with several scattering fingers derived from acrylic scattering solutions (0% wt. propylene glycol) is used to generate a scanner calibration curve (right, in green). Error bars are smaller than symbol size.]
to reduced scatter and hence, a reduction in reported mean attenuation coefficient [5]. Second, the
effect of multiple scattering is clearly observed for the larger scattering volume 1 L PET jars in the
departure from linearity of mean attenuation coefficient at higher scattering concentrations.

Examples of the use of standard scattering solutions for scanner QA are illustrated in Figures 2 and
3. A time trial involving hourly scans of a 0.1 g/L standard scattering solution reveals an instability in
the mean attenuation value calculated from the reconstructed images over 4 hours of scan time (Figure
2). To help determine the source of the instability, the mean intensity value was observed over time
within the scattering (jar) region of the projection bitmaps. The reported mean intensity value is nearly
identical when both the light source and panel are allowed to warm up as when just the light source is
turned on for 3 hours while the camera is blocked (CB) from light exposure. This suggests that the
camera is the primary source of the time dependent drift in reported intensity value. The camera
response stabilizes roughly within the first 2 hours of camera warm up, with an overall apparent
reduction up to 3% reported in average attenuation value at steady state. A second experiment in
which the light source is switched off for 15 minutes then turned on again (Figure 3 left) illustrates the
importance of even a small power interruption on scanner operation. Temporal effects can be
minimized by setting protocols requiring a minimum warm up time of 2-3 hours for the scanner and
ensuring that both the camera and light source remain on between reference and data scans.

A second example of the use of standard scattering solutions for procedural QA is shown in Figure
3. In this experiment, a 0.1 g/L scattering solution was cooled to 10°C before scanning. It was found
that the reconstructed mean OptCT attenuation coefficient was elevated by more than 3% compared to
a room temperature scan of the same scattering solution. This effect is likely due the increasing
difference between the refraction index of the solvent and of the scattering particles with decreasing
temperature. An evaluation of the mean intensity value within the jar region from the projection
bitmaps (as in Figure 2) shows the increase in intensity as the jar warms up (Figure 3 right).

The information gained from this type of scattering phantom trial is important for the establishment
of scanner quality assurance protocols. Acrylic emulsion based scattering solutions and scattering gel
phantoms provides a calibration of OptCT scanner performance that is independent of dose or spatial
uncertainties that could arise with the use of irradiated polymer gels for QA.

Figure 2: The mean reconstructed attenuation coefficient is determined from
reconstructed scans over time of a 0.1 g/L standard scattering solution(left), with
selected region of interest (ROI) shown in yellow. The mean intensity value was
observed within the jar region on the projection bitmaps over a period of 5 hours (right,
ROI in red) for simultaneous power up of camera and light source, and for the situation
where the camera was blocked during the first 3 hours after light source power up (CB 3
hours, right).
Figure 3: A 15 minute power off of the OptCT scanner light source causes a significant change in camera pixel response (left), observed from the mean intensity value. Restabilization of the camera response occurs within 30 minutes. A temperature trial shows an increase in mean intensity value from projection data with increased temperature (right). The mean intensity value ROIs were the same as the one described in Figure 2.

As stated previously, the effects of multiple scattering are clearly observed in scattering solution OptCT data (Figure 1). This highlights the need for a scatter correction strategy to increase the range of the cone beam OptCT scanner for polymer gel dosimetry. However, a simple adjustment of gel chemistry to lower the sensitivity into the linear performance range of the scanner significantly improves the dosimetry for present use (Figure 4). A gamma map of 500 cGy intersecting pencil beam treatment plan delivered to a standard 6%T dosimeter indicates regions of significant failure in the dosimetry for 3% 3mm gamma criteria. From the data obtained in scattering gel phantom QA we have independently determined that these regions correspond to operation outside the linear performance range of the OptCT scanner. The dosimetry is improved by changing the polymer gel preparation to 4%T to restrict dosimeter behavior in a well-behaved region. Then 3D readout shows that actual dose delivery passes the 3% 3mm criteria for the 4%T dosimeter. This approach unfortunately does involve a loss of dose sensitivity through the %T reduction. Scatter correction strategies explored further in an accompanying paper in these proceedings may allow polymer gel sensitivity to be raised back to the level of the standard 6%T dosimeter.

Figure 4: Gamma maps of 500 cGy intersecting pencil beam treatment plan (left) delivered to a standard 6%T dosimeter (centre) and a 4%T dosimeter (right).
Gelatin molding techniques can be employed in combination with a cross-linker to set gelatin shapes such that they cannot be remelted. Unique scattering shapes (Figure 5) can be realized that have a background scatter concentration representing the base scattering level of the polymer gel and an elevated scatter concentration representing dose delivery to that volume. The phantom in Figure 5 roughly mimics a 500 cGy delivery to a 4%T polymer gel dosimeter with a “background” scatter concentration of 0.025 g/L and a “dose” scatter concentration of 0.10 g/L. The ability to produce such phantoms is anticipated to be a powerful tool in the assessment of OptCT performance capabilities and the establishment of quality assurance protocols.

Figure 5: Raw projection (left) and OptCT reconstructed images (right) of a prototype crosslinker-stabilized gel phantom mimicking a 500 cGy delivery to a 4%T polymer gel dosimeter.

4. Conclusions
Independent scattering solutions with good uniformity and long term solution stability have been developed to validate the integrity of the optical CT measurements and investigate different means of multiple scatter reduction in cone beam OptCT. These scattering solutions are compatible with heated gelatin solutions for forming rigid scattering shapes that are suitable for incorporation into a gel phantom for cone beam OptCT quality assurance.

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6. References
[1] Oldham M, Siewardsen J H, Kumar S, Wong J and Jaffray D A 2003 Optical-CT gel dosimetry I: basic investigations Med. Phys. 30, 623-634
[2] Guo P, Adamovics J and Oldham M 2006 Simple 3D validation experiments for PRESAGE\textsuperscript{TM}/optical-CT dosimetry J. Phys.: Conference Ser. 56, 187-190
[3] Bosi S G, Naseri P, Puran A, Davies J and Baldock C 2007 Initial investigation of a novel light-scattering gel phantom for evaluation of optical CT scanners for radiotherapy gel dosimetry Phys. Med. Biol. 52, 2893-2903
[4] Senden R J, DeJean P, MacAuley K and Schreiner L J 2006 Polymer gel dosimeters with reduced toxicity: a preliminary investigation of the NMR and optical dose-response using different monomers Phys. Med. Biol. 51, 3301-3314
[5] Franklin J and Wang Z Y, 2002 Refractive Index Matching: A general method for enhancing the optical clarity of a hydrogel matrix Chem. Mater. 14, 4487-4489.