Measurement of build-up region dose with optical cone-beam computed tomography scanner

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Abstract. Measurement of the dose gradients from the entrance surface to depth is a standard task for characterizing an ionizing radiation beam. Most gel dosimeters provide spurious results near an air interface, limiting their value for this geometry. In this study, a 3D dosimeter system consisting of a low-diffusion, radiochromic hydrogel cast in a custom polyethylene terephthalate (PETE) vessel and imaged with a modified commercial optical cone-beam computed tomography (CBCT) scanner was employed. The cylindrical vessel wall and flat ends were constructed from a 0.025 cm thick PETE sheet. The optical CBCT scanner was modified to place the entire vessel in the centre of the field of view or to have the vessel base at the optical axis. Pre-irradiation and post-irradiation scans were acquired with the sample mounted in the standard and elevated positions. The sample was irradiated with a 2x2 cm square, 6 MV x-ray beam. Normalized attenuation coefficients from the central quarter of the reconstructed beam images were compared to a Monte Carlo depth dose calculation. Placing the vessel base at the optical axis allowed accurate dose measurements to within 0.2 cm of the entrance face and for the standard position to within 0.4 cm. These measurements validated the Monte Carlo calculation and provide an alternative to parallel plate ion chambers for dose measurement in the build-up region.

1. Introduction
Measurement of dose from the entrance surface to depth of maximum dose, the build-up region, is required for characterizing a megavoltage radiation beam. Typically, near surface measurements are obtained with a parallel plate ion chamber and merged with 1D scans with diodes or small cylindrical ion chambers in a water tank. The dose gradients could also be obtained from Monte Carlo calculations once the output has been validated for selected beams. Water-equivalent, 3D gel dosimeters [1] could also be used to measure dose in the build-up region but previous attempts to measure near a gel-air interface have often resulted in spurious results unless the gel has been cast within hours of irradiation. Recently, our group has prepared custom 1 cm square cuvettes for near surface 1D gel dosimetry and recorded 3D doses in custom 15 cm diameter vessels with a planar laser CT scanner. The small cuvettes allowed measurements to within 0.1 cm of the surface and the 3D large vessel system to within 0.3 cm of surface.

A feature of cone-beam geometry is incomplete sampling near the ends of the field of view (FOV). As the horizontal and vertical acceptance angles increase, the fraction of FOV length under-sampled also increases. In this study, custom cylindrical vessels, 10 cm in diameter, having thin flat ends were
scanned using a modified commercial optical CBCT scanner. The goal is to determine how near the entrance planar interface accurate 3D data could be measured.

2. Methods
Low diffusion, radiochromic hydrogel in a custom cylindrical vessel with thin, flat ends was irradiated with a 2x2 cm, jaw-defined, 6 MV photon beam perpendicular to the flat ends with source to surface distance of 90 cm. The sample was scanned with vessel centre and entrance end face positioned at the scanner’s optical axis, analogous to a previous study [2]. Reconstructed 3D, normalized, attenuation coefficients were compared to previous Monte Carlo 3D dose calculations.

2.1. Vessel construction
PETE sheet (Dura-Lar®) was cut to form a cylinder, 10 cm OD x 11 cm height x 0.025 cm thick. The ends were welded to form an opaque seam <0.1 cm wide. The uniform thickness of the sheet provided much higher optical quality than selected samples of blow molded vessels. The ends were flat discs of the same material, welded into the cylinder ends. A small ink dot was placed 5.0 cm above the base on the vessel wall to serve as a height fiducial.

2.2. Optical CBCT scanner
A Vista16 optical CBCT scanner from Modus QA was modified by placing a 1.5 cm diameter aperture at the 530 nm LED source diffuser, similar to a previous study [3]. The smaller area source reduced stray light artifacts. One thousand projections over 360 degrees were acquired in 4 minutes. The natural logarithm of ratios of reference and data image sets formed the projection images. Reconstructions were calculated with VistaScan program: 0.5 mm isotropic voxels, iterative reconstruction algorithm with default parameters (ordered subset convex (initial/final subset count 100/10, iteration=10, power=0.5, ordered subset angular distance) with total variation minimization (iteration count =10, update constant=0.020). Reconstructions were analyzed in Matlab.

2.3. Solution and gel samples
A uniform coloured solution was prepared by adding nigrosin dye to a 3.5% propylene glycol solution to achieve a transmission of ~70% along vessel diameter. For this solution, water was used as a refractive index optimized solution in the aquarium. The radiochromic gel consisted of 5% gelatin (porcine, 300 Bloom, type A), 32 mM trichloroacetic acid, 1 mM leuco crystal violet and 0.7 mM sodium dodecyl sulfate [4]. The gelatin was first dissolved in deionized water with 1 mM H2O2 at 55 °C for 16 hours prior to lowering temperature to 32 °C to add radiochromic chemicals. The sample was placed in a 20 °C water bath for ~3 hours prior to scanning and irradiation. A 7.5% propylene glycol solution was found to optimize refractive index by maximizing the transmitted signal just inside the vessel wall.
3. Results
Inspection of the reconstructed transverse slices from the solution scans, with the vessel base at optical axis, revealed the 4th slice from the end was unaffected by the vessel end. This corresponds to 0.15 to 0.2 cm from the end face. For the gel scans, mean attenuation coefficients per 0.05 cm slice were averaged over the central 0.5x0.5 cm of the beam, normalized and plotted against a Monte Carlo calculation, see figure 2. The gel depths were scaled to water equivalent depths using a mass density of 1.005 g cm$^{-3}$. Note, no additional spatial filtering was applied to remove spurious reconstruction artifacts such as the spikes at maximum dose for the full FOV scan.

![Figure 2. Plot of normalized depth doses with gel scanned in standard, full field of view position (solid line), gel bottom elevated to the optic axis (dashed line, error bars equal twice standard deviation of mean) and Monte Carlo calculation (dotted line, statistical uncertainty 1%).](image)

4. Discussion
The agreement of gel reconstruction with Monte Carlo indicates that accurate, 3D dose measurements within 0.2 cm of the planar, entrance surface are possible with optical CBCT readout. Because small field dosimetry is challenging, larger fields sizes such as 3x3 cm or greater can be used to independently validate the calculations against a Markus parallel plate ion chamber. For the small fields, alternate dosimeters such as radiochromic film, optically stimulated luminescence detectors, thermoluminescent chips and plastic fibre scintillators could provide independent measurements. While a single beam was measured in this feasibility experiment, the capacity to record several small beams in the same 10 cm diameter gel represents a more appropriate use of the 3D dosimeter. Also, analysis of a set of different field sizes in the same experiment versus single beam per dosimeter should provide more robust measurements.

5. Summary
The combination, low diffusion radiochromic hydrogel in a cylindrical vessel with a thin flat end and placing the gel end at the scanner’s optical axis allows accurate 3D dosimetry to within 0.2 cm of the entrance, planar surface with optical CBCT readout. These 3D measurements can then validate Monte Carlo calculations for small field sizes.
6. Acknowledgements
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7. References
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