Optical CT scanning of cross-linked radiochromic gel without cylinder wall

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Abstract. Genipin cross-linked gelatin hydrogels with 0.2 M sulphuric acid are radiochromic and have sufficient sensitivity for investigating doses less than 50 Gray. Because of the gelatine cross-links, these gels have sufficient strength to allow removal from the vessel container in which they were cast. Placing the gels in the same liquid that was used for preparing the gel allows the radiochemistry to the same throughout the gels and provides physical support. In this buoyancy neutral environment the gel has the same shape and the preparation vessel. This allows optical CT scanning without wall artefacts due to reflection, refraction and optical activity. A gel was irradiated to dose of 25 Gray with a 10 MV photon beam of 20 x 20 mm cross section. Full 3D optical CT scanning was performed with a Vista 10 optical cone-beam CT scanner. Central beam axis profiles and depth dose agree with diode and parallel plate ion chamber measurements. These results demonstrate that genipin cross-linked gel can be used for accurate 3D dosimetry, including surface dose measurements.

1. Introduction
Optical CT scanning of radiation sensitive materials is complicated by the need for vessel walls to provide mechanical support for hydrogels and chemical isolation from the environment. For example, polymer gels such as BANG and PAG require isolation from oxygen and ferrous xylenol orange gelatine gels (FX) require a uniform oxygen concentration. Removing the vessel wall from an FX gel and immersing the gel in a FX solution permits wall-less scanning, but this approach can only be used at low temperatures, and dose response is not uniform due to the dissolved oxygen gradient near the gel surface. Also, additional materials for refractive index matching of the surrounding liquid can diffuse into the gel and modify the dose response near the gel surface. Finally, the gelatine itself will slowly dissolve into the surrounding liquid.

Genipin cross-links many types of polymers to form hydrogels. Gelatin is one example. The resulting cross-linked gels are blue in colour and can have much higher melting points than analogous gelatin gels that rely on hydrogen bonding. By lowering the pH of these cross-linked, genipin gels, transparent, radiochromic materials can be formed that have sufficient rigidity and dose sensitivity for radiotherapy dosimetry(1). These materials have several desirable features for 3D radiation dosimetry. In particular, stable dose images both in space and time are formed immediately following irradiation. The gelatine cross-linking also prevents the gel from dissolving into the external liquid.

Removal of the vessel wall eliminates some refraction, reflection and optical activity artefacts(2-4). True refractive index matching also allows the optical CT scanning of complex 3D shapes that can be cast into any shaper with hydrogels. Currently, the only material that has been practical to optically
CT scan, without walls, has been the radiochromic plastic, Presage\(^{(5)}\). Having a material with uniform dose response throughout its entire volume (i.e. up to surfaces) and uniform optical properties would dramatically increase the range of dosimetry problems that could be accurately studied in hydrogels.

2. Materials and methods

Genipin was purchased from the WACO Chemical Company of Japan. Porcine gelatin, 300 bloom and sulphuric acid (ACS reagent grade) were purchased from Sigma-Aldrich. Two percent by mass gelatin was dissolved in water at 43°C in a water bath. Genipin, 2x10\(^{-5}\) by mass was added. Over 18 hours of continual stirring, the solution changed from colourless to blue. Sulphuric acid was added to give a concentration of 0.2 M in the final gel. Other than a slight dilution of colour intensity, no spectral change was observed as the acid concentration increased. Beakers were coated with a thin film of petroleum ‘jelly’ grease to act as a mould release agent and then filled with gel. Samples were stored at 4°C for two days prior to scanning. Gels were released by adding 0.2 M sulphuric acid, with a syringe and tube, between the gel and beaker wall. The beaker was turned nearly upside down and tapped on the bench top. The intact gel slid out and was placed into a modified Vista (Modus Medical Devices, London, Canada) PETE jar half-filled with 0.2 M sulphuric acid. The bottom of the jar had been cut off and a jar lid inserted and taped in place. As a means of holding the gel from moving two small pins were inserted through the jar bottom. A nylon strap fixed as an inverted arch gently pressed the gel to the base plate and pins. The strap also prevented wobbling of the gel top during CT rotation. Pre and post irradiation optical CT scans were collected with the Vista10 (second generation optical cone-beam CT (CBCT) scanner from Modus Medical Devices) at 590 nm. A scan time of 8 minutes was required for a full 3D scan of 512 images over 360 degrees. Reconstruction of a 256\(^3\) array required an additional 12 minutes at 0.5 x 0.5 x 0.5 mm voxel size. The gel was irradiated in an anterior to posterior geometry with a 10 MV photon beam, source to gel top distance of 100 cm and a beam size of 20 x 20 mm at the surface. The liquid in the jar was adjusted to provide a level surface with the edge of the gel and approximately 1 mm of coverage at the gel centre. The nylon restraining arch also slightly depressed the centre of the gel top, estimated to be less that 1 mm of curvature. A dose of approximately 25 Gray was delivered to the gel, at 25 mm depth. The post irradiation scan began 10 minutes after the irradiation was completed. All measurements were performed at a temperature of 21°C.

3. Results and discussion

Figure 1 is a transmission image recorded by the Vista10 CBCT scanner. The gel appears blue and transparent with white light illumination but has low transmission for yellow light. The gel had a density slightly greater than that of water and was essentially buoyancy neutral in water.

Figure 2 is a reconstructed slice at a depth of 20 mm below the top of the gel. The cross section of a 20 by 20 mm photon beam is evident. Note that the gel has moved laterally between the pre and post scans due to handling. The gel had sufficient strength to remain intact when removed from the casting beaker and transferred by hand into the modified Vista jar for scanning. However, the movement associated with handling between pre and post scan caused the small pins through the base to cut the gel and allow it to settle approximately 1 mm from the original position. In order to prevent this shifting from occurring in future scans, a base ring mount will be designed to provide a larger surface area to restrict the gel position. Without the top pressure to hold gel onto the base pins the gel would have floated out of position with the slightest disturbance. Ideally the gel edge should be not detectable in the reconstruction if there is no absorbed dose.

Figure 3, compares profiles at a 20 mm depth for the gel and a diode detector scanned in water. The sharp peak at +20 mm is the edge of the gel that shifted between pre and post scans. The features at -23 mm and -3 mm are reconstruction artefacts that can be seen as rings in the slice presented and spheres in the 3D data set. This artefact occurs near the scanner’s optic axis.
Figure 4 shows the percent depth dose from merged data sets recorded with a parallel-plate ion chamber near surface and diode detector beyond 20 mm. For comparison, normalized attenuation coefficients from the full 3D reconstructed dose distribution are also plotted. A depth offset of 1 mm was applied to the gel data in order to improve agreement. The amount of water covering the gel during irradiation had been visually estimated to be near 1 mm. However, no accurate depth reading was obtained for this feasibility study. The agreement along the entire curve demonstrates the gel dose response linearity, water equivalence and refractive index matching. Since all are required for good depth-dose matching. Without refractive index matching, the gel could not have been scanned to within 2 mm of the surface. Future scans where the top of the gel in only in contact with water will dramatically reduce artefacts in reconstruction very near the surface.

4. Conclusions
Cross-linked genipin gelatin hydrogels were produced with adequate dose sensitivity and mechanical rigidity for optical CT scanning in water with the vessel wall removed. The gel was minimally restrained within a water bath that provided uniformity for irradiation, refractive index matching for scanning and neutral buoyancy for support of the gel. Excellent agreement between depth dose measured with parallel-plate ion chamber and gel near beam entrance surface demonstrate that near surface dose measurements can be obtained with wall-less optical cone beam CT scanning of this gel.

Acknowledgements: This work was supported by the London Regional Cancer Program Endowment Fund and the Ontario Research and Development Challenge fund (ORDCF-OCITS project).
Disclosure: K Jordan has a licensing agreement with Modus Medical Devices concerning optical cone-beam CT scanning.

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Figure 1. Transmission image of genipin gel, without containment vessel, immersed in a 0.2 M sulfuric acid solution. The gel was contained inside a plastic jar for optical CT scanning.

Figure 2. Reconstructed image of change in attenuation coefficient at 590nm, transverse plane at 20 mm depth due to 25 Gy of absorbed dose from 10 MV photon beam. Note the bright and dark crescents at edge of gel are due to lateral movement of gel between pre and post-irradiation scans.
Figure 3. Normalized dose profiles at 25 mm depth (diode scan in water (solid line), gel (o)).

Figure 4. Central axis normalized depth doses (merged parallel-plate ion chamber and diode measurement (solid line), gel (o)).