Non-diffusing photochromic gel for optical computed tomography phantoms

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Abstract. This study examines photochromic response in radiation sensitive hydrogels. Genipin, crosslinked, gelatin gel can support high resolution images because the chromophores do not diffuse. A low power, 633 nm He-Ne laser was used to write lines into the gels by a photobleaching reaction. Optical cone-beam computed tomography (CBCT) scans mapped the high resolution images in 3D with 0.25 mm voxel resolution. A straight line was written into a deformed gel and then readout in its relaxed, initial shape. The curved, photo-bleached line demonstrated deformable 3D dosimetry is possible with this system to the balloon edge. High resolution, photochromic images provide key information for characterizing optical CT scanners and 3D dosimeters. Many, ionizing radiation, dosimeter materials demonstrate either a photochromic or photothermal response, allowing this approach to be widely used in quantitative 3D scanning.

1. Introduction
Optical computed tomography (CT) with visible light can achieve spatial resolutions from 1 micron to greater than 1 mm depending on the application. In order to characterize these systems test images of similar spatial dimensions are required. Images that have similar 3D refractive indices and similar absorption and scatter characteristics are simpler to interpret. In the case of PRESAGE®, high resolution test images have been written with synchrotron beams and UV photo-lithography equipment [1]. In this initial report, a red light, low power laser is used to write high resolution images into a hydrogel that is sensitive to both MeV (radiochromic) and eV (photochromic) photons. Genipin hydrogel was chosen because of chromophore is crosslinked to the gelatin polymer chains, eliminating diffusion [2-4]. Genipin gel radiation response has been characterized and from keV to MeV energies and very similar to Fricke solutions and water [5-7]. It is anticipated that writing photochromic images will be a simple, inexpensive method for preparing calibration images that can be produced in any facility with an optical CT scanner. While not the focus of this study, these results apply to other forms of microscopy such as optical projection tomography.

2. Methods
Genipin gel was prepared with: 3% gelatin by mass, genipin 0.1% mass of gelatin, and 200 mM H₂SO₄. The genipin and gelatin were dissolved in distilled water and stirred at 45 C for 18 hours and acid was added to form the stock gel. A stock gel sample was diluted with blank gel (200 mM H₂SO₄, 3% gelatin) to achieve acceptable levels of transmission at 594 nm for optical CT scans. A commercial
“5 inch clear” latex balloon and a rigid PETE plastic jar from Modus Medical Devices were filled with genipin gel.

The jar sample was scanned with a modified Vista10 optical cone-beam computed tomography (CBCT) scanner (590 nm light, 512 projections per 360 degrees, camera lens aperture of F4 and 8 minute scan time). Reconstruction with Vista software was performed at 0.25 mm³ voxel size with Ramp filter, generating a 512³ array of attenuation coefficients. While the larger, gel filled–balloon was scanned with an in-house prototype laser scanning CBCT scanner (594 nm laser light, 512 projections per 360 degrees, 200 slices, 30 minutes scan time). Propylene glycol aqueous solutions were prepared for refractive index matching. Reconstruction was performed with in-house software implementing the FDK algorithm with 0.34 mm³ voxel size and Ramp filter.

Following pre-illumination (reference) optical CT scans the gel samples were illuminated with a, He-Ne laser (633 nm, 13 mW, 0.7 mm diameter beam) for 30 minutes per position. The gels were positioned in a cubic water phantom to minimize refraction effects. The cylindrical jar was first placed upright in the corner of the water phantom and illuminated with the laser beam near the half radius position and then rotated 90 degrees for second beam to generate orthogonal coplanar rays for illustration purposes. Finally the jar was placed horizontally and a third beam illumination formed the last mutually orthogonal ray. The gel-filled balloon was deformed by another water-filled PETE jar and the laser beam passed within 2 mm in the inner surface of the deformation, see figure 1.

![Figure 1: Photograph of deformed genipin gel balloon in a water phantom during laser photobleaching illumination, viewed from above.](image)

The balloon relaxed for 30 minutes before acquiring the post illumination optical CT scan. Segments from several transverse slices of the 3D reconstruction were stitched together to record the path of the laser beam through the deformed balloon. A centering base ring was made for the balloon and fixed to the CT rotation platform. The liquid level was adjusted so that several centimeters of the balloon neck was above the liquid to provide sufficient friction between the gel and the rotation platform. A black, ink-spot fiducial was placed on the balloon. The laser beam was directed onto the fiducial and the position recorded. After irradiation the balloon was again placed in the scanner and adjusted until the fiducial aligned with the laser beam. Note, this genipin gel balloon was previously irradiated with crossed beams and results were reported in a separate submission related to optical CT scanning of latex balloons.
3. Results and Discussion

A transverse slice from the reconstruction of the 3 orthogonal laser beam illumination is shown in figure 2. Note that the intersecting laser beams do not exactly lie in this plane as seen by the varying attenuation changes. Also, the out of plane beam is not obvious and an arrow points to its location. This ray is offset by ~2 mm from the intersection of the first two beams. If required, much smaller features can be written by focusing the laser beam.

![Figure 2: Transverse slice containing the photochromic image of the intersecting laser beams. Note the arrow pointing to third mutually orthogonal beam.](image)

In figure 3, a composite slice from the 3D reconstruction shows the deformation of the path the laser beam. The photo-bleached path contains the voxels that were illuminated by the laser beam with the gel deformed within the balloon. The ability to probe near the surface of the dosimeter is especially important for deformation experiments since the surface regions experience the greatest deformations. Also present within the slice is an artifact image from a previous dose distribution due to intersecting MV x-ray beams. The dosimeter has been irradiated for another study presented at this conference. The position of dosimeter between the reference and data scans was slightly different allowing the edges of the distribution to be evident in the ratioed images. Examples of other photochromic materials are: Radgel, leuco crystal violet and leuco malachite green micelle gels with Laponite® and Presage®. Since many of the radiosensitive dosimeter materials are also photochromic and thermochromic, this is a general technique for preparing test patterns. While, polymerization gels were not part of this study, it is anticipated that lasers could initiate polymer image formation in these materials as well. Materials with diffusion of reactants or photoproducts can also be studied by monitoring growth or fading of written images. Photochromic or photothermal responses may be alternatives to radiosensitivity calibration procedures providing further simplification of 3D dosimetry.
Figure 3: Composite slice of the photobleached line following relaxation of the deformed gel-filled balloon. Arrow highlights path.

4. Conclusion
Non-diffusing photochromic gels are versatile materials for writing high resolution 3D images. One application of this process is development of test patterns to characterize optical CT performance. Optically probing deformation properties of 3D dosimeters is another application.

5. References
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