A transparent black non-diffusing micelle gel for optical CT performance evaluation phantoms

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Abstract. Performance evaluation of optical CT scanners requires a set of phantoms with well known optical and geometric properties. Gels are often used and tinted with colouring agents but these suffer from wavelength dependencies, diffusion and degradation over time. In this paper we describe a new approach to creating suitable test phantoms using micelles. Adding surfactants to gelatin hydrogels allows materials insoluble in water to become suspended. Carbon black nanoparticles were dissolved into a transparent hydrogel consisting of 4% gelatine and 0.2% Triton X-100. The lack of macroscopic diffusion of the black particles was demonstrated by recording transmission images over 500 hours.

1. Introduction

Optical computed tomography (CT) scanners have been developed for three-dimensional (3D) quantitative measurement of optical attenuation in transparent materials. For dosimetry purposes, polymerization gels form white, translucent images and radiochromic gels form coloured transparent images following the absorption of radiation. In testing their performance, inserts of known optical density are often used. Transparent, blue, finger, hydrogel phantoms were reported by Oldham et al (1). Bosi et al (2) developed a stable white, translucent phantom. These phantoms were applied to the characterization of optical contrast resolution in CT scanners. Diffusion and colour stability limited the practicality of phantoms when prepared simply with food dyes.

Several optical CT geometries and several light sources have been reported. The light sources include; monochromatic coherent lasers, narrow bandwidth incoherent light emitting diodes, low-pressure sodium lamps and mercury arc lamps. Direct scanner comparisons of performance are complicated by the fact that the spectra of the non-laser scanners change as the light passes through the coloured materials. This problem is analogous to that of ‘beam hardening’ in x-ray CT. A transparent hydrogel which absorbs light, independent of wavelength, would therefore be very useful for performance evaluation of optical CT scanners with light sources of different spectra. Neutral density filters are commercially available for evaluating and calibration of traditional (2D) densitometers. These filters are typically made by evaporating different thicknesses of aluminum onto glass windows. Black materials evenly absorb light across the entire visible spectrum. Often several dyes or compounds are added to form a black appearing material, such as black ink. Some of the truly black dye molecules are relatively toxic and should be avoided. Carbon black is essentially a standard material for making black substances such as paints, plastics, papers, inks and printer toners. Carbon
black is a nanoparticle material, relatively inert and inexpensive. However, carbon black is insoluble in water limiting its value for preparing transparent black hydrogel ‘finger’ phantoms. Recent investigations have demonstrated the potential of exploiting radiochromic reactions in hydrogels containing surfactants Jordan(3). In this study, initial results are presented where a surfactant has been employed to form a transparent black, non-diffusing stable hydrogel that can be cast in phantoms for optical CT performance evaluation. The phantom can be used to create sharp optical edges used in spatial resolution tests, or ‘finger’ phantoms used in contrast resolution and attenuation calibration tests.

2. Methods and materials
Carbon black from two sources was investigated. Initially carbon black was produced by placing a metal foil over a candle flame and depositing a black soot film. The second source of carbon black was drawing ink (Staedtler Mars). Both samples were dissolved in Triton X100 aqueous solutions and the absorption spectra were recorded with a visible absorption spectrometer (Hitachi-Perkin Elmer model 139). Subsequent gels were prepared using the black ink. Hydrogels were prepared by dissolving porcine gelatin (300 Bloom, Sigma) 4% by mass in water at 45°C with Triton X-100 (Sigma) 0.25% by mass. The solution was filtered and poured into transparent colourless plastic(PETE) jars. One of the jars also had hollow polymethylmethacrylate rods of 25.4, 12.6 and 4.8 mm outer diameters placed parallel to the rotation symmetry axis. The rods were coated with a thin film of petroleum-based grease and the bottom ends sealed. The ‘finger’ phantom and reference were stored at 4°C in a refrigerator for 24 hours before filling the finger cavities. Plastic 1cm optical cuvettes were half filled with gelatin solution and set aside to gel to form optical edges. The next day, the remaining stock gelatin was melted and darkened by adding drop wise an aqueous solution containing Triton X100 and ink. The end seals were gently removed from the tubes in the finger phantom and the dark gel solution (~25°C) was added as the tubes were withdrawn gently from the cool gel phantom. Also the upper cuvette halves were filled with darkened gel. Cuvette samples were stored both at 22°C and 4°C for subsequent measurements.

Transmission images were recorded through the cuvettes as a function of time with a 16 bit CCD camera (Apogee Alta- U47+). For these studies, the reference image was air. A diffuse light source was constructed by back-illuminating a white plastic sheet with a yellow Luxeon III LED spectrally filtered with 590 nm bandpass filter and an OG570 longpass filter. The finger phantom and uniform reference were both laser scanned at 594 nm, acquiring 225 CT projections over 180 degrees and reconstructed at 0.5 mm pixel size with filtered backprojection (Matlab V7.4, Mathworks algorithm iradon).

3. Results
The visible absorption spectra for solutions containing the candle soot and black ink were similar indicating the primary pigment in this brand of drawing ink was carbon black. Figure 1 is a transmission image of the gel-filled cuvettes. Note the meniscus that formed when the cuvettes were half-filled. Transmission images were calculated by dividing the cuvette images by the corresponding air image. Vertical profiles through the centre of the half-black cuvette stored at 295K are plotted for 20 and 500 hours post sample preparation in Figure 2. Note the profiles are essentially identical, demonstrating that the gel is extremely stable with respect to both optical attenuation and geometry. After two weeks mould growth was observed in the 22°C samples of black gel. The experiment was stopped at 500 hours when the mould colonies started to decrease visible light transmission. Figure 3, is a reconstructed optical laser CT slice through the ‘finger’ phantom. The full width half maximum diameters of the reconstructed fingers were of 25.3, 12.5 and 5.0 mm in agreement with the tube outer diameters 25.4, 12.6 and 4.8 mm. Note that the streaking artifacts present are due to the seams in the plastic jar. Also, darker regions are evident within the fingers. This non-uniformity was due to pouring the black gel in steps as the tubes were withdrawn in increments of a few cm. Finger
uniformity is also very sensitive to the gel temperatures. Casting warmer black gels can provide more uniform fingers at the expense of degrading the boundary sharpness due to side melting.

Figure 1. Transmission image of micelle gelatin gels: left to right, uniform micelle gel, uniform black gel, gradient gels stored at 22°C and 4°C. Vertical profile of 22°C sample plotted in Figure 2.

Figure 2. Plot of vertical profile across meniscus edge in Figure 1 of 22°C gel at 20 and 500 hours post preparation.
4. Conclusions

Black, non-diffusing, gel for finger phantom manufacture can be prepared by using a surfactant to suspend carbon black nanoparticles in micelle gelatin hydrogels. Triton X100 is one example of a nonionic surfactant that adds minimal scatter to 4% gelatin hydrogels and provides a stable optical attenuation over several weeks. These properties allow the production of calibration and test phantoms that can be used with both monochromatic laser CT scanners and broader bandwidth incoherent LED based scanners. Because the gel is black, absorption is nearly independent of wavelength and spectral hardening artifacts are avoided. Future work will investigate the use of micelle gel hosts to prepare imaging performance phantoms for both X-ray CT and magnetic resonance imaging using appropriate contrast agents.

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