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Optical Tomography with Large Data Sets and Analytic Reconstruction Formulas

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Abstract: We use diffuse optical tomography to reconstruct images of complex phantoms with subcentimeter features. A noncontact scanner collects large data sets of over 10^8 measurements. Images are reconstructed using a fast analytic inversion formula.

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The use of near-infrared light for tomographic imaging of biological tissues is a subject of considerable interest. Promising clinical applications include breast imaging and functional brain mapping [1, 2]. Since near-infrared light is multiply scattered in tissue, it is generally accepted that it is difficult to achieve anatomically useful resolution in optically-thick media [3]. Accordingly, the emphasis in diffuse optical tomography (DOT) has been on functional imaging or on multimodal imaging, in which simultaneously acquired MRI or x-ray CT images are used to constrain DOT reconstructions and provide anatomical detail [2]. Recently, however, it has been suggested that the relatively low quality of reconstructed images in DOT can, to some extent, be overcome by the use of large data sets [4, 5]. Such data sets may be easily acquired with noncontact DOT systems [6]. In this manner, Turner *et al.* showed that simple shapes can be imaged in an optically-thin sample by time gating the early-arriving photons, and using a backprojection reconstruction algorithm [7]. However, when imaging optically thick samples, such as human breast, ballistic photons do not reach the detectors. Thus, a reconstruction method based on inversion of a diffusion model for light propagation is required. In this study, we collect data sets consisting of 10^8 measurements, and use a fast reconstruction formula to produce three-dimensional reconstructed images of objects immersed in an optically thick medium with spatially resolved features on the subcentimeter scale. To our knowledge these are the highest resolution DOT images obtained to date.

The experimental apparatus consists of a continuous-wave diode laser (Model TC40, SDL Inc., San Jose, CA) operating at 785nm. It is coupled via a 100μm multimode fiber to a pair of galvanometer-controlled mirrors (Innovations in Optics, Woburn, MA) which scan the beam across the surface of a 6 cm thick imaging tank. Light transmitted through the tank is collected by a 25mm/f 0.95 lens and focused on a front illuminated thermoelectric-cooled 16 bit CCD array (DV887ECS-UV, Andor Technology, Belfast, Ireland). The fluid filling the tank consists of water, a fat emulsion (Liposyn III, 30%, Abbott Laboratories, Chicago, IL), and India ink (Black India 4415, Sanford, Bellwood, IL), and has an absorption coefficient $\mu_a = 0.05\text{cm}^{-1}$ and reduced scattering coefficient $\mu_s' = 7.5\text{cm}^{-1}$. For each experiment, we scan the beam over a 35×35 square lattice of sources with a lattice spacing of 4mm. The 512×512 CCD array collects the transmitted light within a 20cm × 20cm field of view on the detector plane. We record a total of $(35 \times 512)^2 \approx 10^8$ measurements in a single experiment, although somewhat smaller subsets are used for image reconstruction. Three dimensional images are reconstructed using analytic methods for image reconstruction which lead to a dramatic reduction in computational complexity compared to purely numerical approaches. Here we use a reconstruction valid within the first Rytov approximation as previously described [4, 5]. These reconstructions of data sets with 10^7 source-detector pairs require less than one minute of CPU time on a 1.3 GHz workstation.

For the reconstructions shown in Fig. 1, the target was constructed of silicone rubber and shaped in the form of letters “DOT” and “PENN”. The letters were 3 cm tall, 2 cm wide, 5 mm thick, and their individual features were 3 mm in width. The scattering coefficient of the rubber was matched to that of the background fluid, but the absorption coefficient was four times larger. First, we placed the letters “DOT” one cm from the source plane and the letters “PENN” one cm from the detector plane, directly behind the “DOT” letters. The reconstruction is shown in Fig. 1(b). The letters are clearly visible. Note that the central slice is empty,

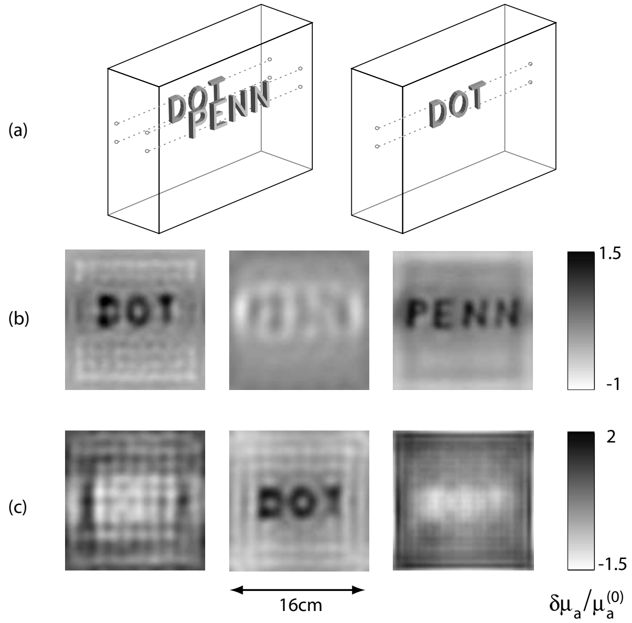

Fig. 1. Slices from three dimensional image reconstructions of the absorption coefficient for targets suspended in a 6 cm thick slab filled with highly scattering fluid. The three slices shown for each reconstruction correspond to depths of 1 cm (left), 3 cm (middle), and 5 cm (right) from the source plane. (a) Schematics of the positions of the letters during the experiments. (b) Reconstructed image of the letters "DOT" and "PENN" suspended 1 cm and 5 cm from the source plane (c) Reconstructed image of the letters "DOT"suspended 3 cm from the source plane, i.e. in the center of the slab.

as expected. We then placed the letters "DOT" in the center of the tank (the letters "PENN" were not present) 3 cm from source and detector planes. The reconstruction is shown in Fig. 1(c). The letters are clearly reconstructed.

In order to quantify the transverse resolution, we have prepared several bar targets from the same material. The bars were 7 mm to 9 mm thick and placed consecutively (one at a time) in the center of the slab. Fig. 2(a) shows the corresponding reconstructions. As the bar widths decrease, the modulation depth between bars decreases. As can be seen, all but the 7 mm bar target are well resolved. Fig. 2(b) shows reconstructions for two experiments in which the 7 mm bar target was positioned one cm from the source and detector planes, respectively. The bars in this figure are well resolved and the images are smoother and have fewer artifacts. As can be expected, the image is better resolved when the target is closer to the detector plane. This is because the detectors are sampled on a finer grid than the sources.

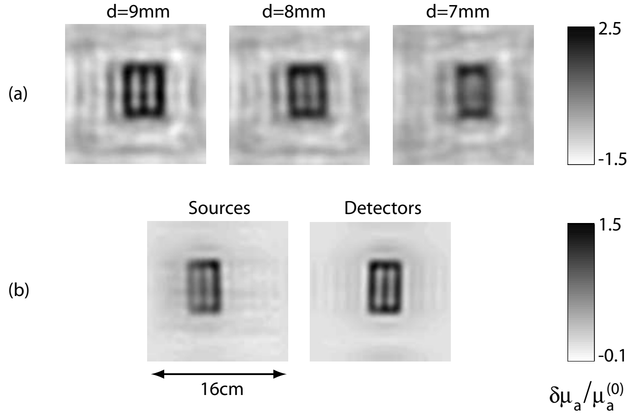

Fig. 2. Reconstructed images of bar targets. Only slices drawn at the depth of the actual target are shown. (a) 7 mm to 9 mm bar targets located in the center of the tank. Here d denotes the width of the individual bars in the targets. (b) The 7 mm bar target located 1 cm from the source (left) and detector (right) planes.

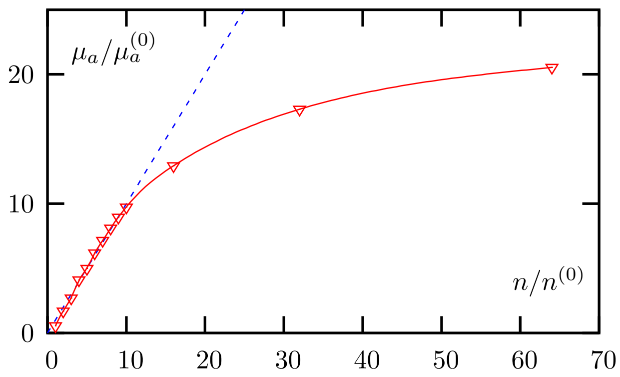

Fig. 3. Reconstructed contrast of the absorption coefficient, $\alpha/\alpha^{(0)}$ vs the relative ink concentration in the tube and the background media, $n/n^{(0)}$.

To investigate the capability for quantitative reconstruction of the absorption coefficient, we have performed a titration experiment. A clear plastic cylinder was positioned in the center of the tank, and laboratory tubing was used to flow fluid through the cylinder. During the first scan, the cylinder contained scattering fluid identical to the fluid in the tank. Twelve titrations were then performed in which the ratio of ink concentration in the cylinder, n, to that in the tank, $n^{(0)}$, ranged from $2:1$ to $64:1$. The absorption contrast, i.e., the ratio of the absorption coefficient in the tube to that in the surrounding fluid, was taken from the corresponding reconstructed value for a single voxel located inside the tube. This voxel was chosen to be the voxel with the maximum reconstructed value of the absorption coefficient for the tenth titration. In Fig. 3, the measured contrast $\mu_a/\mu_a^{(0)}$ is plotted against the known contrast of the ink concentration, $n/n^{(0)}$. It can be seen that the absorption is quantitatively reconstructed with a linear dependence on concentration over nearly a decade in absorption contrast. Deviation from linearity occurs at higher concentrations, as expected.

In conclusion, we have obtained high quality, quantitatively accurate, reconstructed images of complex structures deeply embedded in highly-scattering media. This was achieved by using both a noncontact scanner capable of collecting large amounts of data and a fast image reconstruction algorithm capable of utilizing this data. These techniques hold potential to improve the utility of diffuse optical methods in biomedical imaging.

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