EXPERIMENTAL STUDY OF THE DIFFRACTION OF PHOTON DENSITY WAVES BY AN ABSORBING EDGE IN HIGHLY SCATTERING MEDIA

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ABSTRACT

Near-infrared imaging of bodily tissues is of prime importance in medicine. This study makes further inroads into the understanding of the physical principles behind the optical processes occurring in these highly scattering media. Using frequency-domain methods, we have studied the diffraction of transmitted intensity-modulated light waves on an absorbing edge which could be carried in position relative to the illumination and detection fiber optics. The medium was highly scattering and had a variable, adjustable absorption. We report the experimental conditions for which the highest spatial resolution is obtained and discuss the influence of the various photon paths. This work was funded by the National Institutes of Health, grant RR03155.

INTRODUCTION

Recently, a number of laboratories have addressed the problem of imaging absorbing objects in highly scattering, non-absorbing media. The interest in this method arises because of the possibility in medicine of using near-infrared radiation for obtaining images of the body interior. It has been shown that near-infrared radiation in the region between 650 nm to 850 nm can penetrate about 10-15 cm of tissue. The major source for absorption in this spectral region is due to hemoglobin and other heme derivatives that are generally concentrated in the blood vessels.

There are two different regimes in which it is possible to do imaging: (a) The ballistic regime, which is valid for relatively low scattering, or a thin slab of highly scattering material up to about 1 cm thick (1,2,3) and (b) The diffusion regime, which is valid for thick samples. Several approaches have been proposed to obtain the location of absorbing centers in highly scattering, non-absorbing media based on computer reconstruction of the interior of the material from the light transmitted at different angles (4,5). It has been suggested that, by resolving the time of flight of photons transmitted through a thick tissue illuminated using a narrow light pulse, it should be possible to discriminate the early photons, i.e. those photons that had a few forward scattering events, from the rest of the photons, thus providing the equivalent of a relatively narrow probing beam. If this limit can be reached, the light imaging problem will be similar to the computerized x-ray tomography technique.

Time resolution can be obtained using two alternative techniques: (a) time-domain methods, based on streak cameras or correlated single photon counting apparatuses (6,7); and (b) frequency-domain methods, based on the measurement of the phase and amplitude of an intensity modulated wave diffusing in the tissue (8).

In this manuscript, we have studied the diffraction of intensity modulated photon density waves by an absorbing edge in a partially absorbing and highly scattering medium using frequency domain methods. Our aim is to systematically study the conditions to obtain the highest spatial resolution by observing how the different parameters of the experiment determine the sharpness of the edge.

MATERIALS AND METHODS

The absorbing plane has a dimension of 6.5 cm width. The media consists of 3.78 liters of skim milk containing quantities of black India ink that vary from no ink to 2000 μl of ink. Our light source was a Spectra Diode Laboratories (SDL-2431-H2) diode laser with a 1 m fiber optic pigtail of diameter 100 μm and emitting at 810 nm. The average diode current was set at values ranging from 300 mA to 830 mA and sinusoidally modulated with an RF signal. The light detector was a 3 mm diameter optical fiber attached to a photomultiplier (Hamamatsu R928). The PMT signals were processed by a cross-correlation electronics system using a digital acquisition

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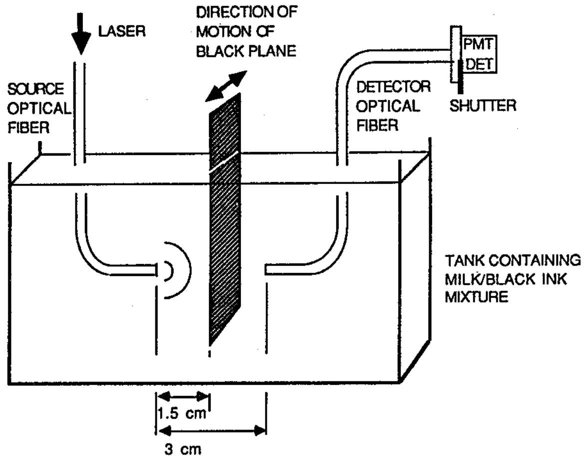

Fig. 1. The experimental setup.

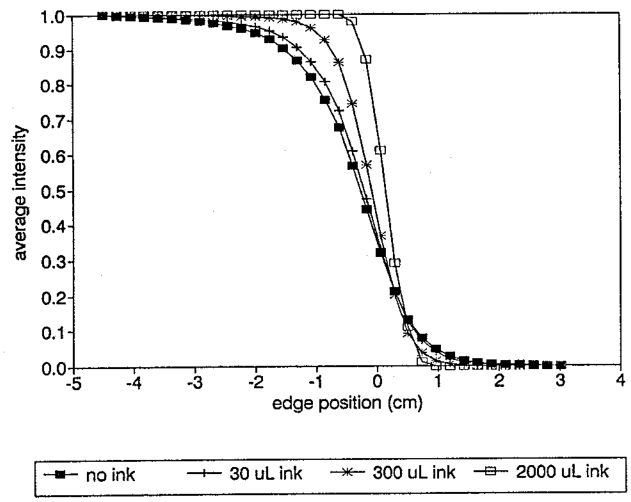

Fig. 2. Average light intensity vs. the position of the edge of the plane relative to the line joining the source and detector optical fibers.

system (9). The source–detector distance was 3 cm and the face of the absorbing plane was oriented perpendicularly to the line joining the ends of the source and detector optical fibers (Fig. 1). The 0 cm position of the edge of the plane is defined to be the point where the edge of the plane crosses the line joining the source and the detector. As a function of the position of the edge of the plane, we measured the phase lag, average intensity, and demodulation of the signal at three modulation frequencies: 20, 60 and 120 MHz. The phase data were recorded relative to the phase measurement made when the plane edge was in its initial position (-4.5 cm) where the plane is not between source and detector, and the average intensity and demodulation data were respectively normalized to the average intensity and the demodulation values made at the initial position of the plane edge.

RESULTS

The steady-state light intensity component as a function of the edge position for different amounts of black India ink added to the scattering medium is shown in Fig. 2. Figure 3 reports the phase and modulation values at 120 MHz modulation frequency as a function of the edge position for different amounts of ink added to the scattering medium. Figure 4 shows the phase and modulation values as a function of the edge position at three different modulation frequencies for the scattering medium without ink.

DISCUSSION

The measurement of the transmitted light intensity shows that when the edge is exactly between the source and detector fibers (zero position), the light intensity is about one third of the maximum. All curves at different ink concentration cross at about one quarter of the maximum and not exactly at the zero position. At present we are investigating the origin of this phenomenon.

The frequency-resolved plots show that the phase first decreases as the edge approaches the zero position and then sharply increases. The modulation increases as the edge approaches the zero position and then sharply decreases. The overall magnitude of the effect decreases as the ink concentration increases. To qualitatively explain this effect, we must consider that, at the detector we are measuring the contribution of photons traveling throughout a distribution of paths. As the edge approaches the zero position half of the field of view is occupied by the absorbing edge and all the longer paths that should cross the edge are deleted. This deletion causes an effective advance of the average wave front and an increase of the modulation of the signal. As the edge reaches the zero position the phase reaches its minimum value and the modulation its maximum value. When the edge passes the zero position all the shorter paths are deleted and the wave front is strongly retarded and demodulated. The addition of ink effectively deletes the longer photon paths, thereby decreasing the overall effect. In the limit of high absorption the phase difference caused by the insertion of the edge becomes very small since the effective wave velocity is very high. Note that the phase plots, measured at different frequencies (for the same ink concentration) cross at the same edge position, which is also at the zero phase level. The modulation curves, in contrast, cross at different edge positions.

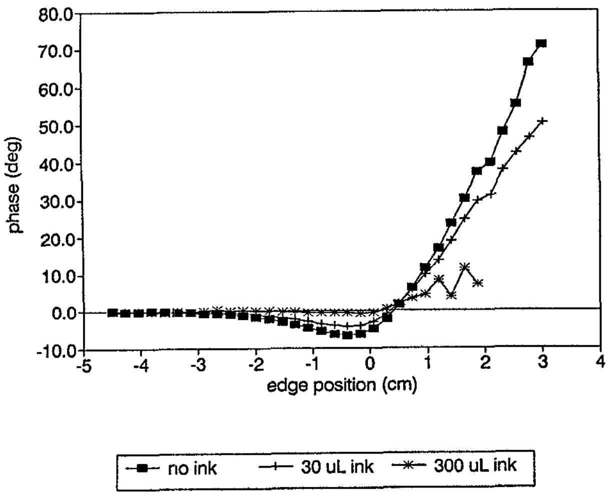

Fig. 3 (a) Phase lag vs. the position of the edge of the plane relative to the line joining the source and detector optical fibers.

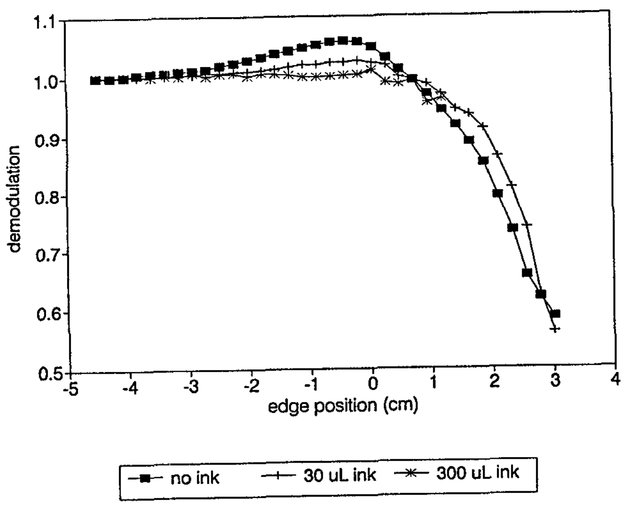

Fig. 3 (b) Same as part (a) except that the data in this figure are the demodulation vs. the position of the edge of the plane.

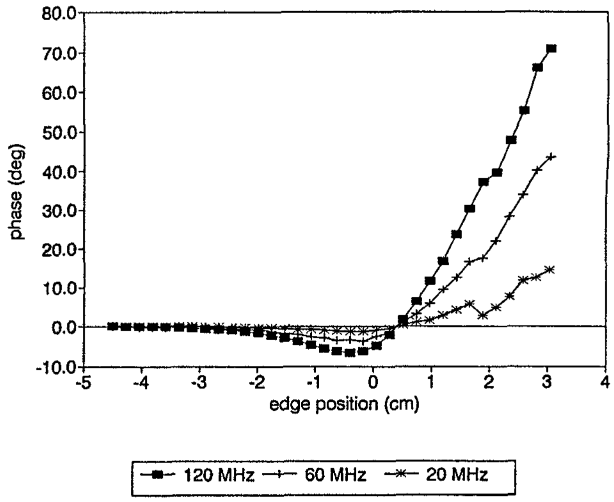

Fig. 4 (a) Phase lag vs. the position of the edge of the plane relative to the line joining the source and detector optical fibers.

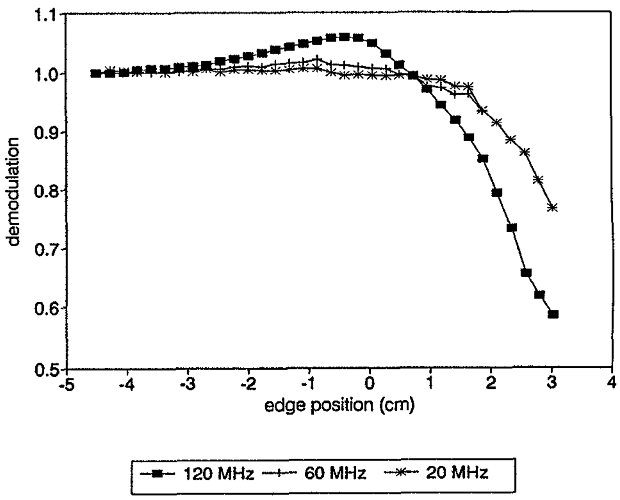

Fig. 4 (b) Same as part (a) except that the data in this figure are the demodulation vs. the position of the edge.

In conclusion, we have shown experimental studies of the diffraction of photon density waves by an absorbing edge. The addition of ink increases the sharpness of the edge because it causes deletion of the longer photon paths. The same effect can be obtained by increasing the modulation frequency used in the frequency-domain experiments, since higher modulation frequencies are more attenuated than lower modulation frequencies.

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