Photoacoustic Measurements in Brain Tissue

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Abstract

In this work, we develop and evaluate the photoacoustic technique for recording spectra of white and gray mammalian brain tissues. In addition to the experimental work, we also discuss the geometric aspects of photoacoustic signal generation using collimated light. Spectra constructed from the peak-to-peak amplitude of the photoacoustic waveforms indicate differences in the two tissue types at wavelengths between 620 and 695 nm. The potential of the technique for non-invasive diagnosis is discussed.

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I. Introduction

The photoacoustic effect has a great potential as a non-invasive technique for many applications in the measurement and characterization of biological tissues and fluids. The potential applications include the differentiation of tissue types, characterization of the disease state of tissues, and the generation of acoustic or ultrasonic waves *in vivo* for diagnosis (e.g., brain injury monitoring, tumor detection). In this work, we present some early measurements of the photoacoustic spectra of white and gray matter from brain tissue of sheep. The spectra were taken from 505-695 nm and show clear differences at wavelengths longer than 620 nm.

II. Theory

IIa. The Photoacoustic Effect

The photoacoustic (PA) effect is the generation of mechanical vibrations at acoustic or ultrasonic frequencies due to the absorption of modulated light. Some of the pathways by which optical energy can be converted to mechanical energy include electrostriction, thermal expansion, photochemical changes, boiling/ablation, and breakdown/plasma formation [1]. In many cases thermal expansion is the dominant mechanism. The PA wave equation with the thermal expansion source term is

$$\nabla^2 p - \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} = -\frac{\alpha\beta}{C_p} \frac{\partial I(t)}{\partial t}$$

where p is the pressure of the acoustic wave, α is the optical absorption coefficient of the target medium, C_p is the heat capacity at constant pressure, β is the coefficient of thermal expansion, and $I(t)$ is the light intensity as a function of time. The light incident on the sample must be pulsed or modulated in order to generate PA waves, which is clear from the derivative in the source term.

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IIb. Geometry of Photoacoustic Waves

With excitation using a collimated beam of light, the PA waves can have simple geometric symmetry. In Figure 1 the limiting case of a weak absorber is depicted. The light is approximately uniform as it passes through the sample and thus serves as a line source. When the light is modulated, it generates acoustic waves of cylindrical symmetry propagating broadside to the incident light in the sample. From the surface of the sample, the waves radiate out with an approximate spherical symmetry (given that the overlying medium is non-absorbing). The strong absorber limit is shown in Figure 2. Here the modulated light gives rise to waves with approximate spherical symmetry radiating in all directions from the region of absorption. Understanding the geometry of PA wave generation is important in interpreting the captured waveforms.

III. Experiment

In this work we used a pulsed laser to produce ultrasonic PA waves in brain tissue from sheep. The tissue samples were taken from the cerebrum of preserved sheep brains (Carolina Biological Supply) and cut to expose both white and gray matter. The tissues were taken from preserved sheep brains obtained from a biological supply company. These measurements examine the differences in the PA spectra of white and gray matter. A black anodized metal plate was used as a reference for these measurements.

The experimental set-up is shown in Figure 3. The source light was from an optical parametric oscillator (OPO) pumped by the 355-nm line from a pulsed Nd:YAG laser. The OPO is tunable across most of the visible spectrum. For the data reported here we looked from 505-695 nm. The beam was spatially filtered and directed onto the sample by a mirror. The sample was submerged in a waterbath. The water served to couple the PA waves to the ultrasonic transducer. The transducer has a 2.5-cm diameter circular aperture and is made for underwater use. It is a broadband device and the center frequency of its response is near 1 MHz. At 1 MHz the transducer is most sensitive to ultrasonic radiation originating about 10 cm away; therefore the transducer was placed about 10 cm from the sample. The detected signals were amplified and captured by a digitizing oscilloscope. The digitized waveforms were then downloaded to a computer and stored to disk.

IV. Data Analysis and Results

In this work, the PA spectra were constructed from the peak-to-peak amplitudes of the photoacoustic waves captured for each wavelength of light. The detected waveforms were averaged by the scope before the peak-to-peak measurement was taken. An averaged PA waveform from the reference plate is shown in Figure 4 and the peak-to-peak amplitude is identified. A PA signal from tissue is shown in Figure 5. Using the OPO, data were acquired from 505-595 nm and 605-695 nm in 5-nm steps.

Some preliminary PA spectra from white and gray matter are shown in Figure 6. (These data are the results of two measurements on a single sample and thus should be considered preliminary. Further

measurements have been planned but due to technical problems, they have not been completed in time for inclusion here). Both spectra have been normalized by the spectrum of the reference reflector (i.e., the reference spectrum defines 0 dB for this plot). The difference in decibels between the white and gray matter spectra is given in Figure 7. At 620 nm and longer wavelengths, the white matter spectrum is from 3 to 6 dB higher than the gray matter spectrum. This shows the white matter PA waveforms to have peak-to-peak amplitudes from 40% to 100% larger than that for gray matter in this region.

V. Discussion

There is a strong need to develop non-invasive techniques for diagnosing brain pathologies (e.g., injury and tumor detection). Invasive brain therapy and surgery occur in confined spaces and require precision to keep from damaging healthy tissues near the target areas. The differentiation of white and gray tissue can have important applications to these types of problems. One potential advantage of PA spectroscopy in such situations is that we are only concerned with the acoustic radiation produced by the target tissue. Unlike the case for optical radiation, soft tissues are largely transparent to ultrasonic waves and thus the signals could be detected remotely and are potentially less sensitive to alignment.

The spectra shown in this work used peak-to-peak amplitude, a relatively simple metric, to quantify the photoacoustic response. However, the waveforms from different sites, as well as at different wavelengths for the same site, display a variety of shapes. Figure 8 shows two waveforms from gray matter at different wavelengths. Considering the thickness of the samples (approx. 10 mm) and the speed of sound (approx. 1.5 mm/ μ s), reverberant echoes will follow roughly 14 μ s behind the initial PA signal. Therefore, only the first 10 μ s of the PA wavetrain can be considered "clean" signal (i.e., free of sonic reverberations). Signal processing techniques such as Fourier analysis can be applied to these early parts of the waveforms to make wider use of the ultrasonic power spectra and phase information. We are investigating more complex measures based on the ultrasonic spectra in order to obtain photoacoustic spectra that yield new or complementary information to the peak-to-peak spectra. Figure 8 shows an example of the variation in the shape of the PA waveforms. Not only do the amplitude of the waveforms differ, but the distribution of the sonic energy with time (i.e., shape) is clearly distinct as well.

VI. Conclusion

The data presented in this study show the potential of photoacoustic spectroscopy for the differentiation of white and gray brain tissues. In this work, we presented PA spectra of white and gray brain tissue using a tunable pulsed laser for the excitation. The spectra were generated from the peak-to-peak values of the captured waveforms. The variation in shape of the waveforms with excitation wavelength and tissue type indicate that more complex signal processing methods such as Fourier analysis may produce alternative ways for quantifying photoacoustic response. These new measures of photoacoustic signals may provide new information about the samples not obtainable from simple peak-to-peak values.

V. Acknowledgements

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VI. References

1. A. C. Tam, "Applications of photoacoustic sensing techniques," Reviews of Modern Physics, Vol 58 (2) pp.381-431 (1986).

Figure 1 The geometry of photoacoustic waves generated by a collimated beam in a weakly absorbing sample.

Figure 2 The geometry of photoacoustic waves generated in a strongly absorbing sample.

Figure 3 The experimental set-up for the photoacoustic acquisitions.

Figure 4 A photoacoustic waveform from the reference plate. The spectra were constructed using the peak-to-peak amplitude of the photoacoustic signals.