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Photoacoustic monitoring of tissue temperature at high temporal resolution

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ABSTRACT

Monitoring of tissue temperature is necessary for guiding energy-based medical treatments. The local temperature information is also important for the safe deposition of light/heat energy into the surrounding healthy tissue. Existing imaging modalities fail to monitor tissue temperature with high accuracy and high resolution. Photoacoustic sensing of temperature was demonstrated using Q-switched Nd:YAG laser. A temperature sensitivity of $\sim 0.15^{\circ}\text{C}$ was obtained at a temporal resolution of ~ 2 s. Photoacoustic imaging is a high-speed, high-resolution, deep tissue imaging modality for both preclinical and clinical applications. In this work, we demonstrate photoacoustic sensing of temperature at high temporal resolution order of microseconds using high repetition rate (7000 Hz) near-infrared (~ 803 nm) pulsed laser diodes. The system will find applications in radiation therapy, photothermal therapy, photodynamic therapy, etc.

Keyword: photoacoustic imaging, tissue temperature, pulsed laser diode, high temporal resolution

1. INTRODUCTION

Now-a-days there are many energy based treatments that are in use in clinics. Radiation therapy, thermotherapy, etc. involve heating the biological tissue. To control the heating, spatially as well as temporally, it is important to noninvasively monitor the deep tissue temperature in real time. This will help clinicians to reach the desired temperature to kill cancerous cells for a sufficient duration and to minimize unwanted damage to surrounding healthy cells. Imaging modalities such as magnetic resonance imaging (MRI)¹, and ultrasound echo-shifts² have been demonstrated for temperature monitoring during deep tissue thermotherapy noninvasively. Among these methods, MRI based on the temperature dependence of the proton resonance frequency, is not fast enough for real-time temperature monitoring. The ultrasound method, based on the temperature dependence of the speed of sound, suffers from low imaging contrast and displays relative temperature changes.

Photoacoustic imaging (PAI) is an advancing real-time imaging modality for surgery and biopsy guidance in clinics.³⁻⁵ PAI has several merits compared with pure optical and pure ultrasonic imaging modalities.⁶ It takes advantages of rich optical absorption contrast, high detection sensitivity, and high deep-resolution ratio. It is a promising non-ionizing hybrid imaging modality combining high optical contrast and ultrasonic resolution for both preclinical and clinical applications. In photoacoustics, a nanosecond laser pulse irradiates the sample with optical absorbers. Due to absorption of incident energy by the absorbers (typically hemoglobin, melanin, lipid, water etc.), there is a local temperature rise, which in turn produces pressure waves emitted in the form of acoustics waves. A wideband ultrasound transducer receives the photoacoustic signal outside the sample surface. If optical absorption by endogenous absorbers is weak, it results in poor PA signal. In such cases to enhance the PA signal numerous biomaterials have been reported in the far visible to NIR-I and NIR-II windows.⁷⁻¹³ Based on the excitation and detection modes, photoacoustic imaging systems have been classified in to four types: (i) photoacoustic tomography (PAT) or photoacoustic computed tomography (PACT),¹⁴⁻¹⁷ (ii) photoacoustic microscopy (PAM),¹⁸⁻²² (iii) photoacoustic endoscopy (PAE),^{23, 24} and (iv) photoacoustic nanoscopy (PAN).²⁵⁻²⁷

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Photoacoustic tomography (PAT) also reported for temperature monitoring in deep tissues noninvasively.²⁸⁻³² In PAT, one of the parameter that influences PA signal amplitude is Grüneisen parameter. A fractional change in Grüneisen parameter introduces equal change in photoacoustic signal amplitude. The Grüneisen parameter is a function of equilibrium temperature; hence PAT allows temperature measurement with high sensitivity. A temperature sensitivity of $\sim 0.15^\circ\text{C}$ at a temporal resolution of ~ 2 s was demonstrated.³² Signal averaging was done over 20 signals. The excitation source was a 532 nm Q-switched Nd:YAG laser with a repetition rate of 10 Hz, providing 6.5 ns laser pulses. The laser fluence on the sample surface was controlled to be less than 20 mJ/cm^2 at 532 nm, accordingly to the American National Standards Institute safety standards. The temporal resolution of PA temperature sensing is limited by the repetition rate of the excitation laser source. In recent years, pulsed laser diode (PLD)³³⁻³⁷ was used as a substitute to conventional Nd:YAG/OPO laser due to the fact that they are less expensive, reliable, ultra-compact, and can provide thousands of pulses in one second for real-time imaging. Demonstration of PLD based PAI systems in various applications, such as, brain imaging,^{38, 39} high-frame rate imaging⁴⁰ have already been successfully performed. In this work, we demonstrate temperature sensing at high temporal resolution order of microseconds using a photoacoustic system that takes advantage of high repetition rate (7000 Hz) of near-infrared ($\sim 803 \text{ nm}$) pulsed laser diode (PLD).

Fig. 1. (a) Schematic illustration of PLD based photoacoustic temperature sensing device, (b) Schematic illustration of the black ink and hot water phantom. PLD- Pulsed laser diode, DAQ- data acquisition card, UFA- ultrasound filter /amplifier, UST- ultrasound transducer.

2. PLD BASED PHOTOACOUSTIC TEMPERATURE SENSING DEVICE

The pulsed laser diode (PLD) based photoacoustic temperature sensing system is shown in Fig. 1(a). The laser diode is from Quantel, France. It is capable of providing ~ 136 ns pulses at a near-infrared wavelength of ~ 803 nm. The maximum pulse energy available at laser window is ~ 1.42 mJ at 7000 Hz pulse repetition rate. The driving unit (LDU) controls the PLD output power and repetition rate. The LDU consisted of a device (MTTC1410) to control temperature from LaridTech, a power supply unit (12V, PPS-11810) from Voltcraft, another tunable power supply (BT-153) from BASETech, and a simple function generator (FG250D) from Funktionsgenerator. This generator can provide a TTL signal to sync DAQ card with PLD pulsing. A transducer from Olympus NDT (V306-SU-NK-CF1.9IN) with central frequency 2.25 MHz, and 13 mm active area was used in the system to acquire A-lines. The acquired A-lines were amplified, and filtered with 1-10 MHz band filter by ultrasound filter/amplifier unit (UFA). The digitized signals were saved by the computer with 25 Ms/s data acquisition card from GaGe (compuscope 4227). The schematic of the black ink and hot water phantom sample used for demonstration is shown in Fig. 1(b). Details of the phantom and experimental results are discussed in section-3 below.

Fig. 2. (a) The measured peak-to-peak PA amplitude plot of PA signals from black ink at room temperature, (b) the measured peak-to-peak PA amplitude plot of PA signals of black ink while heating with hot water, PA signal amplitude from black ink before heating (c), and after heating (d).

3. EXPERIMENTAL RESULTS

As discussed above, photoacoustic signal originates from optical absorption. We have carried out experiments to monitor photoacoustic amplitude change when the absorber or surrounding temperature increased dynamically. The pulsed laser diode based PA sensing device shown in Fig. 1 was used for measurements. The schematic of the black ink phantom is shown in Fig. 1(b). The sample consists of two LDPE tubes: inside tube having dimensions 0.59 mm Inner diameter and 0.78 mm outer diameter was filled with black ink, and outer tube (2 mm ID and 3 mm OD) was filled with room temperature water. The sample was mounted inside a water tank for better coupling of PA signal with UST. Sample was illuminated by the PLD output operated at 7000 Hz repetition rate and 1.4 mJ pulse energy. Initially, PA signals of black ink which is at room temperature were collected continuously with 2.25 MHz UST for 5 sec. The peak-to-peak (Vp-p) amplitudes of all the 35000 A-lines were measured and plotted as a function of number of pulses, as shown in Fig. 2(a). Here Vp-p values are between the red dotted lines, which are also most same for 5 sec due to the constant temperature of black ink. Later, we injected hot water through the outer tube to heat up the black ink. While heating, we collected 70000 PA signals for 10 sec, and plotted their Vp-p values as function of number of pulses. No signal averaging was used so number of pulses is equal to number of A-lines. Here the Vp-p values up to 3 sec (~21000 pulses) corresponds to black ink at room temperature and after 3 sec the black ink temperature hence its PA amplitude raised due to hot water. After heating, the PA amplitude increased by 2-fold i.e. from 0.8 V to 1.6 V. From previous reports on photoacoustic temperature sensing, 4.4% increase in PA amplitude corresponds to 1°C raise in temperature. From the 50% increase in PA amplitude, the estimated temperature raise of black ink while heating with water is approximately 11°C. Typical PA signals of black ink before and after heating are shown in Figs. 2(c) and 2(d), respectively.

4. CONCLUSIONS

In this work, we have demonstrated the PLD based photoacoustic system for temperature sensing under dynamic conditions with high temporal resolution. A high repetition rate (7000 Hz) pulsed laser diode in the near infrared region (~803 nm) was used combined with 2.25 MHz UST detection. The sample used for demonstration was black ink, and hot water was used for instantaneous heating of black ink. We could clearly monitor the rapid temperature rise of black ink by plotting the peak-to-peak values of PA signals as a function of acquisition time. No signal averaging was used, so the fast rise of ink temperature was monitored at a temporal resolution of ~143 μ s using the proposed system. In future we aim to monitor the temperature varying at the order of millisecond to microsecond in biomaterials and biological tissue samples. The system may find applications in radiation therapy, thermal therapy, photothermal therapy, photodynamic therapy, etc.

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