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Improving the Optoacoustic Signal by Monitoring the Changes of Coupling Medium

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Abstract**—**In this paper, we discussed the coupling medium in the optoacoustic imaging. The coupling medium is placed between the scanned object and the ultrasound transducers. Water with varying temperature was used as the coupling medium. The water temperature is gradually varied between 25 to 40 degrees. This heating process is taken with care in order to avoid the bubble formation. Rise in the photoacoustic signal is noted through an unfocused transducer with frequency of 2.25 MHz as the temperature increases. The temperature rise is monitored using a NTC thermistor and the values in degrees are calculated using an embedded evaluation kit. Also the temperature is transmitted to PC through a serial communication. All these processes are synchronized using a trigger signal from the laser source.

Keywords**—**Embedded, optoacoustic, ultrasound, unfocused transducer.

I. Introduction

PHOTOACOUSTIC tomography (PAT) is a combination of high optical contrast and high ultrasonic resolution. PAT is a multimodality hybrid non-invasive imaging technique [1]. One of the key benefits of PAT is that it overcomes the disadvantages of speckle artifact and biochemical contrast in ultrasound, and the disadvantages of spatial resolution in other optical imaging [2].

Photoacoustic (PA) imaging is used in various applications such as imaging the blood vessels, diagnostic in skin disease, prostate cancer, breast cancer and rheumatoid arthritis. Many image enhancement algorithms [3] were developed to enhance the detected PA signal in image. Only the obtained signal can be delineated from the surrounding noise and artifacts; however, PA signals strength can be increased by varying the temperature of the coupling medium. Two types of electromagnetic radiations generate the PA signals: continuous wave electromagnetic waves and electromagnetic pulses and intensity. Both types of sources are used in biomedicine applications. The advantage of using short electromagnetic pulse is that they have a high signal to noise ratio and also the distance of the source can be directly detected through time resolved signals. Electromagnetic waves interact with the particles or systems that are charged by the Raman scattering, elastic scattering, absorption, etc. In this absorption environment, the absorbed energy can be converted to heat and also consumed in chemical reactions. Also these heat signals are transmitted back as fluorescence. The fluorescent effect is used in ultraviolet radiation source [4] and in other sources; the heating effect leads the absorption interaction. The absorption ability of PA detection depends on the electromagnetic wavelength, electromagnetic polarization, molecular constitution, environmental condition and ion density

Traditional optical imaging methods, such as optical coherence tomography, have high imaging contrast but low imaging depth compared to PAT [5]. PAT is a hybrid imaging modality which uses both optical and acoustic properties to form the image. The PAT method for diagnostic applications was used in skin cancer, prostate cancer, breast cancer and rheumatoid arthritis [6], [7]. A 3D image can be obtained by moving a single transducer or placing a various number of transducers in a pattern to reconstruct PA image. For imaging application, PAT is chosen mainly for small animals and sample of tissue due to its property of limited angular view and distortion in image caused due to its property. Therefore, various types of transducers were researched to solve this challenging task. In recent studies [8], a ring shaped two dimensional array probe is used to achieve a 3D full angular view for image reconstruction. In another study [9], a high speed cross sectional imaging of rat deep brain is imaged using the custom developed PA computed tomography and the main advantage of this system was that it uses internal illumination with optical fiber rather than external light source which delivers the low light to the deep brain. This PACT system also has the advantage of imaging the organs and cerebral cortex of small animals extensively.

In the last decade, many innovative forms of PAT have been developed and based on the PA image reconstruction methods; it can be categorized into three major modalities. The photoacoustic computed tomography (PACT), PAT using acoustic lens system and photoacoustic microscopy (PAM) are those three modalities. The PAM detects the incoming PA signal from the transducers' focal zone and uses a positively focused ultrasonic transducer. One dimensional image is formed for each detection. The lateral resolution detection method determines the type of PAM. There are basically two types of PAM namely, optical resolution photoacoustic microscopy (OR-PAM) and acoustic resolution photoacoustic microscopy (AR-PAM). PAT that uses the acoustic lens is analogous to optical imaging system. However, it replaces the optical lens to an acoustic lens. These acoustic pressures are calculated or measured on the imaging plane. Scanning using a single transducer over an object can mainly be time consuming. Thus, to get a 2D or 3D PA signal in a quick succession, the acoustic array is used. In this report, we used a

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single element transducer to measure the incoming PA signal. This single element transducer is a commercially available and it is briefly explained in the next sections. In case of 2D PA imaging systems, the array transducers are used and the collected PA signal then goes through the image reconstruction algorithms. The universal back projection algorithm has been used in the developed real time PAT system [3]. The image quality and imaging speed mainly rely on the PAI reconstruction algorithm. The pressure wave generated by a finite electromagnetic width pulse generally corresponds to convolution of pulse profile. Therefore the delta electromagnetic pulse illumination is considered. The large planar detector and line detector are used in PA image reconstruction. These detectors use the principle of radon transformation. The PA reconstructions also depend on the particular scanning geometrics of this detector. The planar detector scans tangentially over a sphere and line detector scans perpendicularly over circle. This sphere and circle usually encloses the object. The accurate reconstruction algorithms mostly require unbounded open surfaces such as a cylinder or infinite plane and enclosed surface such as spheres. In the practically developed PAT reconstruction algorithms, both time domain and frequency domain formulations are implemented. The most basic PA reconstruction algorithm is the synthetic aperture also known as delay and sum which is mainly used in the ultrasound imaging technique. It projects the time domain original signal and it is the simple back projection algorithm. It projects the time domain original signal to the imaging region over the spherical shells (centered at each detection point) and adding them together. In this summation process, the condition approximates that the object is close to the scanning center and far from detector. The inverse radon transformation is used to derive the filtered back projection reconstruction algorithms. Many geometrics of the PAT systems and their coupling medium contribute to their overall performance. Some of the different geometrical proposed literature are circular [10], linear [11], hemispherical [12], planar [13] and curved [14] measurement apertures. The filtered back projection algorithm was derived based on the property of inverse Radon transformation. However, the frequency domain reconstruction algorithm can be implemented in an effective way compared to time domain by using k-space method for linear [11] and planar [13] scanning. Mostly in these different geometrics systems, water is used as the coupling medium to optimize transmission of sound waves from ultrasound transducers to subject. Also in most of these systems, the temperature of water was not accounted for the rise in the PA signal.

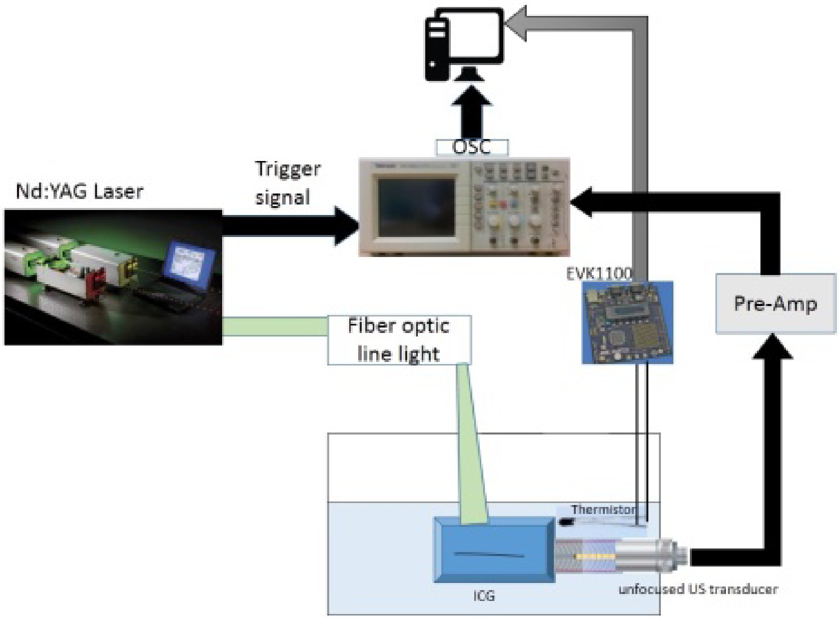

Fig. 1 Temperature controlled PA system setup using unfocused ultrasound transducer

II. Methods

A. PA System

A pulsed Nd:YAG (Continuum Surelite III–10, USA) laser source was chosen to operate at 780 nm with 1 Hz of laser pulse duration between each excitation. The laser power for this experiment is chosen to be 7 mJ/cm^2. In Fig. 1, the PAT system setup using unfocused transducer is shown. In order to measure the optoacoustic signal, an unfocused transducer (Olympus Panametrics-NDT V323) is placed next to the subject near the sample stage. The unfocused transducer has a frequency of 2.25 MHz and nominal element size of 0.25 inches. In a rectangular shaped water tank, the heated water is circulated periodically through two valves. This process needed precautions to avoid bubble formation in tank. The indocyanine green is selected as the agent for this phantom experiment. The indocyanine green solution is injected into a polymer tube with an external diameter of 0.7 mm and internal diameter of 0.5 mm to imitate a blood vessel. The ends of polymer tube are then sealed with indocyanine green inside it. The tube is placed in a holder so that the position of it does not change during the entire experiment. The unfocused transducer is placed adjacent to the sample and fixed to a holder. Other end of the transducer is connected to an ultrasonic preamplifier (Olympus Panametrics - NDT) with 54 dB gain.

The preamplifier is then connected to an oscilloscope (TDS2002) with 60 MHz bandwidth and sampling rate up to 2 GS/s. Later it transmits the acquired optoacoustic signal to the PC via the GPIB connection. In the PC the LabView software (2010; National Instruments) averages the PA signal for image reconstruction In order to measure the temperature in water tank a thermistor (NTCLE100E3103HB0) with 10Kohms 3% Radial is placed next to the sample. The signal from the thermistor is measured and converted as temperature in degrees using an embedded evaluation kit (Atmel 32-bit AVR UC3A microcontroller) and the temperature program is developed in AVR Studio software.

B. Absorption of Electromagnetic and Ultrasonic Waves

PA pressure wave is generated with the help of electromagnetic pulse which usually has a pulse width τ. This pulse width is so short even the thermal diffusion can be neglected and this principle is called thermal confinement condition [15].

$$\tau < \tau_{th} = \frac{d_c^2}{4D_T}, \tag{1}$$

where τ_{th} is the threshold of thermal confinement, D_T is the thermal diffusivity which is approximately 0.14 mm^2/s for tissue [16], and d_c is the spatial resolution (targeted characteristics dimension). Under this condition, PA pressure is generated in non-viscous medium and an acoustically homogenous medium [17], [18].

$$\nabla^2 p(r,t) - \frac{1}{v_s^2}\frac{\partial^2}{\partial t^2} p(r,t) = -\frac{\beta}{C_p}\frac{\partial}{\partial t} H(r,t), \tag{2}$$

where C_p is the isobaric specific heat, H(*r, t*) is the thermal energy converted at spatial time *t* and position *r* which is also known as heating function, v_s is the acoustic speed of sound, and β is the isobaric volume expansion coefficient in K^{-1}.

The generated amount of heat in the tissue is proportional to the strength of the radiation. For radiofrequency and optical illuminations the explicit expression of heating function is:

$$H(r,t) = \begin{cases} \mu_a(r)\Phi(r,t) \\ \sigma(r) < E^2(r,t) \end{cases} \tag{3}$$

where Φ and μ are the optical radiation fluence rate and absorption coefficient respectively, *E* is the electrical field strength and σ is the conductivity which represents the short-time averaging [19].

$$H(r,t) = \rho(r) \bullet SPAR(r,t) \tag{4}$$

The radio frequency heating is usually mentioned by the specific absorption rate (SPAR) and its relation to *H*(*r*,*t*) is given in (4). In most cases, the condition acoustic stress confinement is defined as the electromagnetic pulse is very short that the volume expansion and thermal diffusion during the illumination period is negligible. This acoustic stress confinement is given as,

$$\tau < \tau_{st} = \frac{d_c}{v_s}, \tag{5}$$

where τ_{st} is the stress confinement threshold. Under the stress and thermal confinement condition the delta function is the heating time. Therefore the initial pressure P_0 at the location ***r*** after absorption of electromagnetic energy can be calculated by [20]

$$P_0(r) = \frac{\beta}{\kappa_t \rho C_\upsilon} A(r) = \frac{v_s^2 \beta}{C_p} A(r) = \Gamma A(r) \tag{6}$$

where C_v is the isochoric specific heat and K_t is the isothermal compressibility. A(r) is the absorbed energy density that is transformed into heat at sample location ***r*** and **r** is known as the Grueneisen parameter which changes as the temperature changes and it is dimensionless.

C. Workflow of the Monitoring the Temperature and Acquiring the Optoacoustic Signal

The laser source sends a trigger signal to the oscilloscope and it receives the PA signal as soon the laser light irradiates and the ultrasound signal retransmitted back from the subject.

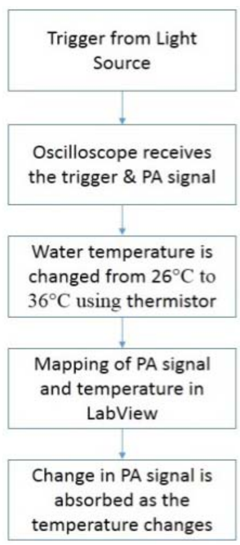

Fig. 2 Workflow of temperature controlled PA system

The GPIB module is used in transmission of trigger and PA signal to PC. The incoming real time values are stored in PC. Now the water temperature is varied by the incoming hot water to the rectangular tank. The water temperature is monitored using the NTC thermistor with the help of EVK1100 embedded evaluation kit. This microcontroller from Atmel transmits the temperature value to the same LabView environment in PC through serial communication. All these data gathering process are synchronized according to the temperature value. Finally the obtained PA Signal and the temperature rises relation are plotted.

III. Results

The PA signals were acquired at 780-800 nm wavelength to test the ability of the developed system using the indocyanine green injected in a transparent polymer tube. The water temperature was increased from 26 °C to 37 °C in the tank and PA signals were acquired in the LabView environment. The change in PA signals at these temperatures is shown in Fig. 3.

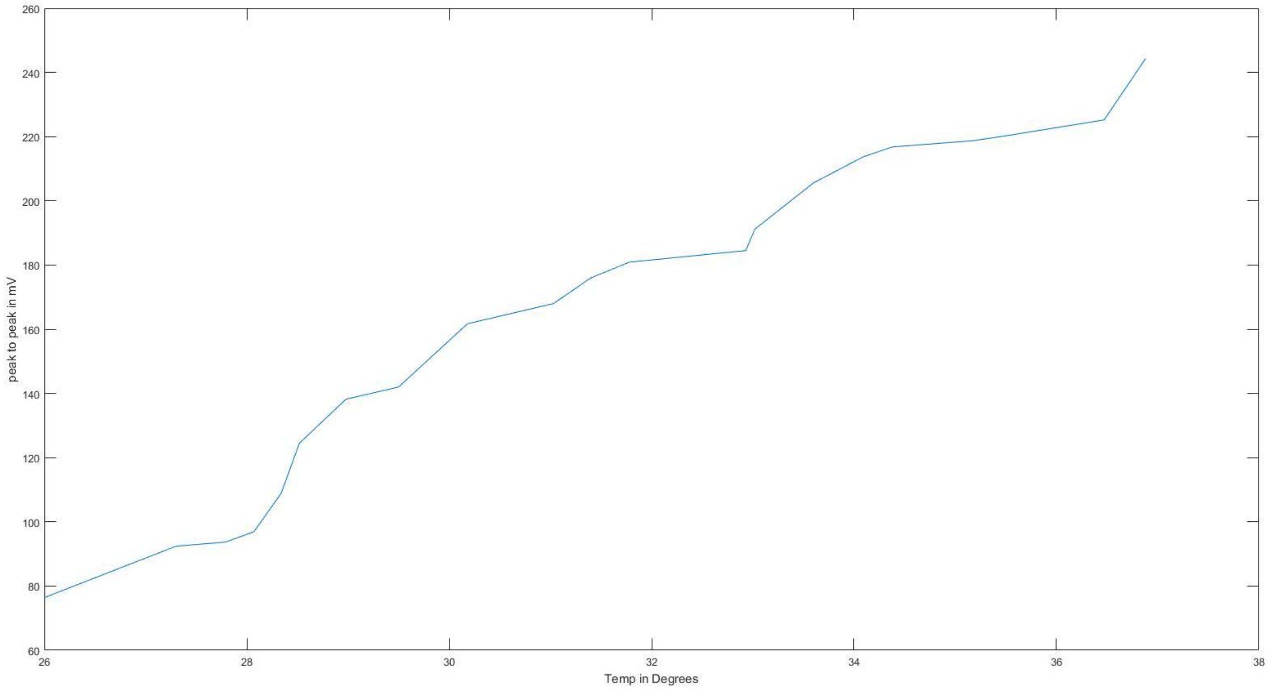

Fig. 3 PA signal response as the change in coupling medium

The indocyanine green is loaded in the transparent tube and the change in PA signal is noted as the light is irradiated. As the temperature is varied from 26 °C to 37 °C, the rise in PA signal is approximately 3.5 times over 11 °C.

IV. Discussion

The change in PA amplitude shows that the water temperature can make a lot of difference in final PA signal. This concept of placing an unfocused ultrasonic transducer is limited in the number of PA signals. It is more over like a one dimensional study but in future we planned to conduct this study by changing the temperature of the coupling medium and placing a linear array transducer and acquiring two dimensional PA images. In the next step the indocyanine green will be replaced with drug loaded contrast agent such as MPEG – Micell infrared and other agents. Various excitation wavelengths will be used depending on the nature of these contrast agents. Also in the future the change in speed of sound should be accounted in the final rise in amplitude. Generally the speed of sound changes as the temperature in water changes. From the previous case studies [21], it has been found out that the speed of sound can contribute to a 0.6% change in the final image of PAT. The varying real time speed of sound is monitored and applied in universal back projection equations [22], [23]. The v_s is the speed of sound in this back projection algorithm. Also in future a rat with developed tumor is exposed to the laser light source and the contrast target agent are injected. The agents accumulate on the infected cell area and the water temperature is varied along with the speed of sound and finally the PAT images will be acquired.

V. Conclusion

A study about the changes in the coupling medium of the PAT has been conducted. An unfocused ultrasound transducer was placed close to the subject and as the light irradiates the polymer tube the indocyanine green contrast agent excites. The transducer acquires the incoming PA signal and sends it to the oscilloscope and later the digital values are transmitted to the system using GPIB module. The temperature is calculated and varied in the tank and the varying values are transmitted to the system using an embedded microcontroller kit. The results show that optoacoustic signal can be improved by varying the temperature in coupling medium. In future studies, the two dimensional optoacoustic images are acquired using the linear array transducer and improved PA images can be obtained.

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