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Research paper

Effect of light pulse width on frequency characteristics of photoacoustic signal – an experimental study using a pulse-width tunable LED-based photoacoustic imaging system

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Abstract

Photoacoustic imaging is a hybrid technique that bridges the depth limits of ballistic optical imaging and the resolution limits of diffuse optical imaging. Using the acoustic waves generated in response to the absorption of pulsed light, it provides noninvasive high-resolution images of optical absorption at depths of several centimeters. This promising technique with optical contrast and ultrasonic resolution has shown potential in wide range of clinical and preclinical applications. In this work, we experimentally study the influence of light pulse width on frequency characteristics of photoacoustic signal, using an LED-based photoacoustic imaging system. We acquired photoacoustic image of the flat surface of a pencil lead at different excitation light pulse widths and the resulting frequency response of the photoacoustic temporal signal is compared with the product of Fourier transform of the light pulse and the frequency response of the ultrasound detector. Our results give a confirmation that frequency characteristics of photoacoustic signal is directly dependent on the combined response of light pulse frequencies and the frequency bandwidth of the ultrasound probe. Also, our results show that it is critical to tune pulse width of excitation light based on ultrasound probe's frequency response, for efficient data acquisition in multiscale photoacoustic imaging.

Keywords: *Frequency Response; LED; Photoacoustic Imaging; Pulse Width; Ultrasound Imaging.*

1. Introduction

Photoacoustic (PA) imaging is a hybrid imaging modality that offers optical spectroscopic contrast and ultrasonic resolution [1,2]. In PA imaging, pulsed light absorbed by the target emits ultrasound (US) by a thermoelastic mechanism. This US is detected and used to build up an image. PA imaging has emerged as a powerful biomedical imaging modality in the last decade with tremendous potential for wide range of clinical and pre-clinical applications [3]. PA imaging can be easily combined with pulse-echo US imaging, since the detection part required for both techniques is same. A dual mode system providing complementary contrast delivers the advantages of both modalities. A US image superimposed on a PA image offers anatomical and structural information combined with unprecedented functional details, which consequently has the potential to improve specificity and sensitivity in diagnosing various diseases [3].

Properties of excitation light are a critical factor that affects the PA image quality [4]. Considering the stress confinement requirement for PA signal generation, illumination sources that can deliver light pulses with low pulse width (5 – 100 ns) are generally preferred for PA imaging systems. However, the effect of pulse width on frequency response of PA signal is not yet explored in detail. Especially, it is of paramount importance to study the impact of pulse width in PA imaging systems utilizing conventional clinical US imaging probes with limited bandwidth (2 – 12 MHz). In this work, we experimentally study the influence of light pulse width on frequency characteristics of PA signal, using a commercially available LED-based PA imaging system with pulse width tuning capability. In a phantom experiment, we acquired PA signal from the flat surface of a pencil lead at different excitation light pulse widths and the resulting frequency response of the PA temporal signal is compared with the product of Fourier transform of the light pulse and the frequency response of the US detector.

2. Materials and methods

2.1. Equipment and setup

We used LED-based PA and US imaging system (AcousticX, CYBERDYNE Inc, Tsukuba, Japan) for all the experiments [5 - 7]. AcousticX is a commercially available LED-based PA/US system, which can perform interleaved PA and US measurements at video rate (Fig. 1). Contrary to conventional PA imaging systems, AcousticX uses LED light sources to illuminate the tissue. Several LED chips are connected in series to build arrays that can produce optical energy and wavelengths required for PA imaging [8].

In this work, we used LED arrays with a wavelength of 850 nm. Size of each LED chip is 1 mm^2 and these were arranged in four rows (36 chips in each row) to develop an array that can generate optical energy of 200 µj per pulse at a pulse width of 70ns . Two of these arrays were fixed on both sides of a linear array US probe (10 MHz) to perform PA/US measurements in reflection mode (Fig. 1). For driving these arrays to obtain high power light output, high voltage is applied to LED chips, resulting in a peak current flow of 20 A. LED chips can be driven at a maximum pulse repetition frequency (PRF) of 4 KHz. One LED array provides an illumination area of 50 mm × 7mm, which covers the whole aperture of the linear array US probe (38.4 mm). Pulse duration of LED light is tunable in AcousticX. In this work, we performed a phantom experiment in which pulse width is tuned from 30 – 110 ns. In AcousticX, pulse width cannot be set lower than 30 ns. This is a technical limitation because of the characteristics of MOSFET used for switching LED elements on and off.

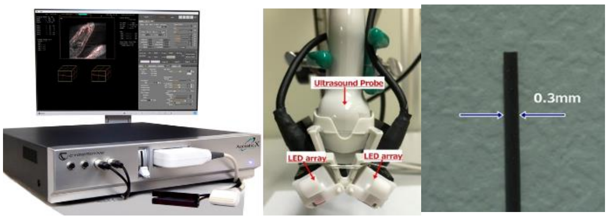

Fig. 1: Photograph of AcousticX System (Left), Arrangement of US Probe and LED Array (Middle) and Pencil Lead (Right).

2.2. Phantom experiment

Figure 2 shows the details of the phantom and the technical details of AcousticX. A pencil lead (0.3 mm) was kept in a water tank in such a way that the flat surface of the lead was facing the imaging plane of the US/PA probe. Middle element (65th US detector) of the US probe was aligned to the flat surface of the pencil lead tip (Fig.1).

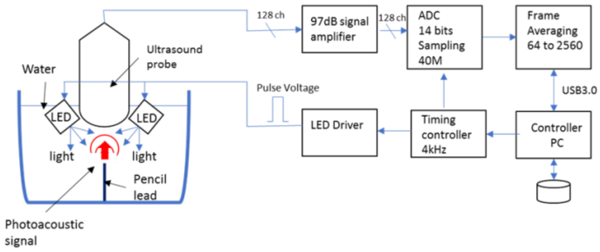

Fig. 2: Phantom Setup and Technical Block Diagram of AcousticX System.

Pulse width of LED arrays was tuned from 30 ns to 110 ns and PA images were saved for all pulse widths. Averaged PA rf data (6400 times) from 65th element was acquired and analysed in frequency domain for studying the effect of light pulse width on frequency characteristics of the PA temporal signal. Experiments were performed at four different pulse widths; 30ns, 50ns, 70ns, and 110ns. Optical waveforms were detected using a fast switching photo diode S5973-01(Hamamatsu Photonics, Shizuoka, Japan) connected to a digital oscilloscope (MDO3054, Tektronix, OR, USA). Optical waveforms at all pulse widths were Fourier transformed and multiplied with the reception bandwidth of 10s MHz US probe used for the experiments.

3. Results and discussion

Figure 3 shows optical waveforms at multiple pulse widths and fig 4 shows Fourier transformed data of light pulses at these pulse widths. Full width half maximum (FWHM) of light pulses with pulse width 30 ns, 50 ns, 70 ns, and 110 ns were found to be 27.1 ns, 42.6 ns, 68.1 ns, and 117 ns respectively. Zero crossing points in the Fourier transformed optical signal were matching well with the FWHM as expected (for example, zero cross point for 50 ns pulse width is 24.5 MHz and 1/42.6 ns =23.4 MHz). Figure 5 shows acquired PA raw signals (65th element) from the pencil lead at different pulse widths. It is clear from the time traces that the PA signal is broadening when the pulse width is increased. It is evident that high frequency content in the PA signal is reduced when pulse width of light is increased. Amplitude of PA signal is different in these because of the light pulse energy difference when the pulse width is varied. However, this difference is not critical and won't affect the frequency analysis performed in this work.

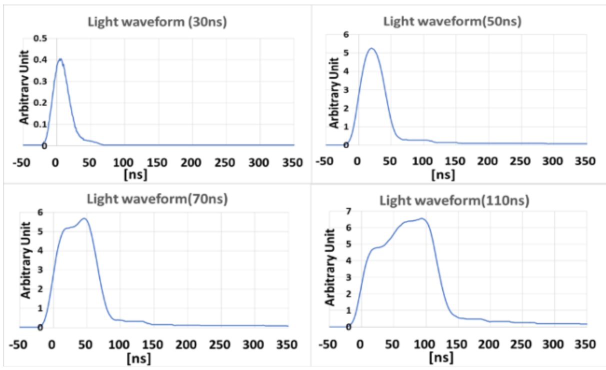

Fig. 3: Light Waveforms at Multiple Pulse Widths.

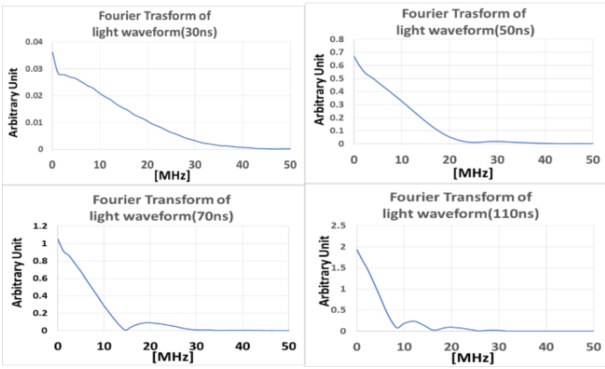

Fig. 4: Fourier Transforms of Light Waveforms at Multiple Pulse Widths.

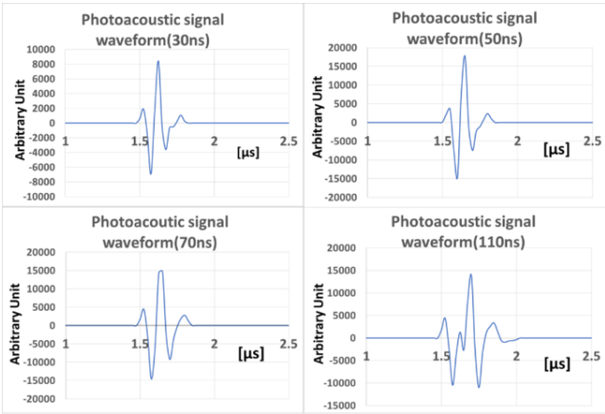

Fig. 5: PA Signal From Pencil Lead Acquired at Multiple Pulse Widths.

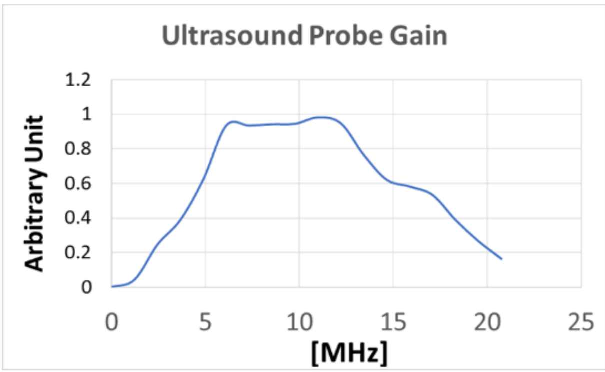

Fig. 6: Frequency Response of the US Linear Array Probe.

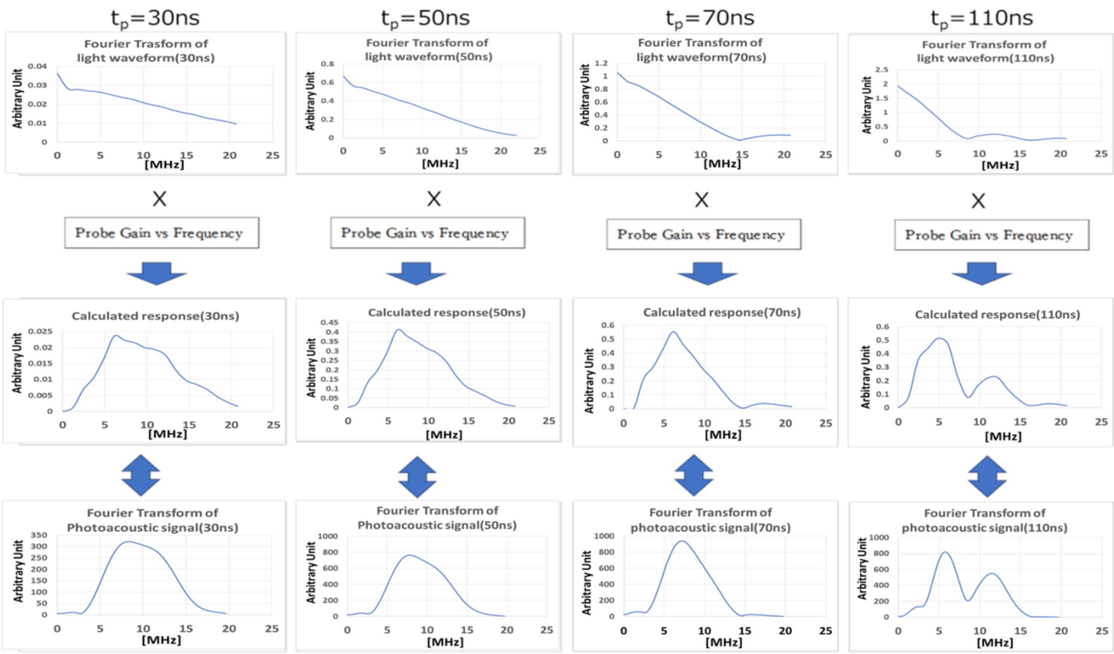

Fig. 7: Effect of Pulse Width on PA Signal Frequency Characteristics. Row 1 = 30 Ns, Row 2 = 50 Ns, Row 3 = 70 Ns, Row 4 = 110 Ns, Probe Gain vs. Frequency = Frequency Response of the US Probe, Tp = Pulse Width.). Multiplying Fourier Transform of the Optical Pulse and the Frequency Response of the Ultrasonic Probe Obtain the Calculated Response for Each Frequency.

Frequency response (Fig. 6) of the linear array US probe was measured using the method described by Xia et al [9]. Highest gain is found to be approximately at 10 MHz. Fig. 7 shows the effect of light pulse width on PA signal frequency characteristics. At all four pulse widths (30 ns, 50 ns, 70 ns, and 110 ns), the calculated response is obtained by multiplying Fourier transform of the optical pulse and the frequency response of the ultrasonic probe for each frequency. The calculated response is corresponding well with the frequency characteristics of the PA signal generated from the pencil lead phantom.

Our results show that frequency response and potentially spatial resolution in PA imaging is directly dependent on optical pulse width and the frequency response of the US detector in use. It can be concluded that it is not necessarily important to use extremely low pulse width light pulses for PA imaging, considering the frequency response limit of the US detectors. Since linear array US probes with limited bandwidth are commonly used for ultrasonography in clinics [10], our results have a direct impact in potential clinical translation of PA imaging.

Frequency response of PA signal is also dependent on the size and shape of the optical absorbers. In this study, we focused on PA signals generated by absorbers with flat surface (flat surface of pencil lead tip). A study with optical absorbers of different size and shape may be interesting, but this is out of scope of this paper. When using a linear array US probe as in this study, optimum pulse width for different transducer elements will be different. However, for transducer elements closer to the center of the US probe, which is perpendicular to the plane of optical absorber (pencil lead), optimum pulse width is expected to be similar. Our future studies will evaluate the effect of pulse width on frequency characteristics of PA signal acquired by different elements in a US probe.

Optical and acoustic attenuation are other important factors affecting PA imaging depth and contrast [10]. For an optical wavelength of 700 nm and US signal frequency of 10 MHz (assuming acoustic attenuation of 0.75 dB cm^{-1} MHz^{-1}), the total attenuation owing to both optical and acoustic attenuation is thus at least one order of magnitude per centimeter. Thus, it is clear that extremely noise sensitive data acquisition system is also a prerequisite for deep tissue PA imaging. Spatial resolution of PA imaging is also limited by the acoustic attenuation of tissue [10]. However, other factors such as detector bandwidth, element size and the detection aperture can be limiting factors in practice. It is of paramount importance to develop US probes with broad bandwidth and spatial sampling requirements suitable for PA detection.

4. Conclusion

Results give a direct confirmation that frequency characteristics of PA signal is dependent on the combined response of light pulse width and the frequency bandwidth of the US probe. Also, our results show that it is critical to tune pulse width of excitation light based on US probe's frequency response. Our findings have profound impact on the design of portable PA imaging systems for clinical applications.

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