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Coherent Photoacoustic-Ultrasound Correlation and Imaging

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Abstract—Both photoacoustics and ultrasound have been researched extensively but separately. In this paper, we report an initial study on the coherent correlation between pulsed photoacoustic wave and pulse-echo ultrasound wave. By illuminating an object with pulsed-laser and external ultrasound sequentially, both the endogenous photoacoustic wave and pulse-echo ultrasound wave are received and coherently correlated, demonstrating enhanced signal-to-noise ratio. Image contrast of the proposed coherent photoacoustic-ultrasound imaging is also demonstrated to be improved significantly on vessel-mimicking phantom, due to fusion of the optical absorption and ultrasound reflection contrasts by coherent correlation than either conventional laser-induced photoacoustic imaging or pulse-echo ultrasound imaging separately.

Index Terms—Photoacoustic imaging, ultrasound, coherent correlation, signal-to-noise ratio, image contrast.

I. INTRODUCTION

PHOTOACOUSTIC and thermoacoustic effects refer to the acoustic generation thermoelastically induced by pulsed electromagnetic wave, e.g. laser, microwave, or very recently proposed magnetic mediation [1]-[4]. In the recent decade, photoacoustic technique shows significant potentials for biomedical sensing and imaging, ranging from contrast-enhanced molecular imaging to whole body tomography of small animals [5]-[12]. Although photoacoustic imaging could break through the optical diffusion limit by converting photons to ultrasound and sustaining high spatial resolution in deep tissue, the sensitive detection of the weak photoacoustic signal is a long-standing challenge especially for deep tissue imaging [13], due to strong optical scattering/absorption, very low energy conversion efficiency from optical to acoustic energy and strict ANSI safety standard limit ($<20 \text{ mJ/cm}^2$) [14]. In a typical photoacoustic imaging system, a pulsed laser will illuminate the sample to induce the transient acoustic emission, which will be detected by ultrasound transducers for image reconstruction. Due to sharing the same

Fig. 1. (a) Diagrams of the coherent PAUS correlation, where the object is excited by both a pulsed laser and external ultrasound. (b) Schematic of the incoherent detection (top), and coherent PAUS correlation including time-shift, multiplication and integration (bottom), where * represents the convolution.

ultrasound components with conventional pulse-echo ultrasound imaging, recent studies have demonstrated the feasibility of photoacoustic-ultrasound dual-modality imaging approaches [15]-[20]. However, these dual-modality approaches all separately explore the pulsed photoacoustic wave and pulse-echo ultrasound wave for complementary imaging reconstructions. Up to now, the coherent correlation between endogenous photoacoustic wave and exogenous ultrasound wave has been an untapped area to be explored.

In this paper, we report the initial research on the study of intrinsic physical correlation between endogenous photoacoustic wave and exogenous ultrasound wave coming from the same object by fusing the optical absorption and ultrasound reflection contrasts based on the coherent detection approach, see Fig. 1. The proposed coherent photoacoustic-ultrasound (PAUS) correlation is implemented by cross-correlating (multiplication and integration) the two signals to enhance the weak PA signal and suppress the uncorrelated strong noise significantly, leading to significantly enhanced signal-to-noise ratio (SNR). The proposed coherent PAUS imaging is also demonstrated through a vessel-mimicking phantom experiment with improved contrast significantly than either conventional pulsed photoacoustic imaging or pulse-echo ultrasound imaging separately.

II. METHODS AND MATERIALS

A. Theory of Coherent PAUS Correlation

In communication, radar and sonar systems, coherent detection (also called matched filtering) is usually applied to recover the weak received signal $r(t)$ immersed in the white

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Gaussian noise introduced by the communication channel [21]. Specifically, a template signal $s(t)$ that is a replica of the transmitted signal highly correlated with the received signal is used to cross-correlate with the received signal $r(t)$ to achieve maximum SNR:

$$\langle s, r \rangle(t) = \int_{-\infty}^{+\infty} s^*(t) \times r(t + \tau) d\tau, \quad (1)$$

where $s^*(t)$ is the complex conjugate of $s(t)$. In a photoacoustic procedure, the laser-induced photoacoustic wave $p(r, t)$ could be treated as the weak received signal suffering the strong noise induced in the acoustic channel. To optimally detect the weak $p(r, t)$, a replica of the true photoacoustic signal is required, which is however physically not available. Here we propose a method to obtain a highly correlated template signal by transmitting and receiving the pulse-echo ultrasound signal $u(r, t)$ with controlled similar pattern to the photoacoustic signal coming from the same object and experiencing the same acoustic channel response.

Firstly the pattern (time domain waveform and frequency domain spectrum) of the photoacoustic signal should be estimated. As shown in Fig. 1(a), using ultra-short laser illumination, the induced photoacoustic wave $p(r, t)$ in a non-viscous medium could be described as [22]:

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

where $H(r, t) = \mu_a(r) \Phi(r, t)$ is the heating function, defining the thermal energy deposited at position r and time t by the laser illumination related with the optical absorption coefficient μ_a and optical radiation fluence rate Φ , C_p is the specific heat, β is the volume expansion coefficient, and v_s is the acoustic velocity. The solution of the wave equation using Green function approach is:

$$p(r, t) = \frac{1}{4\pi v_s^2} \frac{\partial}{\partial t} \left[\frac{1}{|r - r'|} \int dr' H\left(r', t - \frac{|r - r'|}{v_s}\right) \right]. \quad (3)$$

According to (3), the detected pressure at location r and time t comes from sources over a spherical shell centered at r with a radius of $|r - r'|$. For a spherical absorber with radius a , the photoacoustic wave could have an analytical solution [17]:

$$p(r, t) = H(r) U(a - |R - v_s t|) (R - v_s t) / 2R, \quad (4)$$

where $U(x) = \begin{cases} 1, & x \geq 0 \\ 0, & x < 0 \end{cases}$.

Here R is the distance between the absorber and the detector. It is predicted that the pulse width of the 'N-shape' photoacoustic signal is proportional to the size of the absorber, i.e. the laser spot size when the object is much larger. In fact, the photoacoustic signal in real situation $p_r(r, t)$ also depends on the unknown object's properties, and suffering unknown acoustic channel impulse response $I(r, t)$, which could be expressed as:

$$p_r(r, t) = I(r, t) * p(r, t) + N_1(r, t), \quad (5)$$

where $I(r, t)$ is related with the unknown object's properties, acoustic channel's attenuation, distortion, and ultrasound transducer's frequency response. $N_1(r, t)$ is related with the additive white Gaussian noise of acoustic transmission channel. The one-way propagation delay of photoacoustic signal from the object to the detector is $\tau_p = d/v_s$ with distance d and acoustic speed v_s of 1.5 mm/ μ s, as shown in Fig. 1(b). A template signal that is highly correlated with the real photoacoustic signal is to be generated. It should come from the same object, and experience the same acoustic channel impulse response and transducer's frequency response. Therefore, here we employ an external ultrasound signal $u(r, t)$, which is designed to highly resemble the photoacoustic signal: $u(r, t) \approx p(r, t)$. Practically, we can transmit a controlled ultrasound signal, which has similar waveform and spectrum as the photoacoustic signal as much as possible. Then the received pulse-echo ultrasound signal $u_r(r, t)$ is expressed as:

$$u_r(r, t) = \Gamma \times I(r, t) * u(r, t) + N_2(r, t), \quad (6)$$

where Γ is the reflection coefficient due to the acoustic impedance mismatch, and the round-trip propagation delay of the pulse-echo ultrasound signal is $\tau_u = 2d/v_s$, then we have $\tau_u = 2\tau_p$. According to (5) and (6), the photoacoustic signal and ultrasound signal are highly correlated, because they are from same object, experiencing the same acoustic channel and ultrasound transducer's same frequency response, i.e. sharing the same unknown $I(r, t)$.

In conventional photoacoustic imaging and ultrasound imaging, as well as the recently proposed dual-modality PAUS imaging [15]-[20], the laser-induced photoacoustic signal and pulse-echo ultrasound signal are processed separately to acquire two independent images. In this paper, we propose to coherently correlate these two signals that are highly correlated based on the above analysis as shown at the bottom of Fig. 1(b), to achieve significantly enhanced SNR and image contrast through cross-correlation:

$$\text{PAUS}(r, t) = \langle u_r(r), p_r(r) \rangle(t) = \int_{-\infty}^{+\infty} u_r^*(r, t) \times p_r(r, t + \tau) d\tau.$$

(7) signals received by the transducer and pulser-receiver in its

Similar to coherent detection in communication, radar and sonar systems, coherent PAUS correlation is able to significantly improve the detection SNR of received signals by integrating the weak but correlated signal pattern, and suppressing the strong but uncorrelated noise and interference. Moreover, the coherent correlation between photoacoustic and pulse-echo ultrasound signals fuses optical absorption and ultrasound reflection from the same object, which is expected to significantly improve the image contrast. In addition, considering the propagation delay relationship $d = v_s \Delta \tau = v_s (\tau_u - \tau_p)$, the depth information could be extracted accurately by performing both the forward and backward cross-correlations as shown in Fig. 1(b), where the distance between two peaks indicates the accurate depth information. Next we will demonstrate the experiments of coherent PAUS correlation and preliminary imaging results.

B. Experimental Setup

The diagram of the experimental setup for coherent PAUS correlation and imaging is shown in Fig. 2. A Q-switched pulsed laser (FDSS 532-1000, CryLaS, GmbH) with 532 nm wavelength and 1.8 ns pulse width is used to provide the light source. The output laser beam is attenuated by a neutral density filter (NDC-50C-2M, Thorlabs) and then focused into the fiber collimator by a condenser lens (LB1471, Thorlabs). To handle the high peak power laser, multi-mode fiber is adopted. The output of the multi-mode fiber (MHP550L02, Thorlabs) is focused by another pair of condenser lens to a spot with 3 mm diameter, generating 'N-shape' photoacoustic signal of 0.5 MHz central frequency based on analytic solution. Then a beam splitter and a photodiode (DET10A, Thorlabs) are used to monitor the laser intensity fluctuation. The vessel-mimicking phantom is a silicone tube (outer diameter: 3 mm, inner diameter: 2.2 mm) filled with the porcine blood pumped by a syringe, which is designed to model the brain superior sagittal sinus (SSS), human's carotid, jugular with similar vessel diameter (1~5 mm) and measured photoacoustic signal waveform [23-24]. The phantom is immersed in water for optimum light transparency and acoustic coupling. A focused ultrasound transducer (V303-SU, Olympus, central frequency: 0.9 MHz, -6 dB bandwidth: 59.74%, normalized sensitivity at 0.5 MHz: 20%) driven by an ultrasound pulser-receiver (5077PR, Olympus) working in its transmission mode is used to excite the exogenous ultrasound signal, which is matched to the predicted photoacoustic signal's central frequency, and receives both the laser-induced photoacoustic wave and pulse-echo ultrasound wave with pulser-receiver working in its receiving mode sequentially and separately (In some cases, both signals can be recorded at the same time but resolved in time because they appear at different time locations). Both the pulsed laser and pulser-receiver in its transmission mode are sequentially triggered by a function generator (33250A, Agilent) with two TTL trigger signals. Then the acoustic

Fig. 2. Experimental setup of the coherent PAUS correlation and imaging. ConL, condenser lens; FC, fiber collimator; MMF, multi-mode fiber; ND, neutral density; BS, beam splitter; PD, photodiode; US, ultrasound transducer.

Fig. 3. (a) Measured time-domain photoacoustic and ultrasound signals in high SNR situation for system evaluation. (b) The spectrums of them with similar central frequency and bandwidth.

receiving mode are recorded by an oscilloscope (WaveRunner 640Zi, LeCroy) and sent to PC for post data-processing. The water tank could be moved by the XY translation stage (XYR1, Thorlabs) for raster scanning to acquire imaging data. Before the measurement, laser focusing and ultrasound transducer are well aligned by manually tuning the position of the ultrasound transducer until the maximum photoacoustic signal is achieved and observed from oscilloscope. To identify the photoacoustic and pulse-echo ultrasound signals from laser burst induced jitter noise, proper time-gating is applied to remove the unwanted interference before the coherent PAUS correlation and image reconstruction. Moreover, the laser-induced jitter noise is uncorrelated with the photoacoustic and pulse-echo ultrasound signals, and could be easily suppressed by the proposed correlated PAUS approach.

III. RESULTS

A. System Evaluation

Before performing the coherent PAUS correlation and imaging experiments, the validity evaluation of the proposed system is conducted by detecting both the photoacoustic wave and ultrasound wave in high SNR situation shown in Fig. 3(a),

where the signals are aligned for intuitive comparison. The Butterworth filter with cut-off frequency at 1 MHz) of the

Fig. 4. The separately detected (a) pulsed photoacoustic wave, (b) pulse-echo ultrasound wave, and (c) the coherent PAUS correlation wave using backward cross-correlation. (d) and (e) show the low-pass filtered signals of (c) and (a) respectively. In some extreme low signal SNR scenario, (f) pulsed photoacoustic wave, (g) pulse-echo ultrasound wave, and (h) the coherent PAUS correlation using both forward cross-correlation and backward cross-correlation. The (i) and (j) show the low-pass filtered signals of (h) and (f) respectively.

signal patterns of both photoacoustic and ultrasound waves achieve good agreement in both time domain (Fig. 3(a)) and frequency domain (Fig. 3(b)), showing the strong coherent correlation between them.

B. Signal SNR Improvement

Firstly to prove the feasibility of detecting the weak photoacoustic signal by cross-correlating it with a strong and correlated ultrasound signal, the separate laser-induced pulsed photoacoustic signal and pulse-echo ultrasound signal are recorded sequentially with separately triggered laser and ultrasound excitations as shown in Fig. 4(a)-(b), where the photoacoustic signal is suffering low SNR (4.4 dB) due to the weak signal strength and inevitable instrumental noise. The ultrasound signal can be made relatively strong (9.6 dB) by increasing transmit power and treated as the template signal. Then based on the proposed coherent PAUS correlation approach, the photoacoustic signal and ultrasound signal are cross-correlated within 6 μ s time window as shown in Fig. 4(c). The SNR of the coherent PAUS correlation signal is significantly increased to 22.5 dB due to the correlated PAUS signal integration and uncorrelated noise suppression. In the next step, to prove the feasibility of coherent PAUS correlation at a worse case, the SNR of photoacoustic signal and pulse-echo ultrasound signal are set to be below -10 dB by reducing the power of laser and ultrasound sources as shown in Fig. 4(f)-(g). It shows that due to the strong noise background, both photoacoustic signal and ultrasound signal are hardly identified. After performing both the backward and forward cross-correlations within a longer window (10 μ s), two peaks could be clearly identified in Fig. 4(h) to give the depth information ($d = v_s \Delta \tau = 37.5$ mm) of the object. Finally the coherent PAUS signals in Fig. 4(c) and Fig. 4(h) are further low-pass filtered to improve the SNR and peak detection in Fig. 4(d) and Fig. 4(i). Although proper low-pass filtering (4-order

Fig. 5. The SNR of the photoacoustic signal, the coherent PAUS correlation signal and the SNR improvement when the input laser pulse energy is swept from 10 μ J to 200 μ J.

origin photoacoustic signals in Fig. 4 (a) and Fig. 4(f) could improve the signal SNR to a certain extent, which are shown in Fig. 4(e) and Fig. 4(j), it is impossible to suppress the noise components with similar spectrum as the photoacoustic signal. On the other hand, coherent correlation behaves as a matched filter to exactly extract the highly correlated photoacoustic signal and suppresses the uncorrelated white noise, which traditional filtering process can never achieve. It is shown that the low-pass filtered PAUS signals in Fig. 4(d) and Fig. 4(i) perform much higher SNR than low-pass filtered original photoacoustic signals in Fig. 4(e) and Fig. 4(j), especially when suffering strong background noise and interference.

To fully explore the capability of coherent PAUS correlation on SNR improvement, the input laser pulse energy is swept from 10 μ J to 200 μ J to induce the photoacoustic signals with different SNR (from -20 dB to -5 dB) as shown in Fig 5, where the SNR of pulse-echo ultrasound from the blood of the vessel-mimicking phantom remains 9.6 dB. It is clearly shown

that over 20 dB SNR improvement is achieved by coherent

Fig. 6. The reconstructed images of the (a) vessel-mimicking phantom by (b) pulsed laser-induced photoacoustic imaging, (c) pulse-echo ultrasound imaging, and (d) the proposed coherent PAUS imaging.

PAUS correlation across a wide range of input laser energy. More interestingly, the SNR improvement is becoming more significant when the laser energy is decreasing, validating its potential to achieve a superior sensitivity when the photoacoustic signal suffers severe noisy background.

It is worth noting that only one wide ultrasound pulse is received by overlapping the four echos from the four interfaces of the vessel-mimicking phantom due to the small diameter (outer: 3 mm, inner: 2.2 mm) of the tube, and the low 0.5 MHz central frequency (>3 mm resolution) used in the experiment. Then the four ultrasound echos at 0.5 MHz are overlapped significantly and cannot be differentiated.

C. Image of Vessel-mimicking Phantom

The images of the blood in the vessel-mimicking phantom (Fig. 6(a)) are created by laterally moving the object in Y axis by the XY translation stage (Fig. 2). The received acoustic signals are subjected to the low-pass filtering and Hilbert transformation to extract the envelope. Three comparable B-scan images of the pulsed photoacoustic imaging (Fig. 6(b)), pulse-echo ultrasound imaging (Fig. 6(c)), and the proposed coherent PAUS imaging (Fig. 6(d)) are reconstructed respectively. The slight location difference of photoacoustic image and ultrasound image is due to the wider ultrasound pulse and slight time delay difference caused by the different signal generation mechanism. As expected, the proposed coherent PAUS imaging performs much better image contrast (the different between image pixel intensity of object and background pixel intensity) than the separate photoacoustic or

ultrasound imaging that may suffer strong noisy and/or low

Fig. 7. (a)-(b) The photograph of the experiment setup and phantom. (c) Pulse-laser induced photoacoustic imaging, (d) pulse-echo ultrasound imaging, and (e) the proposed coherent PAUS imaging. PR: pulser-receiver; FG: function generator; UT: ultrasound transducer.

contrast background, due to coherently correlating the photoacoustic and ultrasound signals to improve the SNR, fusing both optical absorption and acoustic reflection properties of the same target. It is also observed that the axial resolution of the coherent PAUS imaging is slightly degraded. The reason is that the cross-correlation will induce more cycles than the original signals due to its time-shifted multiplication and integration processing, which leads to a bit larger pulse envelope width.

D. Image of Vessel-mimicking Phantom with Chicken Breast Tissue as Random Scatterer

To validate the proposed PAUS correlation approach in a more realistic scenario, *e.g.* human brain SSS, carotid and jugular vessels in deep tissue, a piece of *ex vivo* chicken breast tissue with 5 mm thickness is placed on top of the vessel-mimicking phantom. Fig. 7(a)-(b) shows the photograph of experimental and phantom setup. The reconstructed images of photoacoustic, pulse-echo ultrasound and the proposed correlated PAUS approach are shown in Fig. 7(c)-(e), respectively. It is observed that due to the existence of the chicken breast scatterer, more distortion is induced in both photoacoustic image and ultrasound image. However, the SNR improvement is still significant by applying the coherent PAUS correlation in Fig. 7(e).

IV. DISCUSSION AND CONCLUSION

The primary application of the proposed coherent PAUS approach is related to photoacoustic tomography for deep tissue imaging. For this first application, such as brain imaging with intact scalp [8], [23], due to the deep imaging depth and much

stronger attenuation (~ 6.9 dB/(MHz cm)) of high-frequency components of photoacoustic signals caused by the scalp, only low-frequency signals could be survived and detected by the transducer with low frequency. High sensitivity detection and low signal SNR are the bottleneck of deep tissue imaging. Other similar applications also include carotid/jugular imaging with > 2 cm penetration depth [24]. In these applications, the imaged vessels (e.g. sheep superior sagittal sinus (SSS), human's carotid, jugular, radial artery, etc.) have a diameter range between 1 mm to 5 mm, where the detected photoacoustic signals have frequency spectrum that is typically from hundreds of kHz to 1 MHz, which are the specifications we have followed for the vessel-mimicking phantom in this paper. Therefore, the proposed PAUS coherent imaging approach is primarily targeting such kind of applications, where low sensitivity and signal SNR are the critical challenges, and low-frequency photoacoustic signals are usually detected. To coherently correlate with the weak photoacoustic signals, low-frequency ultrasound signals are chosen to match the spectrum of the photoacoustic signals to maximize the signal SNR for detection of the proposed PAUS coherent imaging.

For the second application, it is related to high-resolution (but low imaging depth) photoacoustic microscopic imaging. Typical applications include subcutaneous vascular imaging [9], endoscopic, intravascular imaging [19]-[20], and retinal imaging [25]. Due to the low imaging depth and better optical focusing, high-frequency photoacoustic signals can be induced to render high-resolution images, where the requirements of sensitivity and signal SNR are not critically challenging compared to the above deep tissue imaging. Theoretically, the proposed PAUS coherent imaging is also applicable to achieve enhanced sensitivity and signal SNR for such high resolution applications, which may be fully explored in the future work. In summary, this paper is to introduce a novel PAUS method, and address its performance for the applications in the first case, and leave the detailed study for its use in the second case to the future work.

In conclusion, we have conducted the initial study on the coherent correlation of endogenous photoacoustic wave and exogenous pulse-echo ultrasound wave. Due to the coherent correlation of the optical absorption and acoustic reflection properties from the same object, the experimentally detected PAUS correlation signal achieved significantly enhanced SNR than conventional pulsed photoacoustic or pulse-echo ultrasound signals. Preliminary imaging results demonstrated much improved image contrast by the proposed coherent PAUS correlation imaging approach. The proposed PAUS correlation could be treated as a new imaging modality fusing mechanical impedance, optical absorption and thermoelastic properties of the same object, delivering higher sensitivity and image contrast than existing ultrasound or photoacoustic imaging only. Except the anatomical image acquired in this paper, functional information (e.g. blood oxygen saturation) could also be extracted by applying multi-wavelength laser illumination to excite distinct photoacoustic signals. Functional coherent PAUS imaging with dedicated calibration will be explored further. Future work will also focus on the 3D PAUS imaging

implementation for in vivo small animal studies.

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