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Passive ultrasound aided acoustic resolution photoacoustic microscopy imaging for layered heterogeneous media

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Photoacoustic imaging reconstructions usually assume a known speed-of-sound (SOS) distribution; however, in most cases, the SOS distribution is not revealed and is difficult to estimate from photoacoustic signals. In this paper, we propose passive ultrasound aided acoustic resolution photoacoustic microscopy which simultaneously reconstructs SOS distributions and photoacoustic images for layered heterogeneous media. The passive ultrasound is a kind of laser-induced acoustic wave generated by a transducer absorbing the backscattered light. It can be used to measure the layer thicknesses due to its sensitivity to structural information and broad bandwidth and further determine the SOS distributions. After estimating the SOS distributions, a phase shift plus interpolation is employed to reconstruct the photoacoustic image for heterogeneous media. Without introducing additional hardware, this method can be conveniently incorporated into a conventional photoacoustic imaging system. A curved shell immersed in water is adopted as a layered heterogeneous phantom, and the proposed method reconstructs the targets (carbon rods) under this shell. Under the test of a 5 MHz focused transducer (NA 0.25), the maximum reconstruction deviation of 1.2 mm carbon rods is only 0.15 mm. *Published by AIP Publishing.*

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Photoacoustic imaging (PAI) has gained considerable attention in the field of biomedical imaging, due to its unique capability of visualizing optical absorbers with a high acoustic spatial resolution to investigate biological tissues, revealing tissues' anatomical, functional, metabolic, histological, and molecular properties.^{1–3} Generally, the ultrasonic responses are generated from optical absorbing structures of interest, upon irradiation by a short laser pulse, and collected by ultrasonic transducers. When detecting targets at depths beyond the optical diffusion limit, which can be up to a few millimeters, acoustic-resolution photoacoustic microscopy (ARPAM) works with a high resolution benefiting from the low acoustic scattering. However, its lateral resolution is guaranteed only in a limited focal region. To achieve an equally high lateral resolution in the out-of-focus region, advanced reconstruction algorithms should be adopted in ARPAM.⁴

Acoustic mismatches of different tissues, especially skulls and bones, complicate the propagation of acoustic waves. In such cases, reconstruction methods based on an assumption of a homogenous media are invalid. Although some reconstruction methods for heterogeneous media have been investigated, including ray-based propagation,^{5–7} time reversal,^{8–10} and model-based^{11–13} methods, most of them require a prior knowledge of the sound-of-speed (SOS) distribution which is unknown in practice and difficult to estimate from PAI measurements directly.¹³

One way to obtain the SOS distributions is to use adjunct ultrasonic imaging data. Ultrasound computed tomography (USCT) has been previously verified to reconstruct the SOS distributions in breast imaging.¹⁴ In USCT, a SOS distribution is estimated by sending a series of

ultrasonic pulses through the object and measuring the wave-field with an array transducer.^{15,16} Recently, the passive element optical excitation technique is introduced for hybrid ultrasonic and photoacoustic tomography imaging.^{17–19} By fixing an additional strong absorber in front of laser lights, the ultrasound wave is excited by the laser shooting on the absorber. After performing a similar USCT type of measurement, a fan-beam reconstruction allows the SOS tomograms to be generated^{20,21} from this laser-induced ultrasound. Both measurements of the SOS distributions are based on the computed tomography (CT) mode and suit photoacoustic tomography (PAT).

In ARPAM, the passive ultrasound technology also has been realized for hybrid ultrasonic and photoacoustic imaging by using polyvinylidene difluoride (PVDF) polymer films as ultrasound transceivers.^{22,23} However, there is still rare research about using passive ultrasound technology to determine a SOS distribution and further reconstructing an image from ARPAM on the heterogeneous material. In this paper, we propose a passive ultrasound aided acoustic resolution photoacoustic microscopy imaging method for layered heterogeneous materials. As shown in Fig. 1, the laser light penetrates the acoustic mismatch layer, then illuminates the deep targets to generate photoacoustic signals. Meanwhile, a part of laser light is backscattered and absorbed by a piezoelectric transducer, generating the ultrasound wave passively. Such a passive ultrasound (PU) excitation is similar to a generation of laser-induced ultrasound except that the transducer itself is used as an optical absorber instead. As PU waves are sensitive to media structures, one can approach the structure of layered heterogeneous media by analyzing the PU reflection signals then reconstruct the SOS distribution with the media structure and the catalog of sound speed of

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FIG. 1. Passive ultrasound aided acoustic-resolution photoacoustic microscopy system diagram. PA, photoacoustic wave. PU, passive ultrasound wave. TR, ultrasound transducer. LA, laser beam. 1, water coupling layer. 2, acoustic mismatch layer. 3, target.

materials. After the SOS distribution is determined, a high-resolution ARPAM image can be reconstructed by heterogeneous reconstruction methods such as phase shift plus interpolation (PSPI). Moreover, it is convenient to use this passive ultrasound aided APRAM, because no additional bulky elements and replacement on the transducer are needed.

For a short laser pulse, the amplitude of a PU wave can be built using the simple thermodynamic principles as

$$P_t = E\mu_b\alpha\beta v^2/C_p, \quad (1)$$

where E , μ_b , v , α , β , and C_p represent the pulse laser energy, the backscattering coefficient of media, the speed of sound, the light absorptions, the isobaric volume expansion, and the specific heat capacity of a transducer, respectively. To estimate the SOS distribution, we care more about PU reflection waves. According to the acoustic reflection principle, the amplitude of the reflection signal is written as

$$P_r = (Z_2 - Z_1)P_t/(Z_2 + Z_1), \quad (2)$$

where Z_i is the acoustic impedance of the media i -th layer and determined by the media density and speed of sound ($Z_i = c_i\rho_i$). Even though the expression of the PU reflection signal consists of many parameters, the amplitude variations are only caused by the backscattering coefficients and acoustic impedances of the media in a specific photoacoustic system.

The PU reflection waves can be easily detected from most samples, and some even have larger amplitudes than PA waves. For demonstration, we use a black tape plate, a white shell plate, Asian human skins, and a pork rib as phantoms. The whole experiment setup is a standard ARPAM system as shown in Fig. 2(a). A fiber coupled Q-switched laser (DPS-1064-A, CNI) at the 1064 nm wavelength is used as an illumination source, and the incident laser fluence on the target surface is about 3 mJ/cm² with a 10 Hz pulse repetition rate. The photoacoustic signals are detected by a 5 MHz focused transducer (10 mm diameter, NA 0.25), amplified with a 54 dB linear amplifier, and finally sampled using a 400 MHz oscilloscope. All the phantoms are immersed in water with a distance of 20 mm to the transducer, and the signal envelopes of different phantoms are

FIG. 2. (a) The schematic of the ARPAM experiment setup, LD: laser diode, FB: fibre, Ph: phantom, TR: transducer, LNA: low noise amplifier, and OSC: oscilloscope. (b) The normalized envelopes of PA and PU reflection signals.

shown in Fig. 2(b). Note that, the photoacoustic (PA) wave propagates with a time flight of 13.5 μ s, while the PU reflection wave has a round-trip propagation appearing at $\sim 27 \mu$ s.

Among these four phantoms, the black tape and the white shell plate are two special cases. Since the tape has a high light absorption and a low light backscattering, its PA signal is large, but no PU reflection wave exists. On the contrary, the white shell with a low light absorption and a strong backscattering generates a large PU reflection signal, while the PA signal is nearly vanished. However, the PA and PU reflection waves co-exist for most phantoms. In the case of Asian human skins, both PA and PU reflection waves are observed. As the acoustic impedance of the human epidermis is approximately identical to the coupling water, the PU reflection wave is not large. To the pork rib with a large acoustic impedance, the amplitudes of the PU reflection signals are even larger than ones of the PA waves. Although the amplitudes of the PU reflection signals vary with the tested media, we care more about the time flights of the reflection signals when recovering the media structures.

Further trial on a phantom experiment is conducted to present the cooperation of PA and PU reflection waves in photoacoustic imaging. As shown in Fig. 3(a), the phantom is a layered heterogeneous media that defined as a curved shell immersed in water. The curved shell has a strong acoustic mismatch and light scattering properties. Three carbon rods ($\phi = 1.2$ mm) are placed below the shell at a depth of 27 mm from the transducer and served as targets with 2.5 mm and 1.8 mm distances between each other. The other setups are the same as the one shown in Fig. 2(a). During imaging, we scan the multi-layered phantom with a step of 0.15 mm in a range of 12 mm in x and 2.25 mm in y directions. The A-scan signal of raw data at point $x = 6$ mm,

FIG. 3. (a) Phantom structure. (b) The PA signal received by the ultrasound transducer. PA1: PA signal of the shell, PA2: PA signal of the carbon rod, and PU: PU signal of the shell. (c) Deconvolution result of the PU signal. (d) Raw data image of carbon rods. (e) Image reconstructed by the homogenous reconstruction method. (f) A depth map of the upper interface of the acoustic mismatch layer calculated using $d = c_1 t_u / 2$. (g) Thickness map of the acoustic mismatch layer calculated using $h = c_2 (t_b - t_u) / 2$. (h) Image reconstructed by the heterogenous reconstruction method (PSPI). (i) Signal amplitudes of Line-A in the raw data, homogeneous reconstructed and heterogenous reconstructed image. I, II, and III are the FWHMs of red line peaks.

$y = 0.75$ mm is presented in Fig. 3(b), where one can find a PA wave of the shell's upper surface at $11.5 \mu\text{s}$, a PA wave of carbon rod at $16 \mu\text{s}$, and a PU reflection wave of shell at $23 \mu\text{s}$. The raw data image with the top-down maximum values at a range of $10 \mu\text{s}$ – $20 \mu\text{s}$ is depicted in Fig. 3(d), where three carbon rods cannot be distinguished.

Because of a strong acoustic mismatch between the shell and water, the performances of homogeneous reconstructions cannot hold as shown in Fig. 3(e). To correctly recover the image by a heterogenous reconstruction method, we should first use PU reflection waves to estimate the structure of media. A simple way is to utilize sparse deconvolution to find the reflectivity functions of the layer interfaces, then calculate the depth and thickness maps of the acoustic mismatch layer. Before deconvolution, a convolution model is modeled as

$$\mathbf{y} = \mathbf{s} \otimes \mathbf{x}, \quad (3)$$

where $\mathbf{y}$, $\mathbf{x}$, and $\mathbf{s}$ are the received PU reflection signal, reflectivity function, and reference signal, respectively. In this case, the reference signal is an impulse response (IR) of a PU

wave. Such a convolution model can be treated as a shift-invariant linear system and rewritten by a linear equation as

$$\mathbf{y} = \mathbf{A}\mathbf{x}, \quad (4)$$

where $\mathbf{A}$ is the reference signal matrix constructed as

$$\mathbf{A} = \mathbf{F}^\dagger \text{diag}(\mathbf{s}) \mathbf{F}, \quad \mathbf{F} = \begin{bmatrix} 1 & 1 & \dots & 1 \\ 1 & \omega & \dots & \omega^{M-1} \\ \vdots & \vdots & \ddots & \vdots \\ 1 & \omega^{M-1} & \dots & \omega^{(M-1)(M-1)} \end{bmatrix}, \quad (5)$$

$$\omega = e^{-j2\pi/M}.$$

In Eq. (5), the $\text{diag}(\cdot)$ represents a diagonalization operation, † is a conjugate transpose, and $\mathbf{F}$ is a Fourier transform matrix. Similar to the deconvolution on ultrasound waves,^{24,25} a reference signal $\mathbf{s}$ can be approximately measured by a PU wave reflected from a large thick plate or directly estimated from $\mathbf{y}$. To sparsely resolve $\mathbf{x}$, we use the orthogonal matching pursuit algorithm (OMP)^{26,27} (see [supplementary material](#)),

which is widely applied in sparse reconstructions. In our cases, we only concern about the upper and bottom interfaces of the acoustic mismatch layer; therefore, the sparsity factor of OMP can be set as 2. For instance, the zoomed in PU reflection wave at the scanning point $x = 6$ mm, $y = 0.75$ mm and its corresponding deconvolution result are depicted in Fig. 3(c). It can be seen that the time flights of the upper and bottom interfaces are $23.16 \mu\text{s}$ and $25.0 \mu\text{s}$, respectively. Further, the depth and thickness of the acoustic mismatch layer in an arbitrary scanning point can be calculated using

$$d = c_1 t_u / 2, h = c_2 (t_b - t_u) / 2, \quad (6)$$

where d , h , t_u , t_b , c_1 , and c_2 denote the depth of upper interface, the thickness of acoustic mismatch layer, the time flight of the upper interface, the time flight of the bottom interface, the sound speed in water, and the sound speed in shell, respectively. In this experiment, the sound speed of coupling water is approximated to 1480 m/s, and the sound speed of the shell is about 5500 m/s. Using Eq. (6), the depth and thickness maps are calculated and shown in Figs. 3(f) and 3(g), respectively. According to the thickness maps, the curved shell has nonuniform thicknesses. By combining the catalog of the sound speed, the depth, and thickness maps, the SOS distribution can be figured out.

After determining the SOS distribution, many heterogeneous algorithms can be employed to recover the image. Here, we adopt phase shift plus interpolation (PSPI^{28,29}) to reconstruct the image. PSPI is a Fourier-based migration algorithm that is used to reconstruct ultrasound imaging for a complex layered structure. It first decomposes the wave field at the observation plane (transducer scanning plane) into a set of harmonic plane wave components. Then, PSPI, respectively, extrapolates the wave field under different sound speeds and integrates these extrapolated results with a simple window function. Finally, the image can be reconstructed by a Fourier transform on these extrapolated wave fields at different depths. The detailed reconstruction method is explained in the [supplementary material](#). As shown in Fig. 3(h), the image reconstructed by PSPI has a high resolution and SNR that can clearly separate three carbon rods. To quantitatively compare the image resolutions of raw data, homogeneous and heterogeneous reconstructions, the signal amplitudes in line-A are illustrated in Fig. 3(i). In the image of heterogeneous reconstruction, the full width half maximum (FWHM) of each rod is no more than 1.35 mm. Since the rod diameter is 1.2 mm, the maximum deviation is about 0.15 mm. Note that, the amplitude variations between three rods in Fig. 3(h) are caused by non-uniform light scattering losses and acoustic attenuations in the shell layer which can be compensated.^{30,31} In this paper, the SOS distribution is indirectly acquired by combining the calculated layer structure and the catalog of sound speed of materials. For the cases without prior sound speed, it is also possible to use the genetic algorithm to estimate both the material sound speed and media structure.³²

To some extent, a PU reflection wave is similar to a pulse-echo (PE) ultrasound wave because both of them have a round-trip propagation. Nevertheless, the excitation way of PU waves provides PU reflection wave broader bandwidths than PE waves. Here, we use three transducers (Olympus)

with 5 MHz, 10 MHz, and 20 MHz center frequencies to verify this difference. The experiment setup is the same as that depicted in Fig. 2(a), and a white shell is used as the phantom. All the PU reflection waves are generated by the backscattering light of the 1064 nm laser, and the PE waves are excited by 100 V pulses. According to the normalized spectra of received signals shown in Figs. 4(a)–4(c), the center frequencies of PU reflection and PE waves are determined by the transducers. However, the bandwidths of PU reflection waves are 3.25 MHz, 6.15 MHz, and 10.23 MHz which are much larger than the PE waves' 2.5 MHz, 5.83 MHz, and 6.25 MHz. Due to the broader bandwidths, the PU reflection waves have better time resolutions than the PE waves. Taking this advantage, the PU reflection waves can accurately measure the thicknesses of layered heterogeneous media.

Figure 4(d) shows the processing diagrams of the PU reflection and PE wave generations, and the corresponding spectra in each step. Usually, a PE wave is excited through a high voltage pulse working on the piezoelectric wafer, then reflected from the acoustic mismatch layer and received by the same piezoelectric wafer in the transducer. The spectra of PE waves in the transmitting, wave propagation, and receiving are all filtered. In the transmitting and receiving steps, piezoelectric and reverse-piezoelectric effects work as bandpass filters (BPFs) which double filter the PE waves. Different from PE waves, a PU wave is excited by a short backscattering laser radiation on the piezoelectric transducer surface (matching layer). As a result, the excitation of PU

FIG. 4. Comparison of PU and PE waves. (a) The spectra of PU reflection and PE waves excited by the 5 MHz transducer. (b) The spectra of PU reflection and PE waves excited by the 10 MHz transducer. (c) The spectra of PU reflection and PE waves excited by the 20 MHz transducer. (d) Processing diagram of generating PU and PE waves. Yellow region: the spectra of the PE wave and Blue region: the spectra of the PU reflection wave.

waves is not filtered by the BPF of the piezoelectric wafer. Subsequently, the PU reflection waves suffer from the media filter during propagation and the BPF of the transducer during receiving. Both the PU reflection and PE waves have the same round-trip propagations, thus the lowpass effects of media are similar. Because the BPF works on the PU reflection wave only once, PU waves carry broader bands than PE wave as the experiments show.

To conclude, a passive ultrasound aided acoustic resolution photoacoustic microscopy imaging method for layered heterogeneous materials is proposed. This method uses passive ultrasound excited by backscattering laser radiation to determine the structure of media and further estimate the SOS distribution, then accurately recover the ARPAM by heterogeneous reconstruction. Without adding US pulse/receiver circuits nor other optical absorbers, the proposed method can be conveniently implemented in the conventional ARPAM system. For the experiment on phantom with a strong acoustic mismatch layer inside, the passive ultrasound aided ARPAM using a 5 MHz focus transducer (NA 0.25) recovers the shapes of the targets, and its reconstructed deviation is no more than 0.15 mm.

See [supplementary material](#) for a detailed description of the sparse deconvolution and PSPI reconstruction method.

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