Simultaneous photoacoustic imaging technique using an acoustic imaging lens

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Abstract. A simultaneous photoacoustic (PA) tomography imaging technique in multilayer samples was developed. Instead of using the PA image reconstruction methods on the basis of complex algorithms, obtaining a two-dimensional PA image in real time is available by using an acoustic lens that has the ability of parallel imaging. The imaging system can acquire the complete PA signals of high signal-to-noise ratio from all the object planes by utilizing the advantages of the acoustic lens with long focal depth and a fast data acquisition system with a high sampling rate. With the time-resolved technique, the PA signals from different object planes can be distinguished and then the high optical contrast multilayer PA images can be reconstructed simultaneously without any algorithms. The experimental results show that the reconstructed sections agree well with the original samples. [DOI: 10.1117/1.3155525]

Keywords: simultaneous photoacoustic imaging; acoustic imaging lens; time-resolved technique.

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Photoacoustic (PA) waves generated by absorption of short laser pulses in biological tissue are increasingly being employed as a diagnostic and therapeutic tool in recent years. PA imaging is a noninvasive imaging modality for visualizing both the structural and functional information of biological tissues. It combines the advantages of high optical contrast and high acoustic penetration depth. A number of PA imaging techniques, such as PA imaging based on Radon transform,[1] and phase-controlled PA imaging[2] have been proposed and studied. Many reconstruction algorithms have been developed for obtaining images. Examples of current ones include optimal statistical approach,[3] weighted delay-and-sum algorithm,[4] etc.; however, most of them may be time consuming[5] and cannot achieve the multilayer PA images simultaneously. They obtain only one layer's PA image during one experiment. Thus, it limits its application in medical clinic diagnosis and *in vivo* noninvasive imaging.

The experiment proposed in this letter demonstrates a simultaneous multilayer PA tomography imaging technique. Figure 1(a) indicates the diagram of the acoustic lens imaging and tomography system. Similar to the optical lens imaging, different imaging planes of the acoustic lens correspond to different object planes in tissue.[6] However, according to the Fourier imaging theory, the PA signals from different object planes in the range of Δz could precisely image on the same imaging plane because of the long focal depth of the acoustic lens.[7] The PA signals from different object planes almost generate at the same time because the velocity of light is quite fast that it illuminates the multilayer sample almost at the same time. According to the sine condition of imaging system, all PA signals generated by point sources from the same object plane reaching to its conjugate imaging point have identical path lengths. Thus, the PA signals from an object plane need the same delay time to reach their corresponding imaging planes. Figure 1(b) shows the PA signals from points A, B, and C on different object planes being detected on the same imaging plane. By using the time-resolved technique, we could distinguish the PA signals from points A, B, and C, separately. In our previous study, PA imaging by using a polymethylmethacrylate acoustic lens[7] or a 4f aluminum acoustic lens[6] imaging system can achieve the goal of fast imaging. We can successfully attain tomographic imaging by utilizing a boxcar to acquire the peak values of the PA signals. However, they can acquire only imaging information from one plane at a time during one experiment. In the new experiment, the multilayer PA images can be obtained simultaneously to finish a complete 3-D distribution by using a time-resolved data acquisition system. In addition, by using the acoustic lens, the signal-to-noise ratio of the PA signal was obviously improved. For an acoustic imaging lens with a diameter R, the acoustic energy collected by a PA detector with a diameter r can be more than the one without the acoustic lens by $\pi R^2/\pi r^2$ times, while the amplitude of PA signals is larger by R/r times, which was efficient for improving the signal-to-noise ratio and enhancing the imaging contrast.

Figure 2 shows the experimental setup of the simultaneous multilayer photoacoustic imaging system. With a FWHM of 7 ns, 532-nm laser pulses are provided by a Q-switch (Q-SW) Nd: yttrium aluminum garnet (YAG) laser (model no. PRO-230, Spectra Physics, USA) at a pulse repetition rate of 30 Hz. The laser beam is expanded to heat the imaging sample placed in a tank of $60\times20\times10$ cm with the coupling of 3% milk liquor and produce the PA signals. The PA signals generated by the sample are then transformed onto the imaging plane by the polymethylmethacrylate acoustic lens. The aperture of the acoustic lens is 40 mm, with ~50-mm focal length in water. The sample, acoustic lens, and a linear detector array about 10 cm away from each other are centered on the same axis. The linear detector array, which consists of 64 piezoelectric transducer (PZT) probes with a center frequency of 1 MHz, is used to detect the PA pressure distribution. The size of every PZT probe is 0.22×1.0 mm, and the distance between two neighboring probe is 1.5 mm. Thus, the valid detected range of the 2-D transducer is 108.6 mm. Set the step size of the scanning stage to be 1.5 mm, then the orthoscopic PA images of the sample can be reconstructed. The 1-D

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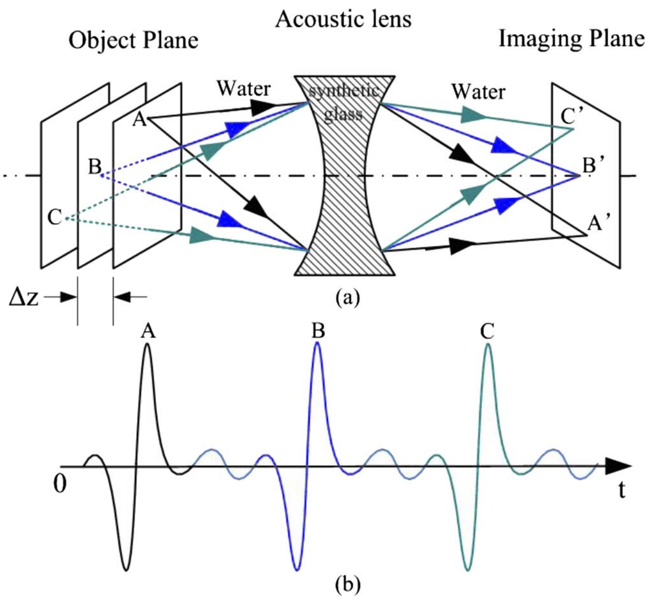

Fig. 1 Diagram of acoustic lens imaging and tomography system.

linear detector array is fixed on a scanning stage, which is driven by a computer scanning vertically. Thus, 2-D planar PA pressure distribution can be detected by the detector, changed into the homologous electronic signals, and sent to the fast data acquisition system [(FDAS), model no. PCI-4712AS1] in serial form by using an electronic switch of 64 channels. With the high sampling rate of the FDAS, which is triggered by the output of the YAG laser's Q-SW synchronous signal, the complete PA signals can be acquired. Setting the vertical scanning range to be 30 mm and each step to be 1.5 mm, the linear detector should scan 20 steps vertically to collect the PA pressure distribution in an experiment. Thus, the PA signals from all the object planes of the sample are then integrally recorded in the computer. As a result, the total pixels of a reconstructed PA image should be $64 \times 20 = 1280$. A complete 3-D PA pressure distribution would be obtained in an experiment when the linearly detector scanning from up to down vertically without moving back and forth because of the spatial Fourier transform ability and long focal depth of the acoustic imaging lens. The PA images of different object

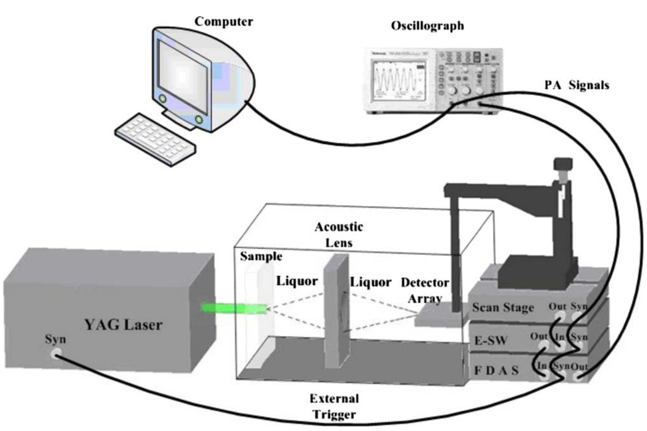

Fig. 2 Experimental system setup.

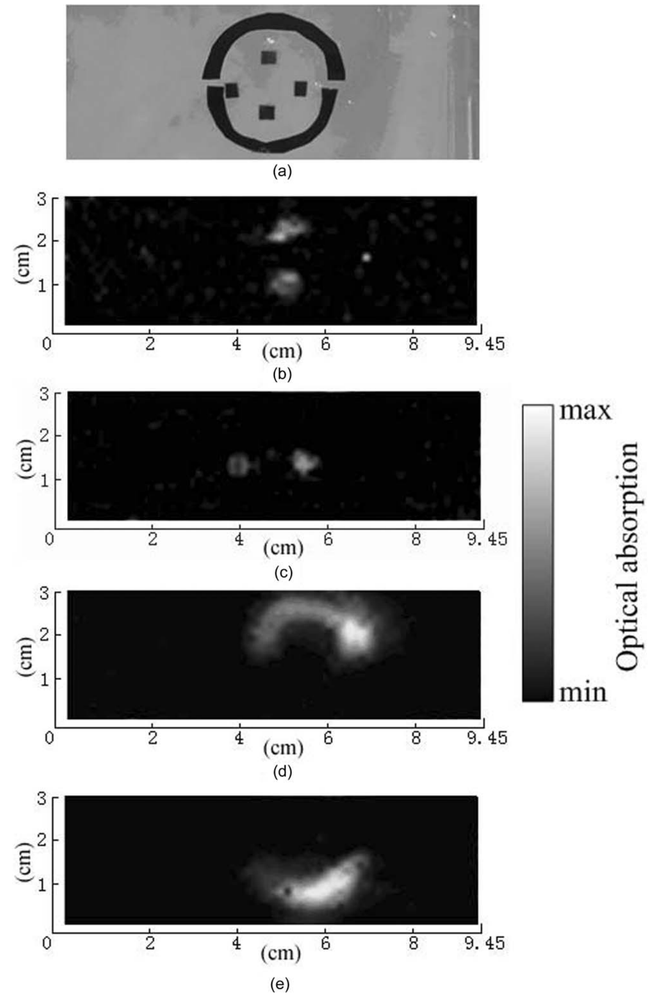

Fig. 3 Front elevation of (a) the sample, which consists of four different patterns: two lengthways black adhesive tape dots stuck to the front, two transverse black adhesive tape dots stuck to the second layer, a lower half ring of black adhesive tape stuck to the third layer, and an upper half ring of black adhesive tape stuck to the back of three pieces of polymethylmethacrylate. (b–e) are the corresponding reconstructed PA images of the four parts of the sample.

planes on the same image planes can be obtained simultaneously by using time-resolved technique when reconstructing the PA images. With different delay time set during the PA image reconstruction, multilayer PA images would be obtained in real time. It takes ~95 s to acquire a complete 3-D distribution in our current system.

A sample with four layers made of black adhesive tape adhered to three pieces of polymethylmethacrylate shown in Fig. 3(a) was put in 3% milk liquor. The distance between the first and second layer is 5.5 mm, the distance between the second and the third layer is 8 mm, and the distance between the third and the fourth layer is also 8 mm. Figure 4 shows reconstructed PA signals generated by the sample of four layers. Because the time difference of the first two PA signals is $\sim 2.1\ \mu s$, and the PA signals travel in the polymethylmethacrylate at a spread speed of $2.640\ mm/\mu s$; thus, according to $D = v\Delta t$, we can calculate that the distance between two surfaces is $2.640\ mm/\mu s \times 2.1\ \mu s = 5.544$ mm, which agrees well with the thickness of the polymethylmethacrylate.

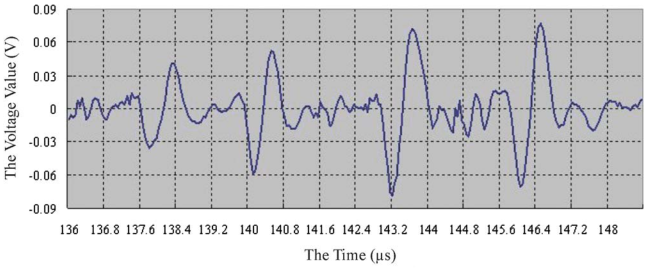

Fig. 4 Reconstructed PA signals from the middle of the four-layer sample.

In the same way, we can guarantee the reliability of the other PA signals. The four PA signals are divided in the time domain, which illustrates that the four layers with light-absorbing objects can be distinguished undoubtedly. Because the PA signals from the same object plane reach the detector at the same time, from the reconstructed PA signals we can find that the peak values from the same layer appear at the same delay time. In this experiment for example, the peak values of the PA signals from four layers always appear at about 138.3, 140.5, 143.5, and 146.5 μs, separately. Thus, we can set different delay time to obtain the peak value of the PA signal when reconstructing images. In the first layer, we can get 1280 different peak values from all the PA signals totally, and transform them into 256 corresponding gray levels to form a 64×20 pixels image, shown in Fig. 3(b). In the same way, we can obtain the reconstructed images from the other three layers, shown in Figs. 3(c)–3(e). The images are inverted compared to those of samples for the acoustic lens forms the inverted real images. Obviously, the reconstructed PA image agrees with the sample well.

In summary, a simultaneous PA tomography imaging technique in multilayer samples based on an acoustic imaging lens and the fast data acquisition system has been demonstrated. The system can acquire the complete PA signals from all the object planes. The PA signals from different object planes can be distinguished by using the time-resolved technique. Without any reconstruction algorithms, multilayer PA images can be reconstructed simultaneously, and then a 3-D PA image can be obtained by combining multiple adjacent 2-D slices. A real-time PA imaging camera similar to the optical camera is what we want to achieve in future. Undoubtedly, the potential advantages of reconstructing multilayer PA images simultaneously without any complex algorithms make it a more convenient and even popular method for *in vivo* noninvasive imaging and medical clinic diagnosis.

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References

1. X. Wang, Y. Pang, G. Ku, X. Xie, G. Stoica, and L. V. Wang, "Noninvasive laser-induced photoacoustic tomography for structural and functional *in vivo* imaging of the brain," *Nat. Biotechnol.* **21**, 803–806 (2003).
2. Y. G. Zeng, D. Xing, and Y. Wang, "Photoacoustic and ultrasonic coimage with a linear transducer array," *Opt. Lett.* **29**(15), 1760–1762 (2004).
3. Y. V. Zhulina, "Optimal statistical approach to optoacoustic image reconstruction," *Appl. Opt.* **39**, 5971–5977 (2000).
4. R. J. Siphanto, K. K. Thumma, and R. G. M. Kolkman, "Serial noninvasive photoacoustic imaging of neovascularization in tumor angiogenesis," *Opt. Express* **13**, 89–95 (2005).
5. J. J. Niederhauser, M. Jaeger and M. Frenz, "Real-time three-dimensional optoacoustic imaging using an acoustic lens system," *Appl. Phys. Lett.* **85**, 846–848 (2004).
6. Z. X. Chen, Z. L. Tang, and W. Wan, "Photoacoustic tomography imaging based on a 4f acoustic lens imaging system," *Opt. Express* **15**, 4966–4976 (2007).
7. Y. H. He, Z. L. Tang, Z. X. Chen, W. Wan, and J. H. Li, "A novel photoacoustic tomography based on a time-resolved technique and an acoustic lens imaging system," *Phys. Med. Biol.* **51**, 2671–2680 (2006).