Fast photoacoustic tomography by use of acoustic lens

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Abstract. Photoacoustic tomography has the potential to image the configuration or function of animal or human organs with simultaneous high contrast and high spatial resolution. This article provides an overview of photoacoustic tomography with an acoustic lens. And a new fast photoacoustic tomography technique is introduced. An acoustic lens is able to map the initial photoacoustic pressure distribution in an object in real time without the need of complicated computational reconstruction. Further more, this method produces no artifacts in reconstructed images. Finally, a new fast photoacoustic tomography system based on acoustic is discussed in detail in this paper.

1. Introduction

When electromagnetic (EM) energy, such as optical or radio-frequency wave, is absorbed by a medium, its temperature will rise rapidly, and then a Photoacoustic (PA) signal will be generated as a result of thermoelastic expansion. That is called PA effect which was discovered by Bell in 1880.[1] Readers are referred to earlier reviews, books and conference proceedings, and original study papers.[2-6]

Because a PA pressure is directly proportional to the optical absorption in a sample, it is possible to reconstruct the optical absorption distribution in the sample by measuring PA pressures at all directions. Another method to map the optical absorption distribution is using acoustic lens to transform the pressure distribution on the image plane. Although several other techniques such as ultrasound imaging, x-ray photography, computerized tomography (CT), magnetic resonance imaging (MRI), and positron emission tomography (PET), have appeared, they are all limited more or less when applied in practice. For example, ultrasound imaging is limited by the relatively poor echogenicity of blood vessels;[7] x-ray photography, which is based on the mass density of biological tissue, cannot tell whether the fracture is beginning to recover or not;[8] the sensitivity of MRI in many instances is not very impressive, and not all types of breast tissues can be differentiated by MRI, what is more, it is too expensive. The significance of photoacoustic tomography (PAT) imaging is that it overcomes the above problems and yields images of high optical contrast at high ultrasonic

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resolution in relatively large volumes of biological tissues. And with the advantages of high optical contrast and high acoustic penetration depth, PAT imaging is widely used in medical imaging technology.[9-12] A number of PA imaging techniques have been proposed and studied. The biomedical applications of PA imaging are comprehensive, including tomographic imaging of the skin and other superficial organs by laser-induced PA microscopy, breast cancer detection by near-infrared light or radio-frequency–wave induced PA imaging, and small animal imaging by laser induced PA imaging. Because an acoustic lens is able to map the initial PA pressure distribution in an object in real time without the need of complicated computational reconstruction, PAT based acoustic lens had became an common method.

This article provides an overview of the acoustic lens based PA imaging method. And then a new fast PA imaging system based on acoustic lens is introduced. With the new fast PAT imaging system, we can obtain multilayer PA images simultaneously. The experimental results from phantom samples show that the reconstructed PA images are in agreement with original samples. The most importance is that we can really achieve the multilayer tomographic images simultaneously, and improve the PAT imaging system efficiency greatly.

2. Photoacoustic imaging techniques
PA imaging is a noninvasive imaging technique for visualizing both structural and functional information of biological tissues. This method has become an active research area in recent years. A number of PA imaging methods have been proposed, such as computed tomography with unfocused transducers,[13-19] depth profiling in layered media,[20,21] scanning tomography with focused ultrasonic transducers,[22-25] optoacoustic imaging using Fabry-Perot etalon[26-29] and with other optical detection methods,[30,31] and imaging with an acoustic lens[32-39]. Each of these methods has its own benefit in some aspects. The acoustic lens based PAT may produce nearly real-time images and eliminate the artifacts associated with the restruciton based method.

The acoustic lens based PA imaging was first reported in Xu’s paper. The paper put forward the PA imaging based on acoustic lens, and described the sound field distribution by using complex amplitude. And then the theory of PAT imaging is reported in the next paper. The acoustic lens was made of polymethylmethacrylate in the two papers. In 2004, J. J. Niederhauser demonstrated a real-time PA imaging with a 4f acoustic lens system. In the paper, an optical dark-field stereo imaging system using a 30ns flash illumination light was used to capture a snapshot of the pressure-induced refraction index changes in a water container at a predetermined time after the original laser pulse. The result showed that the images from different layers agree well with the original samples. The theoretical results indicates that a 4f acoustic lens is able to image the PA pressure distribution and guarantees axial and lateral unit magnification of image and in 3D PAT imaging, the OTI imaging system may provide the PA images with the same magnification on axial and lateral, and the 3D structure of the object can be imaging really. Zhang reported a two dimensional PA imaging system based on an acoustic lens, and provided a new method to produce a two dimensional (2D) PA image using the peak-hold technology. Wan investigated the theory of PAT imaging using an acoustic lens imaging system and presented the PA Fourier imaging property of an acoustic lens. Wei presented a new high-contrast photoacoustic tomography (PAT) system using a 4f acoustic lens and a 64-element linear transducer array by use of peak-hold technology. Without the integration limit of the boxcar, this system has the potential advantage to form real-time images and acquire them more rapidly. However, they only acquire a peak value one time during once experiment. In order to solve this problem, we developed a fast photoacoustic imaging system based on a high speed data acquisition system. With the new experiment setup, we can get multilayer PAT images simultaneously without the need of the Boxcar and peak-hold module. The experiment results from phantom samples show that the reconstructed results agree well with the original samples.

3. Fast photoacoustic tomography imaging
According to the Fourier imaging theory, the PA signals from different object planes in the range of the focal length could precisely image on the same imaging plane at the different time because of the long focal depth of the acoustic lens. So with the time-resolved technique, the PA signals from different object planes can be distinguished. In the previous paper, the proper delay time must be adjusted to catch the peak values of the PA signal. The system with BOXCAR should adjust the delay time in BOXCAR, and the system with peak-hold module should adjust the delay time in the module for acquiring the maximum value in the proper time gate. Since the peak-hold module has the potential advantages of forming real-time images and acquiring them more rapidly without any complex algorithms, it only can reconstruct image for one layer at a time. If there were several layers in the sample, corresponding times experiment must be done. This will waste more time and bring error which is caused by scanning.

To simplify the experimental system and improve the imaging speed of multilayer PAT images, we used one high speed data acquisition card (ADC, Model: PCI-4712AS1) to replace the card employed in the previous system (ADC, Model: Advantech PCL-818HG). The new card has a 50Msps 12bit ADC and an independent programmable gain channel composed of high speed precise operational amplifier and precise attenuation filter network are integrated to achieve an voltage signal acquisition range of ±1V or ±10V. Gain errors and zero-bias of each channel can be eliminated independently by data acquisition controller’s fine-tuning, which facilitates this system with high measurement accuracy and phase consistency. No manually adjustable component ensures the high reliability and stability of the system. With this high speed data acquisition card, we can catch the complete PA signals for further process. Figure 1 shows the experimental setup of the fast PAT imaging system.

![Figure 1](image)

*Figure 1. Experiment setup of the fast PAT imaging system*

In a 60cm × 20cm × 15cm water tank, the sample, acoustic lens and the linear transducer array were placed in line. The distance between the sample and acoustic lens was about 10cm and the distance between the acoustic lens and the transducer was about 12cm. In order to simulate the scattering surrounding, we poured 250ml milk with a concentration of 10% into the water tank. Owing to the scattering effect of milk, the samples became invisible. The samples were irradiated by a Q-switched ND: YAG laser (model: PRO-230, Spectra Physics, USA) operating at 532nm with a 7 ns pulse width and 10mJ optical pulse. The repetition rate of the laser was 30Hz. A beam expander collimator and spatial filter were used to expand the laser output beam to a diameter in excess of 8 mm. PA signal generated from the samples were focused on the imaging plane by a concave acoustic lens made of...
polymethylmethacrylate. The aperture of the acoustic lens was 40mm, with about 50mm focal length in water. A multi-element linear array transducer with 1MHz frequency response was specially produced to collect PA signals and change them into the homologous electric signals. The transducer consists of 64 0.22mm × 1.0mm PVDF detectors, and the distance between two neighboring detectors was 1.5mm. In order to change the parallel signals acquired by the transducer into a series, we designed a 64 electronic switch. The output signals from the electronic switch were amplified by a low-noise amplifier with about tenfold gain and then transmitted to the high speed data acquisition card (ADC, Model: PCI-4712AS1) for DAQ. The scan stage was controlled by the same DAQ card. All of the operations were assigned automatically by the LabVIEW program in the computer. The oscillograph was used to scout the PA signals for comparing with the signals which were shown on the computer’s monitor.

For testing the fast PAT imaging system, the PA imaging of one single layer was first performed. Figure 2 shows the experiment result. An advantage of the fast PAT imaging system is that it can yield the multilayer images of the sample simultaneously.

![Figure 2](image1.png)

**Figure 2.** Sample consisting of two black adhesive tape dots adhered to a piece of polymethylmethacrylate submerged in milk (a) and the reconstructed PA image using the new system (b).

Figure 3 shows the picture of a sample with a three-layer structure: (1) two black adhesive tape dots stuck to the front (shown as figure 5. O1), (2) three black adhesive tape dots stuck to the middle (shown as figure 5. O2) and (3) one black adhesive tape circle stuck to the back (shown as figure 5. O3) of two pieces of polymethylmethacrylate.

![Figure 3](image2.png)

**Figure 3.** The planform photo of the three-layer sample

The distance between the front layer and middle layer is 5mm, and that between the middle layer and back layer is 8mm. The PA signal from the three-layer sample was monitored by an oscillograph (Model: TDS1002). As figure 4 shown, the separate time slot is 2 μs and 3 μs in the PA signal.
Figure 4. The photoacoustic signal of the three-layer sample

Figure 5. The objects at the different layer O1, O2, O3 and the reconstructed PA images I1, I2, I3

The complete system is controlled with LabVIEW. The sample rate and sample length are 20MHZ and 256, respectively. With the 20M sample rate, the sampling interval is 50ns. The duration of the PA signal is about 1 µs. According the Nyquist Sampling Theorem, this data acquisition is valid. With the 256 sample length, the totaled sampling time is 0.05*256=12.8 µs. The PA signal of the front layer is at about 2 µs, and the PA signal of the back layer is at about 10 µs. Thus, all of them are in the sampling range of the system. And the complete data of the PAT signals can be acquired and saved in a computer. If we wanted to get the multilayer tomographic images simultaneously, we need only set the proper rows before the program running, the images of different layers would be reconstructed at the same time. For example, if we wanted to reconstruct the images of the front layer we need only set 40 to 70 rows at the front panel because the PA signal of the front layer was at 2-3.5 µs; if we wanted
to reconstruct the images of the middle layer we need only set 84 to 110 rows at the front panel because the PA signal of the front layer was at 4.2-5.5 $\mu$s; and so on. Figure 5 shows the pictures of the three-layers of the sample and the corresponding reconstructed results.

The experimental results indicate that the fast PAT imaging system may produce multilayer PAT images simultaneously save them for further process.

4. Summary and discussion
The key advantages of the PAT imaging system with an acoustic lens are (1) the initial photoacoustic pressure distribution can be imaged onto an image space in real time without the need of complicated computational reconstruction; (2) No artifacts appear in the reconstructed images. The fast PAT imaging system presented in this paper is simplified and the imaging efficiency of multilayer PAT is much improved by using the high speed data acquisition card. It can acquire the complete PA signals of multi-layers quickly and save them in a computer. The images of multilayer can be reconstructed simultaneously. Further study must put the emphases on the two dimension PA imaging at the same time to reveal the advantage of the PAT imaging system with an acoustic lens.

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