Shape-adapting thermoacoustic imaging system based on flexible multi-element transducer
Zhong Ji, Wenzheng Ding, Fanghao Ye, Cunguang Lou, and Da Xing

Citation: Applied Physics Letters 107, 094104 (2015); doi: 10.1063/1.4929881
View online: http://dx.doi.org/10.1063/1.4929881
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/107/9?ver=pdfcov
Published by the AIP Publishing

Articles you may be interested in
Ultra-wideband microwave imaging of breast cancer tumors via Bayesian inverse scattering

Spectroscopic thermoacoustic imaging of water and fat composition

Three-dimensional endoscopic photoacoustic imaging based on multielement linear transducer array
J. Appl. Phys. 110, 054701 (2011); 10.1063/1.3626789

Ultrasound-guided microwave imaging of breast cancer: Tissue phantom and pilot clinical experiments
Med. Phys. 32, 2528 (2005); 10.1118/1.1984349

Model-based microwave image reconstruction: simulations and experiments
Med. Phys. 31, 3231 (2004); 10.1118/1.1812871
Shape-adapting thermoacoustic imaging system based on flexible multi-element transducer

Zhong Ji, Wenzheng Ding, Fanghao Ye, Cunguang Lou, and Da Xing

MOE Key Laboratory of Laser Life Science and Institute of Laser Life Science, College of Biophotonics, South China Normal University, Guangzhou 510631, China

(Received 6 June 2015; accepted 20 August 2015; published online 31 August 2015)

Microwave-induced thermoacoustic (TA) imaging, which combines the advantages of high imaging contrast due to electromagnetic absorption and high resolution of the ultrasound technology, is a potential alternative imaging technique for biomedical applications. In the past few years, several studies have revealed that TA imaging is efficient in detecting the abnormal microwave absorption of biological tissue, particularly for breast tumor and foreign objects. Breast cancer is the leading cause of cancer deaths among women, while the mortality rate can be effectively reduced by early detection of any malignancy (tumor) in the breast. Ions and water are avidly bounded with the proliferation and angiogenesis at the cancer invasion front, and the microwave absorption would significantly increase with the ionic or water content raise at the margin of the tumor. The changes in microwave absorption of the tissues usually reflect presence of physiological lesions. The dielectric properties of normal and malignant breast tissues have been reported in many studies, and the previous studies suggest that the dielectric-properties of malignant breast tissues are up to 10 times larger than the normal adipose-dominated breast tissues in most of the microwave band. The detection of breast tumor by TA imaging has proven to be feasible, and recently more attention is paid to the research of clinical TA imaging of breast cancer.

The Circular-Scanning (CS) or Linear-Scanning (LS) modes are usually used in traditional TA imaging systems. The CS mode was employed in the early decades of the research on TA imaging techniques, which requires a single-element transducer rotating around the sample in circular fashion to acquire complete information of the target. Therefore, the data acquisition required a long period of scanning time, as dozens or even hundreds of spatial positions were needed to acquire the information necessary for imaging. In order to reduce the imaging time, linear, arc-shaped, and ring-shaped multi-element transducers have been introduced to acquire more information simultaneously. The LS mode usually employs a single-element transducer or a linear transducer for one-dimensional scanning, which is similar to B-Scan in medical ultrasound imaging.

However, both CS and LS techniques have some disadvantages. As shown in Fig. 1(a), the CS mode employs a fixed scanning radius to acquire information from different positions. However, for irregular samples, the scanning radius must be large enough to cover the longest axis of the imaging geometry. As a consequence, a large amount of coupling liquid is required to fill in the gap between sample and transducer. Although this strategy is feasible in phantom study, it hinders the practical application of TA imaging. On the other hand, the LS mode has been widely used in medical ultrasonic imaging for body scanning, while it is not suitable for TA imaging of large objects. As shown in Fig. 1(b), the LS technique can realize seamless contact with sample. However, the utilization rate of the transducer elements is low due to the existence of idle elements. Moreover, the TA wave at opposite location and lateral direction of the transducer is difficult to be detected, thus missing some information necessary for imaging. As a result, the reconstructed TA image is not completely correct, mainly corrupted with distortion and other artifacts.

In this letter, a Sample-Cling-Scanning (SCS) model is proposed, which combines the advantages of both CS and LS modes, and a flexible multi-element transducer and adaptive back projection algorithm are presented to implement this model. As shown in Fig. 1(c), most of the elements in SCS model can be brought in close contact with sample due to the controllable shape of the transducer. Theoretically, it can adapt to samples with any shape without requiring coupling liquid. When the length of flexible multi-element transducer is more than the perimeter of the sample, it can enclose the sample, so that relatively complete information can be acquired. Afterwards, the acquired information can be used to reconstruct image by the adaptive back projection algorithm.

Author to whom correspondence should be addressed. Electronic mail: xingda@scnu.edu.cn
algorithm. As shown in Fig. 1(d), after the microwave radiation of point object, the propagated TA wave can be approximated in the form of spherical wave. The TA wave arrives at element $k$ at the time $t_k = R_k/c$, where $R_k$ is the distance between element and the point object, and $c$ is the acoustic velocity, which is assumed as constant. The back projection formula can be written as

$$P(i,j) = \sum_k g_k(t)R_k = \sum_k g_k \left( \sqrt{(i-x_k)^2 + (j-y_k)^2} / c \right).$$

(1)

where $(i,j)$ is the 2D spatial coordinate of the point object, $g_k(t)$ is the time-domain signal received at element $k$, $(x_k, y_k)$ is the spatial coordinate of the element $k$, and $N$ is the total number of elements. The TA image can be reconstructed by traversing all discretized spatial points in the suspicious areas under investigation. In summary, this algorithm is a transformation of the unfiltered (or simple) back projection algorithm, and the difference is the feedback of coordinates of a group of elements when the transducer adapts the geometrical shape of the sample. This algorithm, although not theoretically true, is numerically equivalent to the delay-and-sum beam forming method used in ultrasound imaging systems. Therefore, it is readily implemented in combined ultrasound-thermoacoustic imaging systems. 18 Meanwhile, due to low computational complexity of the algorithm, the image reconstruction time is minimal to realize a real-time imaging system.

The experimental setup is shown in Fig. 2(a). The microwave generator used in this study is operating at 6 GHz, radiating a pulse width of 500 ns and peak power of 350 kW (Ref. 13) from a waveguide (BY56). A flexible 64-elements transducer (7.5S64-0.5*10, Doppler Ltd., China) is used as energy converter from ultrasound to electrical signal with an operational frequency of 7.5 MHz and 70% bandwidth. The transducer is made of composite material, which composes of piezoceramics (BaTiO3) and polyvinylidene difluoride. The underlayment is made of rubber, so this transducer has a good flexibility, and its smallest curvature radius is about 5 mm. The transducer can endure at least one hundred thousand times bending. The effective length of the non-focusing transducer is 32 mm, and each element has a size of 0.5 $\times$ 10 mm$^2$. The relative echo sensitivity of each element is about $-34.2$ to $35.1$ dB. Fig. 2(b) shows the photographs of flexible multi-element transducer with two different shapes. The signals from each element are amplified (30 dB), filtered, and acquired by two 32 channel acquisition cards (5752, National Instruments, USA) at a sampling rate of 50 Msamples/s, which is similar to that used in the previous article.13 The channel acquisition cards are synchronized by two onboard Field Programmable Gate Arrays (FPGAs, 7965 R, National Instruments, USA), which are controlled by Labview software in computer. In order to

![FIG. 1. The principle of adaptive TA imaging and the adaptive back projection algorithm. Demonstration of signal acquisition of CS (a), LS (b), and SCS (c) mode; (d) the process of adaptive back projection algorithm.](image-url)
explore the overall ability of data acquisition system, a typical signal, which generated from a plastic tube with a diameter of 0.5 mm, is acquired as shown in Fig. 2(c). The central frequency of this system is about 6.2 MHz through Fourier transformation. The acquired information can be used to reconstruct the image by the adaptive back projection algorithm.

An experiment is performed to demonstrate the data integrity of the SCS mode. The target object is a water-filled plastic tube with a diameter of 5 mm, and the sample is immersed in mineral oil, which is serving as coupling liquid. In the CS mode, a single-element transducer is used with a fixed scanning diameter of 20 cm. The linear transducer is 5 cm wide, and the central frequency of each element is 7.5 MHz. The TA measurements are acquired by single-element transducer, linear transducer, and the proposed flexible transducer, respectively, and the results are shown in Fig. 3(a). In the TA image, by taking the center of the sample as the origin of polar coordinates, and making statistics of the maximum pixel value along the arrows in (a) changing with \( z \), the result is shown in Fig. 3(b). About 39% of the circumference is less than the intensity of maximal noise in the LS mode imaging, and the values are near to zero in CS and SCS mode imaging. The results indicate that both the CS and SCS mode can obtain a relatively integrated data. In contrast, the LS mode failed to capture the details of the whole structure of the sample, particularly for that in lateral direction. It should note that the effective receiving area of single-element transducer, linear transducer, and the flexible transducer is \( \pi \times 5^2 \) mm\(^2\), 0.39 \( \times \) 6, and 0.5 \( \times \) 10 mm\(^2\), respectively. Meanwhile, the materials of each transducer are not the same, so the comparison of signal to noise ratios of the three images is not necessary.

Another experiment was conducted to study the energy transmission efficiency of three modes. As shown in Fig. 4(a), the transducer is in close contact with sample in array \( a_1 \sim a_8 \) and approximately 5 cm away from the sample in array \( b_1 \sim b_8 \). The formation of array \( a_1 \sim a_8 \) represents close contact mode, similar to SCS and LS modes. On the other hand, the array structure in \( b_1 \sim b_8 \) represents the liquid coupling mode, similar to CS mode. The detected signal intensity at each position is shown in Fig. 4(b). It can be found that the transmission efficiency of close contact mode is approximately 80% higher than that of liquid coupling mode. One of the possible reasons for this improvement comes from the reduced acoustic reflections in the contact mode. It is well known that the acoustic reflections and scattering can lead to energy dissipation in the interface. The TA wave only
propagates through one interface (fat/transducer interface), but liquid coupling mode has two interfaces (fat/mineral oil interface and mineral oil/transducer interface). Meanwhile, the transmission distance of SCS mode is shorter than the CS, which reduces the energy attenuation that is another possible reason of high transmission efficiency. Considering the results in Figs. 3 and 4, it can be concluded that the employment of SCS mode in TA imaging system has considerable advantages over the CS and LS, including shape adaptation, information integrity, and efficient transmission.

The proposed scanning mode is well suitable for samples whose shapes approach to round, particularly for breast tumor, so it can be a better choice for the TA imaging system of breast tumor. As a demonstration, an experiment of tumor imaging has been conducted in this study. The X-ray mam- mogram of an in vitro tumor from breast cancer patient is shown in Fig. 5(a). The size of the tumor is approximately $16 \times 10$ mm, and it is embedded into simulated normal breast tissue in a rounded mould, whose diameter is 50 mm. The corresponding TA image using the proposed system is shown in Fig. 5(b), and it can be observed that the shape is accurately matched with the X-ray image. Meanwhile, the TA image has shown higher contrast. On the other hand, when...
the shape of sample is highly irregular, especially with sharp corner, this method may not be the most suitable option.

As the effective length of flexible multi-element transducer used in this letter is 32 mm and the sample usually has a larger size, the transducer needs to acquire information from several positions (3 positions in Fig. 3(c) and 10 positions in Fig. 5(b)). But it does not hamper applications of this scanning method. Furthermore, a longer transducer, which can enclose most of human breast, could solve the problem.

The positions of each element \((x_k, y_k)\) are necessary to be obtained for image reconstruction by the adaptive back projection algorithm, and the precision of position will severely affect the image resolution. One of the possible approaches to estimate the position is optical method. By using Charge Coupled Device (CCD), a picture of the whole system can be taken from top view, so the coordinates of the elements can be measured. Considering typical values, for example, for a CCD with 1024 \(\times\) 768 pixels, when the size of view field is 100 \(\times\) 100 mm\(^2\), the corresponding area of a single pixel is approximately 0.1 \(\times\) 0.1 mm\(^2\). Therefore, the precision is in the order of magnitude of 0.1 mm, which is enough for the existing systems. In the future, increasing pixel number and reducing the field of view is conducive to improve the precision. The main limitation of this method is requirements of additional instruments. Another possible approach is using acoustic method. The target positions can be worked out by using the geometrical relationship of ultrasound waves comes from two fixed positions. This method is simple and convenient, but the precision is limited to wavelength of the ultrasound, which is relatively large.

In conclusion, a shape-adapting TA imaging system operating in SCS mode and based on flexible multi-element transducer has been developed in this letter. The experimental results show that the proposed system combines advantages including shape adaptation, information integrity, and efficient transmission. These advantages make it a preferred system for TA applications, especially in breast tumor detection.

This research was supported by the National Basic Research Program of China (2011CB910402), the National Natural Science Foundation of China (Nos. 61331001, 61361160414, 81127004, 11104087, 81402187, and 11304103), the National High Technology Research and Development Program of China (2015AA020901), The Science and Technology Planning Project of Guangdong Province, China (2013B090500122), the Guangdong Natural Science Foundation (S201302012646 and S201304016419), the Pearl River S&T Nova Program of Guangzhou (2014J2200028), and the Scientific Research Foundation of Graduate School of South China Normal University.