Acoustic methods for cavitation mapping in biomedical applications

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Abstract. In recent years, cavitation is increasingly utilized in a wide range of applications in biomedical field. Monitoring the spatial-temporal evolution of cavitation bubbles is of great significance for efficiency and safety in biomedical applications. In this paper, several acoustic methods for cavitation mapping proposed or modified on the basis of existing work will be presented. The proposed novel ultrasound line-by-line/plane-by-plane method can depict cavitation bubbles distribution with high spatial and temporal resolution and may be developed as a potential standard 2D/3D cavitation field mapping method. The modified ultrafast active cavitation mapping based upon plane wave transmission and reception as well as bubble wavelet and pulse inversion technique can apparently enhance the cavitation to tissue ratio in tissue and further assist in monitoring the cavitation mediated therapy with good spatial and temporal resolution. The methods presented in this paper will be a foundation to promote the research and development of cavitation imaging in non-transparent medium.

1. Introduction
Acoustic cavitation is the phenomenon observed when ultrasound of sufficient intensity is transmitted through a liquid causing micron-sized gas bubbles, termed as active cavitation bubbles, to oscillate, grow, and violently implode giving rise to extreme, but localized, conditions within the collapsed cavities. When ultrasound exposure is turned off, these residual cavitation bubbles tend to dissolve. With pulsed ultrasound, residual cavitation bubbles between successive ultrasound exposures may be acted as cavitation nucleus to enhance cavitation effects. An understanding of spatial-temporal distribution of both active and residual bubbles is essential to optimize cavitation induced various applications. In this paper, several acoustic methods for cavitation mapping developed or modified on the basis of previous study will be summarized to help to depict spatial-temporal distribution of both active and residual cavitation bubbles in non-transparent medium.

2. Methods and Results

2.1. Microsecond Resolution Ultrasound Line-by-line 2D Mapping
As cavitation is highly complex with transient characteristics, it is essential to develop a standard cavitation mapping similar to the exact acoustic field characterization with both high spatial and
temporal resolutions. A novel precise active cavitation mapping (ACM) by a modified ultrasound line-
by-line scanning method is proposed by Ding et al [1]. Scattered signals from cavitation bubbles are
firstly obtained by a scan line immediately after one high intensity focused ultrasound (HIFU)
exposure, and then there is a waiting time (2s) to make the liquid back to the original state. As this
pattern extended, an image can be built up by sequentially acquiring a series of such lines. The
synchronization of HIFU exposure and radio frequency (RF) data acquisition by a programmable
ultrasound scanner (Sonix-RP, Ultrasonix, Burnaby, BC, Canada) is illustrated in figure 1 (a). T and D
which can vary from microseconds to seconds are HIFU exposure time and time delay between RF
data acquisition and the end of HIFU exposure, respectively.

The temporal evolution of cavitation bubble cloud in tap-water is shown figure 1 (b). The principle of this technique is very simple while it may be a useful tool in cavitation mapping for
different cavitation sources which can be repeated.

2.2. Ultrafast Active Cavitation Mapping with Plane Wave

The method introduced in section 2.1 is time-consuming and restricted within the medium with
repeatable cavitation distribution. Nevertheless, the due to the transient characteristics, mapping of
cavitation should be achieved with high frame rate, preferably at one time over the entire region. Hu et
al. employed an ultrafast ACM (UACM) with high temporal resolution and relatively good signal-to-
noise ratio (SNR) by combining plane wave transmission, minimum variance (MV) beamforming and
coherece factor (CF) weighting to monitor the evolution of residual cavitation bubbles during
histotripsy process [2]. The schematic representation of the process is shown in figure 2 (a).

Figure 2 (b) shows the representative image sequence of residual bubbles around the water-tissue
interface in histotripsy (Pulse Duration = 10 μs, PRF = 2 kHz, total HIFU pulses = 840000), from
which the residual bubbles are distributed at the interface of the tissue initially, then gradually
expanded to the internal region of the tissue with an increasing HIFU pulse number, and finally the
entire bubble cloud gets distributed within the tissue. However, there are no significant differences
between the B-mode images before and after histotripsy. A direct relationship with a coefficient of
1.0365 between histotripsy lesion area and inner residual bubble area was found, as shown in figure 2
(c). These results can assist in monitoring and optimization of the other cavitation enhanced therapy
further.
2.3. Microsecond Resolution Ultrasound Plane-by-plane 3D Mapping
Combining the methods presented in section 2.1 and 2.2, an ultrasound plane-by-plane method for 3D cavitation mapping is proposed by our group [3]. Scattered signal from cavitation bubble cloud immediately after one HIFU exposure was obtained by plane wave. Then a series of spatial channel-domain raw RF data were obtained in plane-by-plane mode. The cavitation bubble distribution in 3D was reconstructed by reconstruction algorithm. MV adaptive beamforming, CF weighting and compressive sensing (CS) theory were used to process the raw RF data to improve the spatial resolution, SNR and calculation speed.

2.4. UACM with Enhanced Cavitation to Tissue Ratio Based on Bubble Wavelet Transform and Pulse Inversion Technique
Due to the low transmission pressure of plane wave, a reduction in the backscattering signals occurs, leading to poor image quality aggravating cavitation detection. To solve this problem, a UACM method that combined wavelet transform with pulse inversion (PI) technique was modified on the basis of our previous work on ultrasound contrast imaging [4]. A mother wavelet named “cavitation bubble wavelet” was constructed according to Rayleigh-Plesset-Noltingk-Neppiras-Poritsky model. A high correlation between cavitation bubble wavelet and backscattering signals was expected to obtain [5].

Results showed that the image quality was associated with the initial radius of bubble and the scale. The SNR of the best cavitation bubble wavelet transform (CBWT) mode image (right panel of figure 4(a)) was improved by 3.2 dB compared with that of the B-mode image (left panel of figure 4(a)) in free-field experiments. Figures 4(c) and 4(d) showed that cavitation to tissue ratio (CTR) of the optimum PI-based CBWT mode image was improved by 2.2 dB compared with that of the PI-based B mode image in tissue experiments. Based on this method, the spatial distribution of the cavitation bubbles was clearly observed.
2.5. Passive Cavitation Mapping

Conventional algorithm of PCM is to calculate short-term energy accumulation of channel data in time domain or frequency domain. Figure 5 is spatial distribution of active bubbles in free field during HIFU exposure with a temporal resolution of 0.5ms. Through calculating energy accumulation of acoustic emission received by a linear array, process of bubble cluster evolution within 12ms can be tracked. Besides, sonoluminescence, the most direct indicator of bubble inertial collapse, has been employed to map the active cavitation bubbles. However, it is limited in the transparent medium and might not be applied to investigate the active bubble distribution in tissue.

Figure 5 Passive cavitation mapping within 12ms.

3. Conclusions

The proposed novel ultrasound line-by-line/plane-by-plane method can map residual cavitation bubbles with high spatial and temporal resolution and may be developed as a potential standard 2D/3D cavitation field mapping method. The modified UACM based upon plane wave transmission and reception together with bubble wavelet and PI technique can apparently enhance the CTR in tissue and further assist in monitoring the cavitation mediated therapy with good spatial and temporal resolution. All the developed or modified acoustic methods for cavitation mapping established solid foundation for cavitation imaging in non-transparent medium.

References
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