Dual-frequency Shear Wave Motion Detection

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Abstract—Shear wave motion detection is a critical part of ultrasound shear wave elastography (SWE). Shear wave signal-to-noise-ratio (SNR) is strongly related to the ultrasound RF (radiofrequency) signal SNR. Recently, we demonstrated substantial improvement of shear wave motion detection using pulse-inversion harmonic imaging (PIHI). In this study we propose to use filter-based harmonic imaging (FHI) to realize dual-frequency shear wave motion detection. With a filter-based approach, one can calculate shear wave motion signal from both the fundamental component and the harmonic component of the RF signal that is acquired from a single pulse-echo cycle. Two types of common shear wave imaging methods were investigated using dual-frequency detection: shear wave imaging with acoustic radiation force (ARF) as the shear wave source, and shear wave imaging with external mechanical vibration as the shear wave source. Phantom studies showed that for ARF based SWE, the push beam attenuates faster than the harmonic signal, and therefore, one can use harmonic signal for shear wave detection throughout the range of depth; for external mechanical vibration-based SWE, one can use harmonic signal to calculate shear wave motion for shallower region of the tissue for better SNR, and fundamental signal to calculate shear wave motion for deeper region of the tissue for better penetration, so that robust shear wave motion detection can be achieved throughout a large range-of-depth.

Keywords—shear wave detection; harmonic imaging; dual-frequency; mechanical vibration; acoustic radiation force

I. INTRODUCTION

Ultrasound shear wave elastography characterizes tissue mechanical properties with shear waves. Shear waves can be induced into the tissue by external mechanical vibrations [1], acoustic radiation force [2], and intrinsic physiological motions [3]. Different shear wave elastography techniques utilize different shear wave post-processing techniques to recover tissue mechanical properties [4]. Regardless of the source of the shear waves and the post-processing method, shear wave detection plays a very important role for robust assessment of tissue mechanical properties, because it is directly associated with the quality of the shear wave signal.

Recently, we demonstrated a substantial improvement of shear wave motion detection using pulse-inversion harmonic imaging (PIHI) [5]. Ultrasound harmonic signals are less vulnerable to clutter noises caused by reverberations from subcutaneous tissues [6], and have a finer resolution cell which favors accurate shear wave motion calculation [7]. While PIHI intrinsically enhances the second harmonic signal and suppresses the fundamental signal, the pulse repetition frequency (PRF) is reduced by a factor of two because PIHI requires two transmit-receive events. This can be problematic for acoustic radiation force (ARF) shear wave detection because ARF shear waves are fast and transient. Filter-based harmonic imaging (FHI) [8], on the other hand, does not have the PRF loss but is less efficient in harmonic imaging than PIHI. One advantage of FHI though is that both the fundamental and harmonic components of the RF signal are preserved, such that shear wave motion can be calculated from both, whereas for PIHI fundamental signal is typically lost after the summation. In this study, we propose to use FHI to realize dual-frequency shear wave detection. The hypothesis was that for shallower regions one can achieve high shear wave SNR from the harmonic component of the RF signal, and for deeper regions one can use the fundamental component of the RF signal to calculate shear wave for better penetration. The dual-frequency technique was tested on ARF-based and mechanical vibration-based shear wave imaging methods using tissue-mimicking phantoms.

II. METHODS

A. Dual-frequency shear wave detection

In this study, a wide detection beam was designed on a curved array C5-2v (Verasonics Inc., Redmond, WA) for dual-frequency shear wave detection, as shown in Fig. 1. All experiments were conducted on the Verasonics Vantage system (Verasonics Inc., Redmond, WA). The wide beam was formed by transmitting a weakly focused beam. The focal depth was placed very far from the transducer surface, and then the calculated transducer delay profile was further tuned (e.g. divide the delay profile by a constant number) to widen the beam and spread the acoustic energy more uniformly in space. To increase ultrasound SNR, a plane wave compounding method [9] was used with three different steering angles (-2°, 0°, 2°), as shown in Fig. 1. The resulting beam has an approximate width of 7 cm, which is sufficient to capture both ARF and mechanical vibration-induced shear waves.

To realize dual-frequency shear wave detection, the detection beams were transmitted with a frequency of 2.25 MHz, which produces second harmonic signals around 4.5 MHz, so that both the fundamental and harmonic components of the RF signal are within the bandwidth of the C5-2v transducer. During receive, the RF signals from three steering angles were first compounded. Then a digital finite-impulse-response (FIR) filter was used to extract the fundamental and the second harmonic components of the RF signal separately. The shear wave motion signals can then be calculated from both components using 1D autocorrelation method [10].
to the detection noise.

Shear wave SNR was considered as shear wave detection noise. Shear wave signal, and the rest of the spectrum was averaged and pixel, the signal energy at 50 Hz was considered as the shear wave motion signal was calculated from both the fundamental and harmonic components of the RF signal. To compare the shear wave SNR, a Fourier transform was performed on the shear wave signal along the temporal direction for each imaging pixel. In each spectrum from each pixel, the signal energy at 50 Hz was considered as the shear wave signal, and the rest of the spectrum was averaged and considered as shear wave detection noise. Shear wave SNR was then obtained by calculating the ratio of shear wave signal to the detection noise.

I. RESULTS

A. ARF shear wave experiments

Figure 2 shows the shear wave motion signal detected by the fundamental and harmonic components of the RF signal at different depths. The shear wave signal detected by the harmonic component has higher quality than that detected by the fundamental component. The harmonic shear wave signal is better delineated and there is significantly less jittering than the fundamental shear wave signal.

B. ARF shear wave experiments

This part of the experiment was conducted on a liver fibrosis phantom (Model 039, CIRS Inc., Norfolk, VA) with Young’s modulus of 3.5 kPa. A focused ultrasound push beam (center frequency = 2.25 MHz, duration = 600 μs, F/# = 2) focused at different depths (30, 40, 50, 60, 70 mm) were used to produce shear waves. The shear wave detection PRF was 2.2 kHz after compounding. The shear wave motion signals were calculated from both the fundamental and harmonic components of the RF signal and then compared at the focal depth of the push beam.

In the second part of the experiment, an excised piece of pork belly (~2.5 cm thickness) was placed in between the transducer and the phantom surface to simulate subcutaneous tissue. A thin layer of degassed water was poured in between the pork belly and the phantom to ensure good coupling. The F/# of the push beam was changed to 1.5 to improve shear wave generation. The rest of the experiment procedure was the same as the first part of the study above.

C. Mechanical vibration shear wave experiments

This part of the experiment was conducted on a large phantom (Model 040GSE, CIRS Inc., Norfolk, VA) with a dimension of 17.8 cm x 12.7 cm x 20.3 cm (length x width x height). A loudspeaker was used to provide stable shear waves throughout the phantom. The loudspeaker setup is similar to the one used in [11] and is not described here for succinctness. A 50 Hz continuous vibration was used to generate shear waves. Shear wave motion signal was calculated from both the fundamental and harmonic components of the RF signal. To compare the shear wave SNR, a Fourier transform was performed on the shear wave signal along the temporal direction for each imaging pixel. In each spectrum from each pixel, the signal energy at 50 Hz was considered as the shear wave signal, and the rest of the spectrum was averaged and considered as shear wave detection noise. Shear wave SNR was then obtained by calculating the ratio of shear wave signal to the detection noise.

Figure 3 shows shear wave motion signal after adding the excised piece of pork belly. One can immediately see the significant deterioration of the shear wave signal by the pork belly. In general, the harmonic signal provided better shear wave signal quality than the fundamental signal. The “butterfly-shaped” shear wave is more discernable from the harmonic component from 30 mm to 60 mm than that from the fundamental component. At 70 mm, neither fundamental nor harmonic could detect any discernible shear wave motion. This is either because the push beam was significantly attenuated and either no shear wave or very weak shear wave was generated at this depth, or the detection fell apart: for the harmonic component, the harmonic signal might have been severely attenuated at 70 mm; for the fundamental component, similar to other depths, the clutter noise and phase aberration introduced by the pork belly might still be strong and thus no motion can be detected.

Fig. 1. Dual-frequency detection beams with three different steering angles (left to right: -2˚, 0˚, and 2˚).

Fig. 2. Shear wave motion signal detected by the fundamental (left column) and harmonic (right column) components of the RF signal. Note the color scale difference for depths 60 and 70 mm.

Fig. 3.
In in vivo applications, a shear wave imaging depth around 7 to 8 cm is typically expected for abdominal imaging using the curved array. For this range of depth, one can use harmonic components of the RF signal to calculate shear wave motions instead of using fundamental components, based on the results from Fig. 3. Note that the pork belly used in this study was not warmed up to body temperature and therefore the attenuation can be much stronger than in vivo subcutaneous tissue. Nevertheless, the harmonic signal should be able to sustain to about 7 to 8 cm of depths and therefore, one can use harmonic imaging for ARF-based shear wave detection throughout the field of view (FOV).

### B. Mechanical vibration shear wave experiments

Figure 4(a) shows the shear wave particle velocity signal plots from 5 depths calculated from the fundamental and harmonic components of the RF signals. The SNR of the shear wave from fundamental signal is 6.0, 7.8, 5.3, 6.5, and 5.5 dB at the 5 depths, as compared to 9.1, 10, 4.4, -0.31, and -14 dB from the harmonic signal. This corroborates with the plots in Fig. 4(a) which shows that the shear signal quality from harmonics is better than that from the fundamental in depths < 90 mm, and the fundamental outperforms the harmonic signal in depths > 90 mm. The harmonic signal had better performance in the near field because it is less vulnerable to the clutter noise introduced by the pork belly and has finer resolution cell. However the harmonic signal gets significantly attenuated beyond 90 mm depth, and the fundamental signal begins to have better performance because it has better penetration than the harmonics.

To take advantage of the dual-frequency detection, one can use the harmonic signal to reconstruct the first part of the 2D shear wave speed map for depths < 90 mm, and then use the fundamental signal to reconstruct the second part of the 2D map for depths > 90 mm. Figure 4(b) shows the final 2D shear wave speed map reconstructed using local frequency estimation (LFE) [12]. The measured shear wave speed within the ROI is 2.87 m/s (nominal value = 2.89 m/s). An alternative way of using the dual-frequency-detected shear wave signal is to combine the shear wave motion signal first and then use the combined shear wave signal to reconstruct a 2D shear wave speed map. One can also use the shear wave SNR as a weighting coefficient to weighted sum the shear wave signal detected by the fundamental and harmonics so that at each spatial location, a robust shear wave signal is used for shear wave reconstruction.

### II. DISCUSSION AND CONCLUSIONS

This study introduced a dual-frequency shear wave detection method that uses filter-based techniques to separate the fundamental and harmonic components of the RF signal, from which shear wave motion signal can be calculated separately and then combined to achieve high SNR shear waves. It was found that for ARF-based shear wave elastography, one can use the harmonic component for shear wave detection throughout the range of depth because shear wave generation typically becomes very weak beyond 7 to 8 cm of depth. For mechanical vibration-based shear wave elastography, however, because shear wave can be produced at a much deeper depth, one can use harmonic signals for shear wave detection up to 9 cm based on the results shown in this study, and then switch to fundamental signals for depths beyond 9 cm. In this way one can benefit from the better portion of the RF signal to ensure robust shear wave detection, which would ultimately facilitate more robust shear elasticity.
mechanical vibration-induced shear waves, which make them therefore could not robustly detect the shear wave motion. The detection that was more affected by the pork belly and therefore shear wave generation was poor; another possible reason is that the push beam was fine and shear wave generation was robust, but the shear wave detection was significantly deteriorated by clutter and phase aberration noise from the pork belly. Figure 5(a) shows an experimental setup that uses two transducers (Probe1 for push and Probe2 for detect) to study this problem. Figure 5(b) shows that when using Probe1 to detect the shear waves produced by itself through the pork belly with harmonic signals, the shear wave signal is very noisy; however when using Probe2 to detect the same shear wave produced by Probe1, the shear wave motion is very strong and the signal is very clean. This indicates that the shear wave generation is robust even though the push beam had to penetrate the pork belly. It is the shear wave detection that was more affected by the pork belly and therefore could not robustly detect the shear wave motion. The ARF-induced shear waves are with small motion amplitude and have much smaller size (i.e., wavelength) as compared to mechanical vibration-induced shear waves, which make them more sensitive to phase aberration and clutter noise. Although harmonic signal has much less clutter noise and finer resolution cell than the fundamental signal, it still suffers from phase aberration. One can potentially use phase aberration correction approaches to further optimize shear motion detection, as one can clearly see that there is still significant difference between the detected shear wave signal (Fig. 5(b)) and the true shear wave signal (Fig. 5(c)).

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Fig. 5. (a) Two-probe setup for the study of the effect of the pork belly on the push beam and on the detection beam. (b) Shear wave detected by Probe1 through the pork belly. (c) Shear wave detected by Probe2.