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Development of a Shear Wave Propagation Simulation Model for Liver Viscoelasticity Measurement

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1. Introduction

Nonalcoholic steatohepatitis (NASH), a lifestyle disease often linked to obesity, is highly prevalent and can lead to severe complications such as hepatocellular carcinoma and cirrhosis[1]. Given the association of NASH with liver fibrosis, there is a growing need for noninvasive diagnostic methods to assess liver viscoelasticity.

Ultrasound-based measurement of tissue viscoelasticity has been the subject of numerous studies over an extended period. One prevalent approach involves the quasi-static method, where internal strain is applied to the tissue, and the resulting strain is quantified using Doppler measurement[2]. However, this approach assumes a constant internal stress distribution, which can compromise the diagnostic quality of the resulting images[3]. In contrast to the quasi-static method, transient elastography estimates tissue viscoelasticity by exciting shear waves in the tissue using the acoustic radiation force (ARF) of an ultrasound transducer[4]. Unfortunately, the high frame rate requirement for ARF-based methods often leads to increased costs. To address this issue, we developed continuous shear wave elastography (C-SWE), which utilizes an external vibrator to excite the shear wave, presenting a cost-effective alternative approach[5]. However, extensive in-vivo experiments are necessary to comprehensively optimize the performance of C-SWE, assess its robustness, and expedite the computation.

In this study, we present the development of a Doppler signal simulator for the proposed method, C-SWE. To investigate and enhance the performance of the algorithm, intentional noise was incorporated into the simulator. The simulation process is elaborated upon in the subsequent section, and the results obtained are provided to demonstrate the efficacy of this simulation algorithm. Moreover, we assess the robustness of the algorithm by evaluating its performance under the varying intentional noise conditions.

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2. Doppler Signal Simulation

In C-SWE, the excited shear wave reflects transmitted ultrasound by frequency shifting. The received signal at the ultrasonic probe can be mathematically represented as follows:

$$\boldsymbol{y} = y_0 exp\left(j\left(2\pi f_0 t + \frac{4\pi f_0}{c}\xi(t)\right)\right), \quad (1)$$

where y_0, f_0, c, and $\xi(t)$ indicate the amplitude of the received ultrasound, the central frequency of the transmitted ultrasound, the speed of sound, and the displacement of the ultrasonic scatterer by the shear wave, respectively. Next, quadrature detection is performed to extract the Doppler frequency shifts using the reference signal $\boldsymbol{R}$ as follows:

$$\boldsymbol{I} = \boldsymbol{y}\boldsymbol{R}^* = \boldsymbol{y}\, exp(-j2\pi f_0) = y_0 exp\left(j\frac{4\pi f_0}{c}\xi(t)\right), (2)$$

By processing the signals, the real and imaginary parts are restored as simulated Doppler signals:

$$I = y_0\, cos\left(\frac{4\pi f_0}{c}\xi(t)\right), \quad (3)$$

$$Q = y_0\, sin\left(\frac{4\pi f_0}{c}\xi(t)\right). \quad (4)$$

Here, the displacement of the ultrasonic scatterer caused by the shear wave, $\xi(t)$, can be modeled as a sine wave, and it can be expressed as:

$$\xi(t) = \xi_0\, sin(\omega_b t + kx + \phi_b), \quad (5)$$

where ξ_0, ω_b, k, x, and ϕ_b represent the amplitude, the angular velocity, the wave number of the shear wave, the position of the ultrasonic scatterer, and the initial phase of the shear wave, respectively. By combining equations (3), (4), and (5) and adding Gaussian white noise components of $n(t)$ to the signal, the simulated Doppler signals can be expressed as follows:

$$I = y_0\, cos\left(\frac{4\pi f_0 \xi_0}{c} sin(\omega_b t + kx + \phi_b) + n(t)\right), (6)$$

$$Q = y_0 \sin\left(\frac{4\pi f_0 \xi_0}{c} sin(\omega_b t + kx + \phi_b) + n(t)\right), (7)$$

Finally, the generated Doppler data is processed, and the shear wave velocity can be obtained using the methods described in our previous work[6].

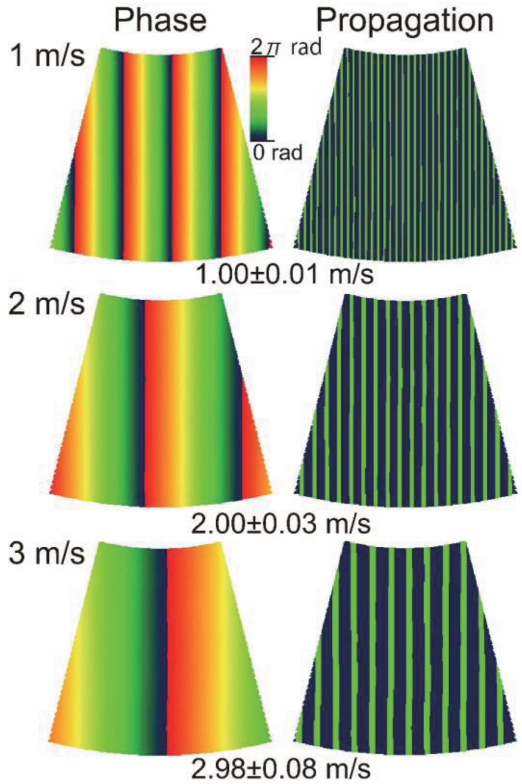

Fig. 1 Phase maps and propagation maps at varying shear wave velocities. The additive noise, normalized by signal amplitude (standard deviation = 3.0), is demonstrated thorough the simulator.

3. Result

In accordance with the aforementioned calculation process, Doppler data was generated at various shear wave velocities. Subsequently, the simulated datasets were processed utilizing the algorithm developed in our previous work. As illustrated in Figure 1, the resulting phase and propagation maps from the simulated datasets exhibited significant agreement with the shear wave velocity used as input before simulation. This observation indicates the effectiveness and validity of our simulation process.

Accuracy of the estimated shear wave velocity under additive noise to the Doppler signal was thoroughly investigated, as demonstrated in Figure 2. To assess the algorithm's resilience, the proposed Doppler signal simulator was utilized to introduce varying amplitudes of noise into the signals. Subsequently, the standard deviation of the estimated shear wave velocity was computed, serving as a measure of C-SWE's robustness. As illustrated in Figure 2, C-SWE exhibits a negligible error of under 5 % in subjected to 3.5 dB of the noise. This confirms the algorithm's significant immunity to noise and underscores its reliability in challenging environments.

4. Conclusion

Doppler signal simulator for C-SWE has been

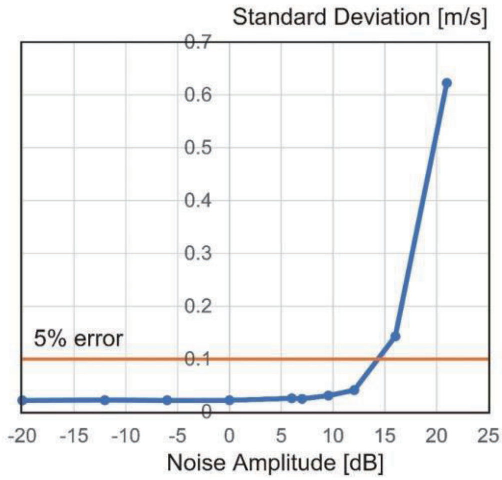

Fig. 2 Accuracy of the estimated shear wave velocity under additive noise to the Doppler signal. The x-axis represents the noise amplitude, calculated as the ratio of the additive noise to the signal amplitude. The y-axis depicts the standard deviation of the estimated shear wave velocity.

developed in the presented process and its validity has been confirmed through a good agreement between the calculated shear wave velocity and preset velocity to the simulator. Furthermore, robustness analysis on C-SWE has been conducted using the presented simulator.

However, in the context of creating a more realistic simulator, it is essential to consider the inclusion of noise arising from various sources, such as standing waves resulting from reflected shear waves and displacement fluctuations caused by body motion and pulsation. To address this, further comprehension on the shear wave propagation on the tissue is required.

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References

1) White DL, Kanwal F and El-Serag HB, CGH, 10(12), 1342–1359 (2012).
2) O'Donnell, Matthew, et al., IEEE Trans Ultrason Ferroelectr Freq Control, 41.3, 314-325 (1994).
3) Doyley, Marvin M, Phys. Med. Biol. 57.3, R35 (2012).
4) Nightingale, Kathryn, Stephen McAleavey, and Gregg Trahey, Ultrasound Med Biol 29.12, 1715-1723 (2003)
5) Tsuchida, Wakako, et al., Sci. Rep., 10.1, 22248 (2020).
6) Yamamoto, Atsushi, et al., J. Med. Ultrasound, 45, 129-136 (2018).