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Measurement of Shear Wave Absorption with Correction of the Diffraction Effect for Viscoelasticity Characterization of Soft Tissues

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1. Introduction

Shear elasticity (G) and viscosity (η) are two important parameters to characterize the mechanical properties of soft tissues. In medical diagnosis, the determination of the G has been a popular topic since it can be used to evaluate the soft tissue health according to the stiffness difference between normal and abnormal tissues.[1] Many studies also suggested that η could be a useful index of tissue health.[2] These parameters can be estimated by tracing and analyzing shear wave (SW) propagation inside a specimen.[3]

Several studies estimated η from v_S dispersion measurement and analysis.[4-5] The advantage of such a method is that it avoids a direct measurement of SW absorption (α_S), which is rather challenging to measure precisely since the reflections and diffraction of SW within a specimen could deform SW waveforms observed, resulting in the measurement error. Also it requires multiple measurements at different frequencies to obtain the v_S dispersion unless an impulse SW having a broad frequency bandwidth is used with a high frame-rate ultrasound system to trace the impulse SW.[6]

In our previous study, a measurement method of SW velocity (v_S) was investigated by using conventional ultrasound B-mode scanning with continuous SW.[7] We proposed a method using a B-mode scanning time delay that could effectively reduce the influences of undesired SW reflections. In this paper, a measurement of α_S is studied based on the SW attenuation measurement of a soft tissue mimicking phantom with a compensation of diffraction effect using the conventional B-mode scan of focused ultrasound.

2. Methodology

SW attenuation is represented by the amplitude loss of a SW propagating a certain distance. Absorption, scattering, diffraction, reflection, and mode conversion are the main sources of the SW attenuation. In this study, it is assumed that a specimen is homogenous and isotropic having a finite size, and the scattering effects and mode conversion are negligible. The SW reflection can be compensated by the method using B-mode scanning time delay.[7] Therefore, the absorption and diffraction are the main factors of the SW attenuation in our experimental configuration.

Fig. 1 shows the measurement configuration of α_S. The origin of the coordinate system is at the center of the interface between the SW source and the specimen. The ultrasound probe is placed on the top of the specimen. The SW source contacts one side of the specimen and induces the continuous SW propagating along the positive z-direction, while the B-mode scanning is toward the negative z-direction. Tissue displacements along the x-direction caused by the SWs are detected by the ultrasound probe. At a certain time, the induced SW displacement $V_I(z)$ and its amplitude $A_I(z)$ are expressed as follows:

$$V_I(z) = A_I(z)\cos\left[-\omega_S\left(\frac{1}{v_S}+\frac{1}{v_{scan}}\right)z+\varphi_I\right], \quad (1)$$

$$A_I(z) = A_S \cdot ATT(z) \cdot e^{-\alpha_S z}, \quad (2)$$

where A_S and φ_I are the initial amplitude and phase of the induced SW at the SW source (z = 0), respectively. ω_S (= $2\pi f_S$) is the angular frequency of SW, where f_S is the SW frequency. v_{scan} (= Δz / Δt) is the speed of the B-mode scan, where Δz and Δt are the spatial and temporal interval, respectively, between two consecutive A-mode ultrasound measurements. $ATT(z)$ is the attenuation due to the diffraction effect and α_S is the SW absorption coefficient. $ATT(z)$ can be calculated using a Huygens-Fresnel diffraction theory.[8]

A Hilbert transform ($\mathcal{H}_z$) is applied on the observed $V_I(z)$ to create a complex signal $V_I{}^*(z)$, and then A_I is obtained by:

$$A_I(z) = |V_I{}^*(z)|. \quad (3)$$

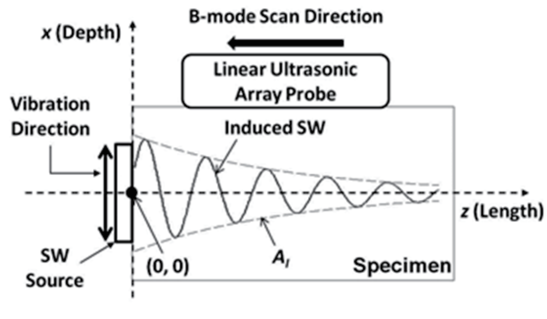

Fig. 1. Measurement model of SW absorption.

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Therefore, α_S can be estimated from $A_I(z)$ obtained and $ATT(z)$ calculated. In this study, the A_I obtained from Eq. (3) in a chosen range of z is compared to the A_I numerically calculated by Eq. (2), to find the best fitting value of α_S which gives the least square error between the measured and calculated A_I.

3. Experiment and Result

A homogeneous hydrogel phantom was fabricated for the experiment to test the proposed method. The phantom had a cubic shape with a side length of 50 mm. It was made of 9-W% gelatin and 2-W% graphite. The averaged v_S of the phantom was measured 2.15 m/s by the v_S measurement method presented in [7].

In this experiment, the size of the plate SW source was 10 mm × 10 mm square, and f_S was set 227 Hz. According to a preliminary investigation, it was found that the z-region from 2 mm to 32 mm would result in a best measurement accuracy with our experimental setup. Thus the measurement of α_S was taken place at this z-region. The detailed study in the measurement accuracy according to the z-region employed will be presented elsewhere. Ultrasound rf signals were acquired with a B-mode frame rate of 30 Hz for 6 seconds.

A chosen B-mode frame with the induced SW over the FOV is presented in Fig. 2(a). SW amplitude A_I at each frame was calculated by Eq. (3) and then averaged with 180 frames. The 2-D result of A_I is shown in Fig. 2(b) which was used to find the centerline (x = 0) indicated by the dash-line. The A_I on the centerline is shown in Fig. 2(c) by the blue-dotted line. By using the least square curve fitting technique, the calculated best fitted curve (red-solid line) to the experimental result (blue-dot line) was obtained when α_S = 11.6 Np/m.

Finally, G and η of the phantom were

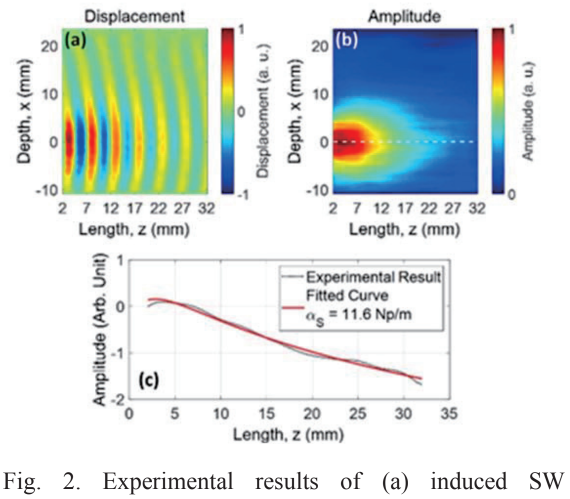

Fig. 2. Experimental results of (a) induced SW displacement (V_I), (b) SW amplitude (A_I), and (c) SW amplitude on the centerline (x = 0) in (b).

calculated by assuming that the phantom was a Voigt material.[9] The G calculated was 5.06 kPa, and the η was 0.12 Pa·s. Although the η obtained in this experiment was less than those of the published results, it was still a reasonable value by considering that the water-based phantom could be a less viscous material.[4,5,10,11] Fabrication and study on the viscous phantom could be future research subjects.

4. Summary

This study investigated the estimation of the SW absorption from the measured SW amplitude by considering the diffraction effect. In the phantom experiment, shear elasticity and viscosity of a specimen were estimated from the SW velocity and absorption obtained by the same SW measurement. It should be noted that the SW absorption measured in this study was an averaged value of the specimen where the SW propagated. Thus, the estimated shear elasticity and viscosity also represented the average viscoelastic properties of the specimen. The proposed measurement method of SW absorption could be useful as it could be used to provide reference parameters of viscoelasticity for a phantom study and/or an *in-vitro* tissue study such as a biopsy.

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