Evaluation of shear wave dispersion in hepatic viscoelastic models including fibrous structure

肝線維化に伴う構造変化を有する粘弾性モデルにおけるせん断波位相速度分散の評価

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1. Introduction

Shear wave speed measurement using shear wave elastography (SWE) or transient elastography (TE) has been developed for clinical assessment of mechanical properties in soft tissues. Some studies investigated the relationship between changes of viscoelastic properties in tissues and shear wave phase velocities over a given frequency range [1,2]. One of the viscosity estimation, the dispersion slope analysis use the gradient of shear wave phase velocity over a frequency range. Although the viscosity evaluation was often based on the Voight model, it was only valid in homogeneous media. It is well known that healthy liver tissues are broken and extracellular matrix proteins including collagen accumulate excessively resulting in complicated composites with liver fibrosis progression. These fibrous structure is often as large as a wavelength of propagating shear wave and may influence the shear wave propagation.

Our previous study showed that the fibrous structure have an influence on the viscosity evaluation by simulating shear wave paropagation in two types of models with elasticity distributions representing fibrosis progression [3]. Even though the viscosity values in simulation models were set to 0, the dispersion slope increased with the progress of liver fibrosis stage. The objective of this study is to confirm how the fibrous structure may effect on the dispersion slope analysis by simulating shear wave propagation in viscoelastic models with elastic distribution representing fibrous structure and homogeneous viscosity.

2. Methods

A liver fibrosis progression model is explained exactly in [3]. The model used in this study is given in **Figure. 1**. The averaged Young elasticity of this model is 4.35, 6.54, 10.40, 18.20 and 34.59 kPa from F0 to F4. The viscosity η is given homogenously and changed ranging over 0.1, 0.5, 1.0 and 1.5 Pa s to investigate the effect of fibrous structure in various viscoelastic properties.

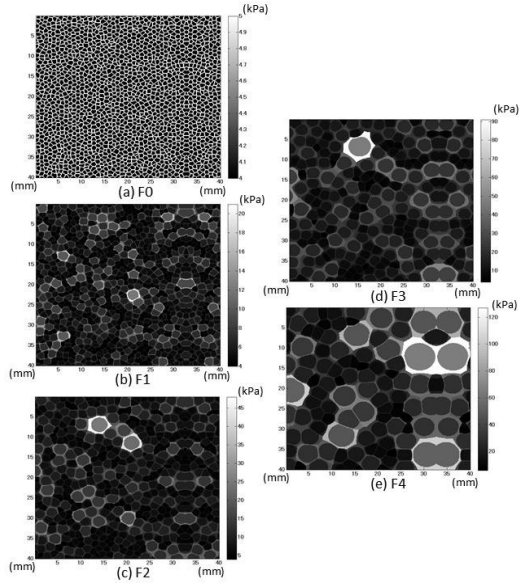

Fig. 1 Elasticity distribution of the fibrosis progression model representing fibrosis stage F0 (a) to F4 (e). The gray scale indicates the value of Young's modulus at each pixel, and the side bar shows the range of Young's modulus (kPa).

Shear wave propagation within this model is simulated using LS-DYNA3D (Livermore Software Technology Corp., Livermore, CA). The simulation area is 40mm × 40mm, and the acoustic radiation force excitation is set at the left edge of the model. Rotation symmetry simulation is performed with the left edge of the model as symmetry axis. Shear wave is excited by a Gaussian function that has 1 mm full width at half maximum (FWHM). The simulation time is 30 ms and the tracking PRF is 5 kHz.

The shear wave dispersion slope is calculated from the simulated shear wave particle velocity using the phase spectroscopy method and the least-square linear regression method. The lateral area of ROI is 1 – 4 mm from the excitation and its depth is 15 – 25 mm from the top of the model. The phase velocity is calculated from the phase difference and interval between two points

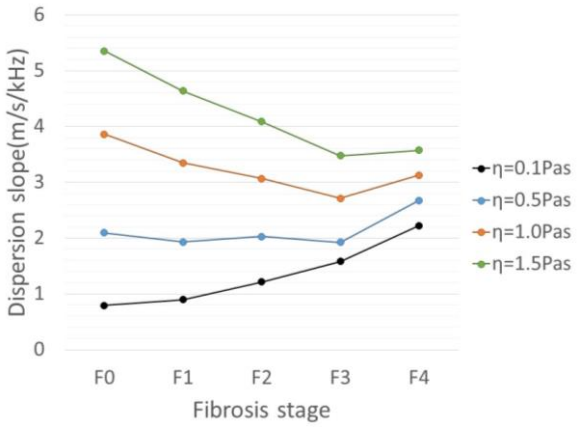

Fig. 2 Dispersion slope estimated from the simulation data.

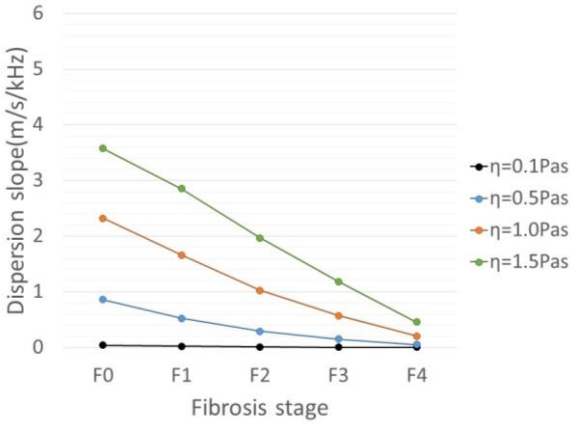

Fig. 3 Dispersion slope calculated based on uniform Voigt model.

separated by 0.3 mm. The dispersion slope is derived from an approximated straight line of frequency vs. averaged shear wave phase velocity using the least-square linear regression method. The frequency ranges to calculate dispersion slope is chosen based on the -20dB energy contour of propagating shear waves compared to excitation source.

3. Results

We simulated shear wave propagation using viscoelastic model including elastic distribution representing fibrous structure and homogeneous viscosity, then we investigated how the dispersion slope changed according to given fibrous structures or viscosity. **Fig. 2** shows the dispersion slope at each fibrosis stage F0 – F4 and each viscosity η = 0.1, 0.5, 1.0 and 1.5 Pa s. **Fig. 3** shows the dispersion slope calculated by assigning the averaged elasticity and viscosity value of the simulation model to a theoretical function based on the Voigt model. In Fig. 2, when η is set to 0.1 Pa s the dispersion slope goes up with the progress of fibrosis stage from F0 to F4. When η = 0.5 Pa s the dispersion remains flat with fibrosis progression F0 – F3, goes down when η = 1.0 and 1.5 Pa s. In all case, the dispersion at F4 stage is larger than at F3 stage. The dispersion slope at each fibrosis stage increases as the viscosity changes higher.

Comparing results in Fig. 2 with results in Fig. 3, the dispersion slopes in Fig. 2 have different tendencies with fibrosis progression at each viscosity nevertheless all dispersion slopes in Fig. 3 decrease with fibrosis stage.

4. Discussion & Conclusion

The numerical dispersion slope is calculated by using a theoretical function based on Voigt model. The calculated shear wave phase velocity is mainly depend on the ratio of viscosity to elasticity in materials. In Fig. 3, when the viscosity is fixed, all dispersion slopes decrease with fibrosis progression because the ratio of viscoelasticity change by the elasticity increase. As the viscosity is smaller, the dispersion slope in Fig. 2 shows a different tendency against the calculated slope in Fig. 3. It shows that the fibrous structure may cause this difference and its effect will appear especially in materials with less viscosity.

Generally, several studies have reported that the tissue viscosity increase with the progress of liver fibrosis [4, 5]. Considering from results in this study, at the serious fibrosis stage, the effect of fibrous structure will be small due to high viscosity. On the other hand, the dispersion slope at the middle fibrosis stage will be affected by both the fibrous structure and the viscosity. This will work to make the difference of the dispersion slope at middle or more fibrosis stage smaller and to lead to a difficult diagnosis of fibrosis stage.

Consequently, we verified that the fibrous structure may influence on the dispersion slope larger in materials with less viscosity and it will reduce a gap of the dispersion slope between fibrosis stages. An evaluation of tissue viscoelasticity considering the influence of the fibrous structure is necessary for accurate fibrosis staging.

References

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