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Liver fibrosis structure effects on viscoelasticity estimation using group shear wave speeds

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***Abstract*— Viscoelasticity measurements can improve the accuracy of liver fibrosis diagnosis for chronic hepatitis. Methods to estimate tissue viscoelasticity using frequency characteristics of the shear wave phase velocity are common but not robust. Therefore, in recent years, a technique to estimate viscoelasticity from group speeds in displacement and particle velocity has been proposed as a robust method [1]. However, we earlier reported that the liver fibrotic structure can change the frequency characteristics of phase velocity [2]. Therefore, in this study, we evaluated the influence of the liver fibrosis structure on the estimation method using group shear wave speeds. We used the previously developed liver fibrosis progression model to investigate the effect of the fibrous structure. Shear wave propagation was simulated using this model. Viscoelasticity was estimated using lookup tables that represented the relation between group speeds in displacement and particle velocity and viscoelasticity. When a shear wave reflection component is present, a directional filter is required. The directional filter affects the group speeds of the shear wave. Therefore, we established lookup tables considering the characteristics of the directional filter. Using these tables, we performed viscoelasticity estimations on liver fibrosis models and corresponding uniform models. In the uniform models, the viscoelasticity was estimated correctly. However, in the liver fibrosis models, the Young's modulus was estimated to be smaller than the actual value, and the shear viscosity coefficient was estimated to be greater than the actual value with the difference from the actual value increasing as fibrosis progressed.**

Keywords*— *Shear wave, Elastography, viscoelasticity measurement, group velocity, liver fibrosis structure

I. INTRODUCTION

Shear wave elasticity imaging has been developed to evaluate fibrosis progression for chronic hepatitis diagnosis. It has been identified that liver stiffness and the hepatic fibrosis stage are positively correlated [3,4]. Recently, liver viscosity was also found to have a positive correlation with hepatic fibrosis [5,6]. Therefore, it is expected that, in addition to elasticity measurements, viscosity analysis can improve the accuracy of staging fibrosis. In tissue viscoelasticity was also found to have a positive correlation with hepatic fibrosis [5, 6].

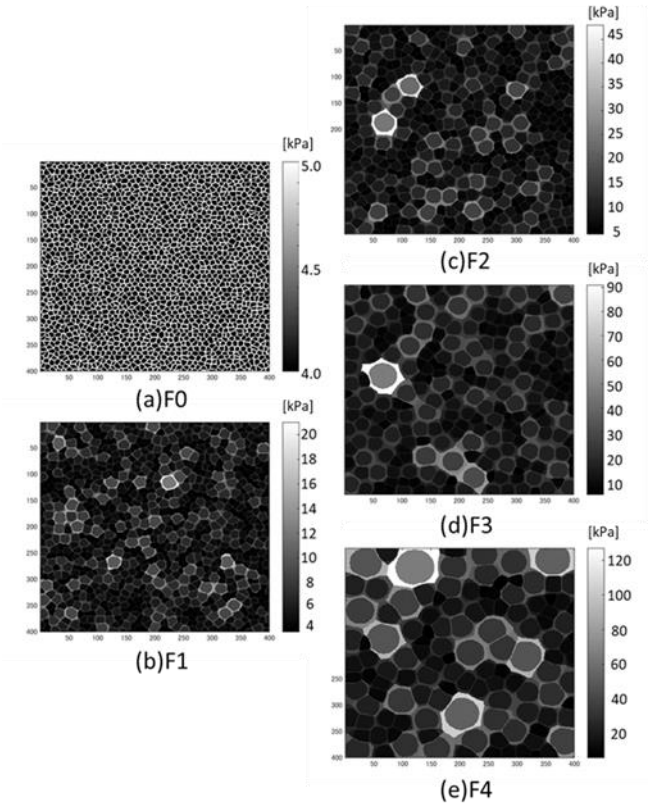


Fig. 1. Elasticity distribution of the fibrosis progression model representing fibrosis stages F0 to F4. The gray scale shows the Young's modulus value at each pixel. The side bar shows the range of Young's modulus (kPa).

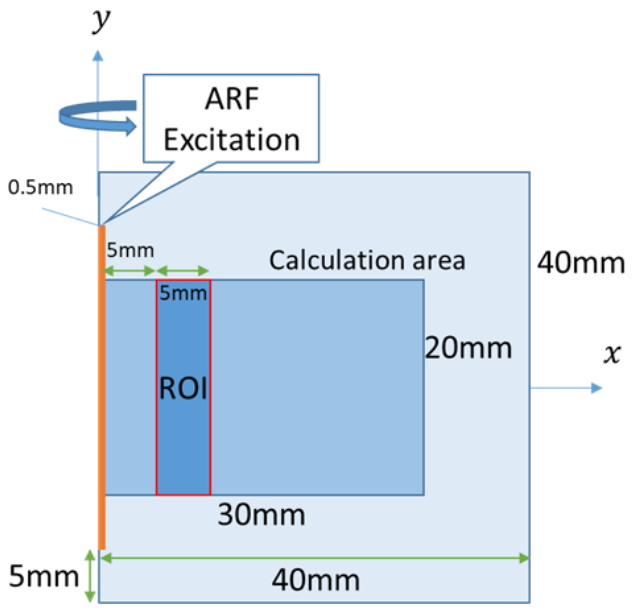


Fig. 2. Two-dimensional simulation image. The orange line indicates the acoustic radiation force excitation area, and the red area shows the ROI used in the group shear wave speed estimation.

Therefore, it is expected that, in addition to elasticity measurements, viscosity analysis can improve the accuracy of staging fibrosis. In tissue viscoelasticity measurements, estimation methods using frequency characteristics of the shear wave phase velocity are common. However, these methods are not robust. Thus, in recent years, a technique to estimate viscoelasticity from group speeds in displacement and particle velocity has been proposed as a robust method [1]. However, we previously reported that the liver fibrotic structure changes the frequency characteristics of phase velocity [2]. Therefore, in this study, we evaluated whether the method using group shear wave speeds was affected by the liver fibrosis structure.

II. Methods

A. Fibrous Structure Modeling

A liver fibrosis progression model has been developed [7,8]. This model has been explained in detail in [2]. Liver fibrosis stages F0–F4 have already been proposed to model the progression of regenerative nodules and the structure of fibrosis with the progress of cirrhosis. Ten different models were created for each stage by changing the structural pattern. We set the actual value of the Young's modulus as the average Young's modulus within the region of interest (ROI). In addition, in this study, we set the shear viscosity coefficient to a uniform distribution and set its value based on the results of a previous study [9]. Examples of models for each fibrosis stage are shown in Fig. 1.

B. Shear Wave Propagation Simulation

We simulated shear wave propagation in this model using LS-DYNA3D (Livermore Software Technology Corp., Livermore, CA). The simulation area was 40 mm × 40 mm, and the acoustic radiation force excitation was set at the left edge of the model as seen in Fig. 2. Rotation symmetry simulation was performed with the left edge of the model as the symmetry axis.

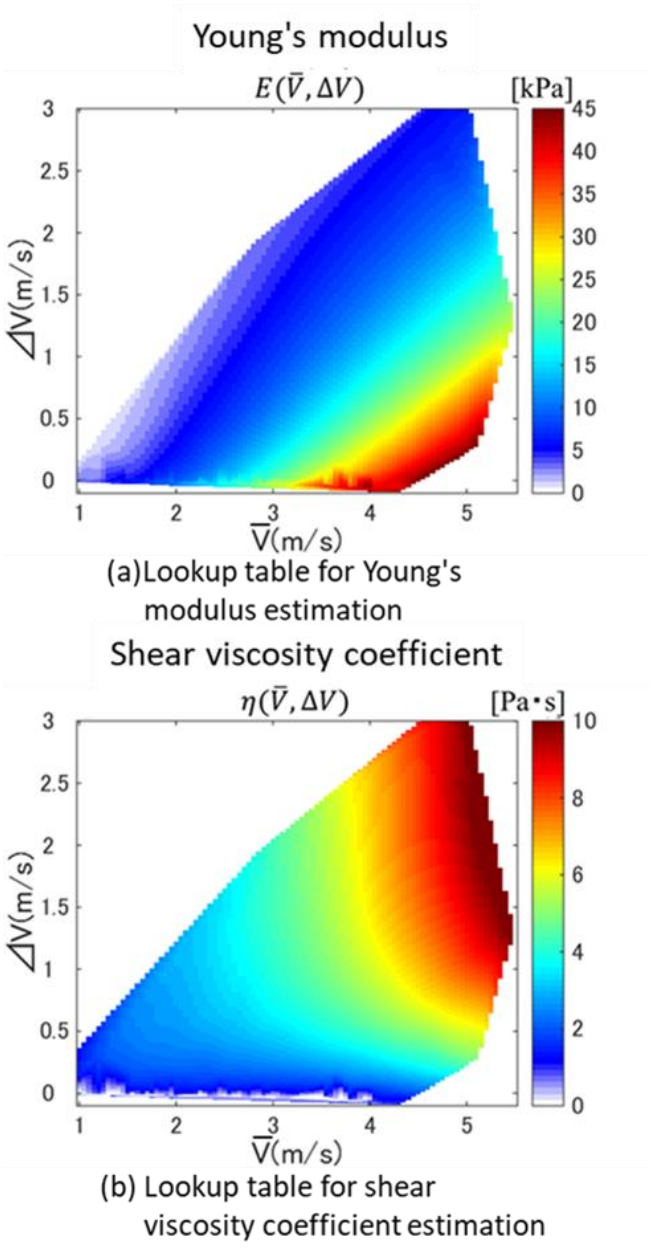
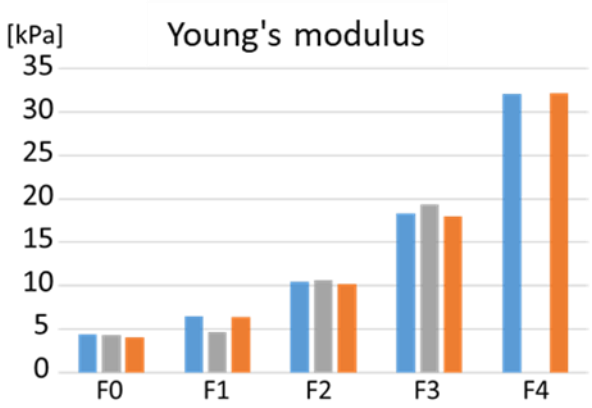


Fig. 3. Lookup tables considering directional filter for estimating Young's modulus and shear viscosity coefficient from $\bar{V}$ and ΔV

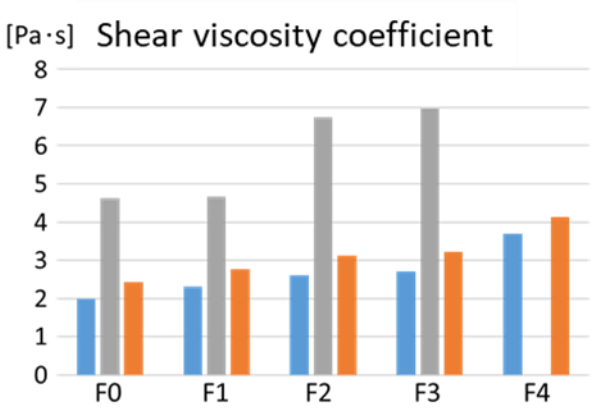
The shear wave was excited by a Gaussian function with a full width at half maximum (FWHM) of 1 mm. The simulation time was 30 ms and the tracking PRF was 5 kHz.

C. Viscoelasticity Estimation Using Group Shear Wave Speeds

First, as a preparation step, we simulated the displacement and particle velocity waveforms while changing the values of Young's modulus, E, and shear viscosity coefficient, η, (E: 5–45 kPa, η: 0–10 Pas); we then and calculated the respective group speeds V_{disp} and V_{vel}. While two group speeds are faster for hard tissues, the particle velocity group speed, V_{vel}, is faster



(a) Differences in Young's modulus estimation results depending on the lookup table



(b) Differences in shear viscosity coefficient estimation results depending on the lookup table

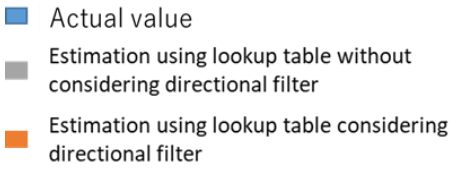


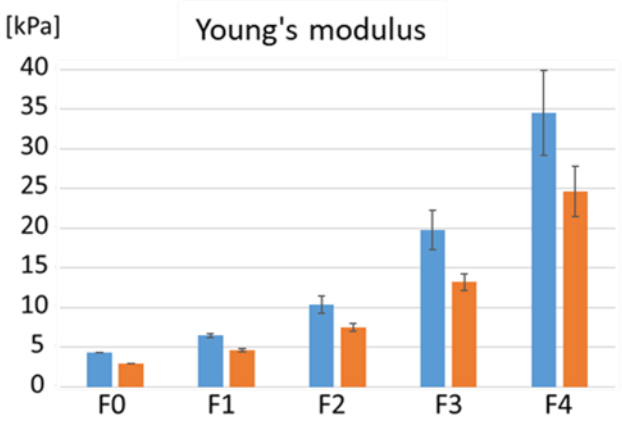
Fig. 4. Comparison of viscoelasticity estimation results of uniform viscoelastic distribution models with different lookup tables.

than the displacement group speed, V_{disp}, in a viscoelastic medium. This is because the high-frequency shear wave component is emphasized owing to the particle velocity being a time derivative of the displacement. (In a viscoelastic medium, the shear wave phase velocity increases as the frequency increases.) Next, the average and difference of the two group speeds $\bar{V}$ and ΔV were obtained as follows.

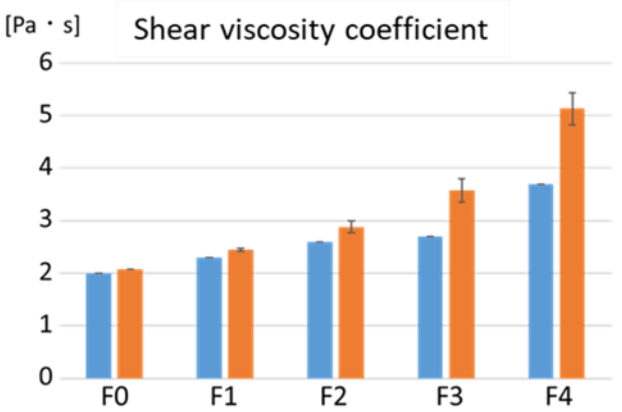
$$\bar{V} = \frac{V_{disp}+V_{vel}}{2} \qquad (1)$$

$$\Delta V = V_{vel} - V_{disp} \qquad (2)$$

Then, from the results obtained for each Young's modulus, E, and shear viscosity coefficient, η, lookup tables were established (Tables for estimating E and η from measured values) (E ($\bar{V}$, ΔV) and η ($\bar{V}$, ΔV)) (refer to Fig. 3).



(a) Estimation results of Young's modulus in liver fibrosis structure model



(b) Estimation results of Shear viscosity coefficient in liver fibrosis structure model

Fig. 5. Estimated viscoelasticity results in liver fibrosis structure models

Next, we measured the displacement waveform and particle velocity waveform using ultrasonic measurements. The respective group speeds V_{disp} and V_{vel} were obtained by the time-of-flight method using the cross-correlation function for each waveform. From these two group speeds, the average, $\bar{V}$, and the difference, ΔV, were calculated, and the Young's modulus and shear viscosity coefficient were estimated by referring to the lookup tables created in advance. When there is a shear wave reflection component, a directional filter is required. However, a part of the shear wave velocity dispersion component generated by the influence of viscosity is cut by the directional filter. Therefore, if each group velocity is obtained by applying a directional filter and estimation is performed using a lookup table created without using a directional filter, the shear viscosity coefficient cannot be estimated correctly (see the gray graph in Fig. 4(b)).

In the F4 model of Fig. 4, the group velocity measurement value was outside the range of the lookup table that did not consider the directional filter; thus, an estimate could not be made. Therefore, the lookup tables were recreated using the group

velocity results after applying the directional filter. They are shown in Fig. 3. The estimation results for the uniform viscoelastic distribution model using the lookup tables that take into account the effect of the directional filter are shown in the orange graph of Fig. 4. These results show that the lookup tables considering the influence of the directional filter provided correct estimations. Therefore, by using this method to estimate the viscoelasticity of the fibrotic structure model of liver fibrosis stages F0–F4, the effect of changes in tissue structure on the estimation can be evaluated.

III. Results

In the liver fibrosis structure model, the shear wave was propagated and directional filter was applied. Then, the Young's modulus and shear viscosity coefficient were estimated using lookup tables considering the effect of the directional filter. Fig. 5 compares the average Young's modulus and average shear viscosity coefficient in the ROI of the liver fibrosis structure model with the actual values at each stage. The standard deviation of the results for the ten models is shown as an error bar. These results showed that the estimated Young's modulus is less than the actual value and the estimated shear viscosity coefficient is larger than the actual value in the fibrotic structure model with the difference from the actual value increasing as fibrosis progresses. In estimations made using group shear wave speeds, the Young's modulus tends to be smaller than the actual value when the shear viscosity coefficient is estimated to be larger than the actual value. This is similar to the phase velocity dispersion method. Moreover, as a result of verifying the influence of the change of the liver fibrosis structure, it was confirmed that the viscoelasticity estimation using group shear wave speeds is also affected by the structure.

IV. Discussion and Conclusions

This study investigated the effect of fibrous structure on the viscoelasticity estimation using group shear wave speeds in fibrosis progression. The Young's modulus was estimated to be smaller than the actual value, and the shear viscosity coefficient was estimated to be greater than the actual value with the difference from the actual value increasing as fibrosis progressed. Generally, when there is a structure smaller than the wavelength of the shear wave, reflected waves are generated in various directions, and velocity dispersion occurs. That is, the phase velocity of the high frequency component increases. Therefore, the group speeds of the particle velocity that differentiated the displacement are more influenced by the structure, and the difference between the two group speeds is larger than the actual value; therefore the estimation result of the shear viscosity coefficient is larger than the actual value. Additionally, in viscoelasticity estimation using group shear wave speeds, the Young's modulus tends to be smaller than the actual value when the shear viscosity coefficient is estimated to be larger than the actual value. This is similar to the phase velocity dispersion method.

In conclusion, in this study, we verified the effect of changes in the liver fibrosis structure, and as a result, we confirmed that the viscoelasticity estimation by this method is also affected by the liver fibrosis structure. From the results of liver fibrosis stages F0–F4, it was found that the estimated Young's modulus of the model with the structure is smaller than the actual value and the estimated shear viscosity coefficient is larger than the actual value. One way to solve the problem that this method cannot correctly estimate when there is a structure is to use lookup tables that take into account the influence of the structure. In the future, we plan to develop a method that can accurately and robustly estimate viscoelastic properties even when there is a liver fibrosis structure, including the ones described herein.

References

[1] N. C. Rouze, Y. Deng, M. L. Palmeri, and K. R. Nightingale, "Robust characterization of viscoelastic materials from measurements of group shear wave speeds," in Proc. IEEE Int. Ultrason. Symp., Sep. 2016, pp. 1–4.

[2] S. Fujii, M. Yamakawa, K. Kondo, T. Namita, and T. Shiina, "Evaluation of shear wave dispersion caused by fibrous structure and tissue viscosity using hepatic fibrosis progression and historogical models," in Proc. IEEE Int. Ultrason. Symp., Sep. 2017

[3] E. Bavu, J. L. Gennisson, M. Couade, J. Bercoff, V. Mallet, M. Fink, A. Badel, A. V. Pichard, B. Nalpas, M. Tanter, and S. Pol, "Noninvasive in vivo liver fibrosis evaluation using supersonic shear imaging: a clinical study on 113 hepatitis C virus patients," Ultrasound Med. Biol., vol. 37, pp. 1361-1373, 2011.

[4] G. Ferraioli, C. Tinelli, B. D. Bello, M. Zicchetti, G. Filice, and C. Filice, "Accuracy of real-time shear wave elastography for assessing liver fibrosis in chronic hepatitis C: a pilot study," Hepatology, vol. 56, pp.2125-2133, 2012.

[5] S. Chen, W. Sanchez, M. R. Callstorm, B. Gorman, J. T. Lewis, S. O. Sanderson, J. F. Greenleaf, H. Xie, Y. Shi, M. Pashley, V. Shamdasani, M. Lachman, and S. Metz, "Assessment of liver viscoelasticity by using shear waves induced by ultrasound radiation force," Radiology , vol. 266, pp. 964-970, 2013

[6] X. Chen, Y. Shen, Y. Zheng, H. Lin, Y. Guo, Y. Zhu, X. Zhang, T. Wang, and S.Chen, "Quantification of liver viscoelasticity with acoustic radiation force: a study of hepatic fibrosis in a rat model," Ultrasound Med. Biol., vol. 39, pp. 2091-2102, 2013.

[7] T. Yamaguchi, K. Nakamura, H. Hachiya. "Three-dimentional model of the scatterer distribution in cirrhotic liver," Jpn. J. Appl. Phys., vol. 42, part. 1, pp. 3292-3298, 2003.

[8] T. Shiina, T. Maki, M. Yamakawa, T. Mitake, M. Kudo, and K. Fujimoto, "Mechanical model analysis for quantitative evaluation of liver fibrosis based on ultrasound tissue elasticity imaging," Jpn. J. Appl. Phys., vol. 51, paper 07GF11, 2012.

[9] T. Deffieux, J. ennisson, L. Bousquet, M. Corouge, S. Cosconea, D. Amroun, S. Tripon, B. Terris, V. Mallet, P. Sogni, M. Tanter, S. Pol, "Investigating liver stiffness and viscosity for fibrosis steatosis and activity staging using shear wave elastography," J Hepatol, vol. 62, pp. 317-324, 2015.