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Preliminary study on cartilage tissue evaluation based on longitudinal and shear wave speeds

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1. Introduction

Knee osteoarthritis is a serious disease in an aging society. In the current situation that there is no radical cure, early diagnosis is very important, and it is necessary to slow down the progress of the disease. Articular cartilages have a structure in which the interstices of a mesh-like three-dimensional network composed of type II collagen are filled with the proteoglycan. The collagen is responsible for load bearing and the proteoglycan is responsible for water retention. In healthy articular cartilages, the water stored in the proteoglycan is reduced under the pressure due to the joint flexion and extension, and the shock is absorbed. However, when the proteoglycan decreases, the water-retaining capacity also decreases, and the shock cannot be absorbed. As a result, the collagen is damaged, the cartilage tends to peel off, and eventually the knee osteoarthritis occurs. Therefore, it is important to evaluate the water retention capacity of the proteoglycan in the early diagnosis of the knee osteoarthritis. Such articular cartilages are often modeled as a poroelastic body with a deforming solid matrix internally filled with fluid or water. The water retention capacity is evaluated by the rate at which water is reduced when the poroelastic body is pressurized, i.e., the time-dependent change in water content in the poroelastic body.[1)]

In this study, we focus on the Poisson's ratio as an evaluation index of water content of the cartilage. As a preliminary study of the cartilage evaluation, we attempted to estimate the Poisson's ratio of cartilage phantoms based on the propagation speeds of longitudinal and shear waves.

2. Cartilage tissue evaluation

Assuming that the cartilage tissue is a linear and isotropic elastic body, the Poisson's ratio is obtained by referring the longitudinal wave speed c_l and the shear wave speed (SWS) c_s as follows.

$$\nu = \frac{1}{2}\left(1-\frac{1}{\left(\frac{c_l}{c_s}\right)^2-1}\right) \qquad (1)$$

Here, the longitudinal wave speed is referred to as the speed of sound (SoS). The SoS and SWS measurements are conducted as shown in **Fig. 1**. For the SoS measurement, a pulsed wave with a focal point on the surface of subchondral bone is transmitted using the full aperture focusing. The echoes are received on all channels on a linear array probe as if they were generated from a single scattering point, and the SoS is measured by the improved focusing method.[2)] For the SWS measurement, a push pulse is transmitted to generate a shear wave in the cartilage, and the SWS is measured by the time-of-flight (TOF) method.[3)] Finally, the Poisson's ratio is estimated by substituting the measured SoS and SWS into Eq. (1).

3. Experiment

Three types of plate cartilage phantoms (50 × 50 × 10 mm) with the SoSs of 1500, 1540, and 1580 m/s was prepared based on the mixture of agar with constant concentration and glycerol with varying concentration. All phantoms included the polyethylene powder with lower concentration as the scatterers. As shown in Fig. 1, a cartilage phantom was placed on a 10 mm thick sound absorber simulating subchondral bone, and a linear array probe (L7-4, Philips; 5.2 MHz) was placed on the phantom. By using a research platform (Vantage, Verasonics), the SoS and SWS were measured by the methods described in the previous section, and the Poisson's ratio was estimated.

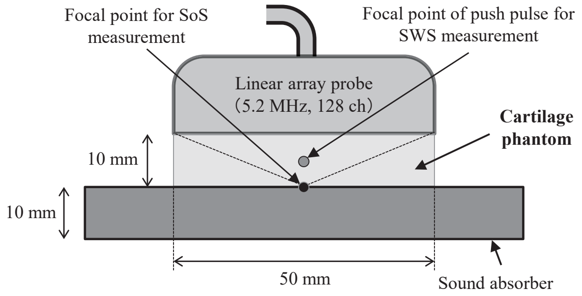

Fig. 1 Experimental setup for a cartilage phantom.

4. Results

4.1 Speed of sound

Figs. 2(a)–(c) show the channel data obtained by transmitting a pulsed wave focused using the full aperture focusing on the surface of sound absorber to three cartilage phantoms, respectively. The beam width at the focal point was theoretically 0.1 mm,

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and echo patterns similar to ones from a point scatterer were reproduced, as indicated by the black arrows. Figs. 2(d)–(f) show the wavefronts corrected using the SoS measured by the improved focusing method, respectively. The horizontal wavefronts indicate successful SoS measurements.

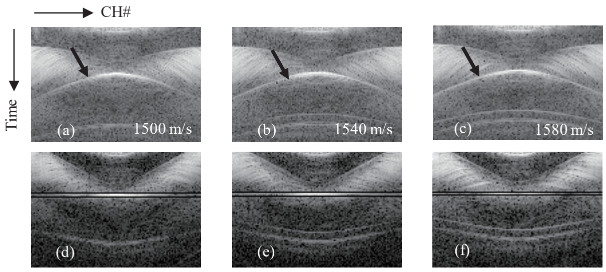

Fig. 2 (a)‑(c) channel data obtained by transmitting a focused wave to three cartilage phantoms, respectively. (d)‑(f) wavefronts corrected using the SoS measured by the improved focusing method, respectively.

4.2 Shear wave speed

Figs. 3(a)–(c) are the snapshots of shear wave propagation at 0.5 ms after transmitting the push pulse to three cartilage phantoms, respectively. The white dashed lines indicate that the arrival positions of the shear waves were almost the same. Fig. 3(d) plots the relationship between the travel time and distance of the shear wave peak measured by the TOF method. It was confirmed that all phantoms have similar slope values (i.e., SWS).

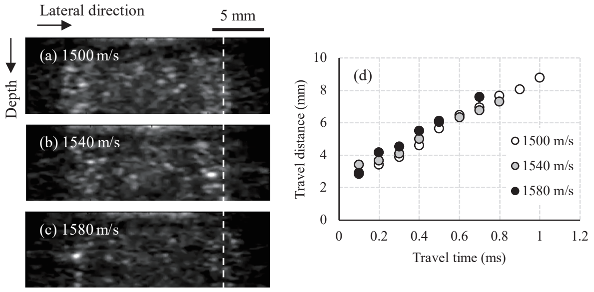

Fig. 3 (a)‑(c) snapshots of shear wave propagation at 0.5 ms after transmitting the push pulse to three cartilage phantoms, respectively. (d) relationship between the travel time and distance of the shear wave peak measured by the TOF method.

4.3 Poisson's ratio

Fig. 4(a) is a comparison of the measured SoS and the reference SoS and indicates that the SoS measurements were performed correctly. Fig. 4(b) shows a comparison of the measured SWS and the reference SoS. As expected, the correlation between the measured SWS and the reference SoS was low. This is a reasonable result because the effect of the glycerol concentration on the elastic modulus in the cartilage phantom was smaller than the effect one on the SoS.[3)]

Figs. 4(c) and (d) show the results of Poisson's ratio estimated by substituting the measured SoS and SWS into Eq. (1). Fig. 4(c) shows the relationship between the Poisson's ratio and measured SoS, and Fig. 4(d) shows the relationship between the Poisson's ratio and measured SWS. The Poisson's ratio had a lower correlation with the SoS and a higher correlation with the SWS. This result suggests that the Poisson's ratio is responsible for the decrease in the SWS, and the increase in water content (Poisson's ratio approaches 0.5) may be causing the decrease in the SWS.

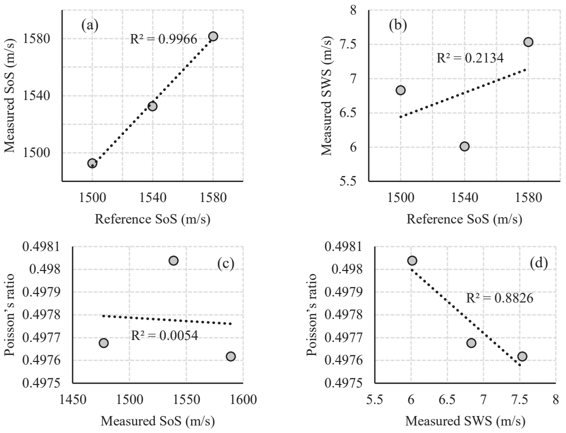

Fig. 4 (a) a comparison of the measured SoS and the reference SoS. (b) a comparison of the measured SWS and the reference SoS. (c) relationship between the Poisson's ratio and the measured SoS. (d) relationship between the Poisson's ratio and the measured SWS.

5. Conclusions

In this study, we focused on the Poisson's ratio as an index of water content in the cartilage evaluation and estimated the Poisson's ratio from the SoS and SWS measured in cartilage phantoms. As a result, it was shown that the Poisson's ratio may serve as an evaluation index for cartilages. In the future, we will evaluate the estimation accuracy of the Poisson's ratio and evaluate the Poisson's ratio using actual cartilage tissues.

Acknowledgment

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References

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