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Preliminary study on the speed-of-sound measurement of cartilage tissue based on a two-layer model

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1. Introduction

The knee osteoarthritis is a serious disease in an aging society. In the current situation where there is no fundamental treatment, early diagnosis is very important, and care to delay the progression of the disease must be started early. Articular cartilage has a structure in which proteoglycans fill the gaps in a three-dimensional network of type-II collagen, with collagen supporting the load and proteoglycans retaining water. In healthy articular cartilages, the water stored in the proteoglycans is lost when the joint is flexed and extended, absorbing shock. However, when the proteoglycans decrease, the water retention decreases and the shock cannot be absorbed, the collagen is damaged, and the cartilage becomes easily peeled off, eventually suffering from osteoarthritis of the knee. Since the evaluation of the water retention of proteoglycans is important in the early diagnosis of osteoarthritis of the knee, a method for estimating the water content has been developed using the Poisson's ratio as an evaluation index of the water content.[1,2]

On the other hand, the speed of sound (SoS) is also a promising evaluation index that reflects the water content. In the conventional focusing method using a handheld probe,[3] although the SoS was determined based on the time delay correction of the scattered wave from a strong scattering point, the improvement was made so that it could be applied to cartilage where there were no strong scattering points.[1] However, this improved method did not consider the presence of tissues such as muscle. Therefore, in this study, we investigated a method to measure the SoS of cartilage using a two-layer model consisting of tissues such as muscle and cartilage.

2. SoS measurement based on a two-layer model

Figure 1 shows a two-layer model consisting of muscle tissue (soft tissue) and cartilage. The SoS and thickness of the soft tissue are c_1 and l_1, respectively, and the SoS and thickness of the cartilage are c_2 and l_2, respectively. A linear array probe is placed on the skin, and the full aperture focusing is conducted on each surface of the boundaries A and B to generate pseudo point scattering waves, and the SoS is measured by applying the focusing method to the received channel data. That is, c_1 is measured when focusing on the boundary A, and the average sound speed $\bar{c}$ of the entire two-layer model is measured when focusing on the boundary B. When the round-trip times of ultrasound pulses to boundaries A and B are expressed by t_1 and t_{12}, respectively, these times can be measured, so the SoS c_2 of the cartilage can be calculated as follows.

$$c_2 = \frac{\bar{c}t_{12} - c_1 t_1}{t_{12} - t_1} \tag{1}$$

Note that l_1 and l_2 are unknown parameters but are not necessary for measuring c_2.

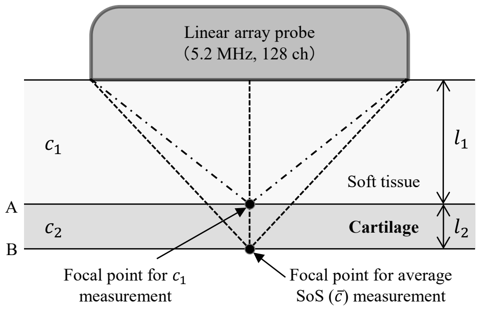


Fig. 1 Two-layer cartilage tissue model.

3. Simulation

Based on the two-layer model in Fig. 1, the theoretical validity of this proposed SoS measurement method was verified by simulations. Here, c_1 was constant at 1540 m/s, and c_2 was changed in increments of 5 m/s from 1540 m/s to 1660 m/s. And l_1 was constant at 10 mm, and l_2 (i.e., cartilage thickness) was changed to 2 mm and 5 mm.

Assuming the use of a linear array with a frequency of 5.2 MHz and 128 channels as shown in Fig. 1, c_1 and t_1 were measured using the pseudo-point scattered waves from the boundary A, and then $\bar{c}$ and t_{12} were measured using the pseudo-point scattered waves from the boundary B. Then, c_2 was calculated based on Eq. (1).

4. Results

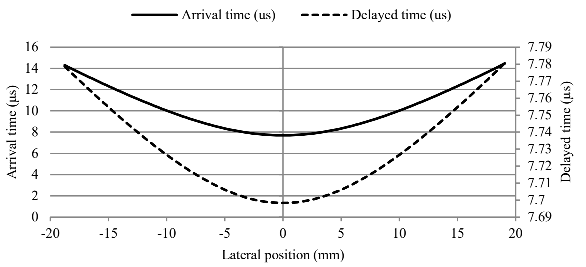
4.1 Average SoS measurement

Figure 2 shows the channel data of the pseudo point scattering waves generated at the boundary B. The horizontal axis "Lateral position" corresponds to the position of the element on the probe, the left vertical axis "Arrival time" is the time of arrival at each element, and the right vertical axis "Delayed time" is the appearance time of the wavefront after correction by the time delay in the focusing method. In the case of the homogeneous medium, the delayed time should be the same for all channels and aligned horizontally, but in the case of the two-layer model consisting of the layers with different SoS values, the delayed time was not aligned horizontally and was not corrected to be the same time for both l_2 = 2 mm and 5 mm.

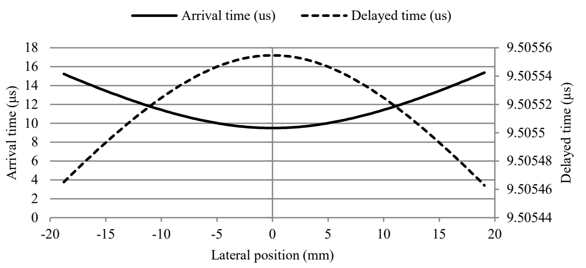
Figure 3 shows the measurement results of the average SoS of the entire two-layer model measured using the pseudo point scattering waves generated at the boundary B. Figure 3(a) shows the result when l_2 = 2 mm and Fig. 3(b) shows the result when l_2 = 5 mm, where the horizontal axis shows the true average SoS (i.e., $(l_1 + l_2)/(l_1/c_1 + l_2/c_2)$) and the vertical axis shows the SoS obtained by the focusing method. From these results, it was confirmed that the SoS obtained by the focusing method in this two-layer model was equal to the true average SoS $\bar{c}$, even though the delayed time was not horizontally aligned.

4.2 Cartilage SoS measurement

Figure 4 shows the results of measuring the SoS c_2 of cartilage by using Eq. (1). Here, the horizontal axis is the true c_2, and the vertical axis is the c_2 measured by using Eq. (1), where the SoS obtained by the focusing method for the boundary B was substituted as $\bar{c}$. From these results, it can be confirmed that the measured c_2 agreed with the true c_2 for both l_2 = 2 mm and 5 mm.

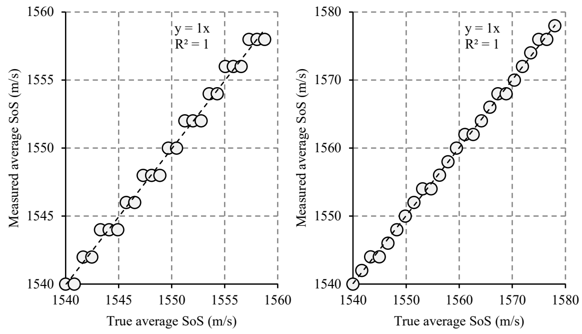


(a) l_1 = 10 mm, l_2 = 2 mm



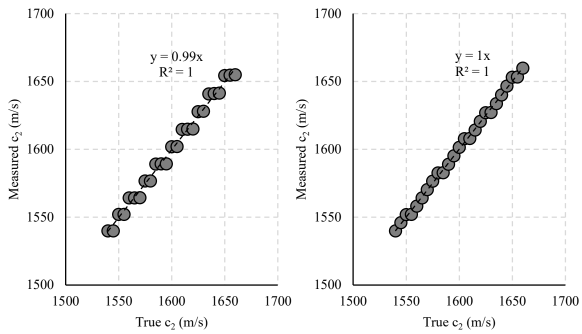
(b) l_1 = 10 mm, l_2 = 5 mm

Fig. 2 Channel data of the pseudo point scattering waves generated at the boundary B, (a) for l_2 = 2 mm and (b) for l_2 = 5 mm, respectively.



(a) l_1 = 10 mm, l_2 = 2 mm (b) l_1 = 10 mm, l_2 = 5 mm

Fig. 3 Measurement results of the average SoS of the entire two-layer model measured using the pseudo point scattering waves generated at the boundary B, (a) for l_2 = 2 mm and (b) for l_2 = 5 mm, respectively.



(a) l_1 = 10 mm, l_2 = 2 mm (b) l_1 = 10 mm, l_2 = 5 mm

Fig. 4 Results of measuring the SoS c_2 of cartilage by using Eq. (1), (a) for l_2 = 2 mm and (b) for l_2 = 5 mm, respectively.

5. Conclusions

In this study, we focused on the SoS as an evaluation index for water content in cartilage evaluation, and proposed a method for measuring the SoS in cartilage tissue that assumes the presence of tissues such as muscle. The theoretical validity of the proposed method was verified by the simulation, and it was shown that the cartilage SoS could be measured correctly using the two-layer model that was close to the actual knee joint structure. In the future, we plan to conduct evaluations using phantoms and excised cartilages. We will also verify the applicability to the curved cartilage in vivo.

Acknowledgment

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References

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