3P5-14

Observation of Lamb wave-like propagation behavior of shear waves propagating near lung tissue

Ren Koda[1†*], Kazumasa Osawa[1], Kento Shimizu[2], Naoki Tano[2], Hayato Taniguchi[3], Yasuyuki Shiraishi[4], Marie Tabaru[2] ([1]Grad. School of Science and Technology, Gunma Univ.; [2]IIR, Tokyo Tech; [3]Yokohama City Univ. Medical Center Advanced Critical Care Center, [4]IDAC, Tohoku Univ.)

1. Introduction

Continuous Shear Wave Elastography (C-SWE) [1] is a technique for visualizing the elasticity of internal tissues in living organs. Recently, C-SWE has been applied to measure the shear wave velocity propagating through the lung parenchyma by determining the phase difference of the shear wave between B-lines from the Doppler signal through B-lines [2]. However, B-lines are not always observed stably with a number and intensity suitable for shear wave velocity measurement. Although lung ultrasound surface wave elastography [3] measures the surface wave velocity in lung tissue, surface wave velocity is thought to be affected by local density changes due to fluid accumulation on the inflamed lung.

In this study, we will measure the shear wave propagation in the chest wall using the C-SWE method, and estimate the state of the lungs from the shear wave propagation in the chest wall. If the chest wall can be considered as an elastic body that is thin compared to the wavelength of the shear wave, it is assumed that the shear wave propagating through the chest wall exhibits properties similar to Lamb waves, a type of guided wave [4], and it is expected that there will be a difference in the components of the shear wave reflected from the boundary between aerated normal lung tissue and inflamed lung tissue.

2. Wave propagation through chest wall

Consider a plane wave propagating obliquely in *x*-*z* space inside a thin elastic body such as a chest wall. The relationship between the magnitude of the wave vector in the *x*- and *z*- directions of the wave number *k*, which indicates the diagonal propagation of the wave, is

$$k^2 = {k_x}^2 + {k_z}^2 \qquad (1)$$

Here, we consider that the incident wave is reflected at a boundary. If the thickness of the elastic body is *L*, then in the case of plate waves, resonance occurs in the thickness direction, and the following relationship holds:

$$k_z L = n\pi, \qquad n = 1,2,3,\cdots \qquad (2)$$

where *n* indicates the mode number.
From equations (1) and (2),

$$k_x = \sqrt{k^2 - \left(\frac{n\pi}{L}\right)^2} \qquad (3)$$

In equation (3), in order for k to propagate in the positive x-direction, $k \geq n\pi/L$ must be satisfied. Therefore, the frequency of the shear wave *f* must satisfy the following condition using the shear wave velocity *v* (=2π*f*/*k*).

$$f \geq n\frac{v}{2L}, \qquad n = 1,2,3,\cdots \qquad (4)$$

For example, assuming that the shear wave speed propagating through the chest wall is 4 m/s, when *L* = 25 mm, the cutoff frequency f_{cutoff} of the first mode is derived to be f_{cutoff} = 50 Hz.

3. Results

Fig. 1(a) shows a simulation model using the Finite Difference Time Domain (FDTD) method

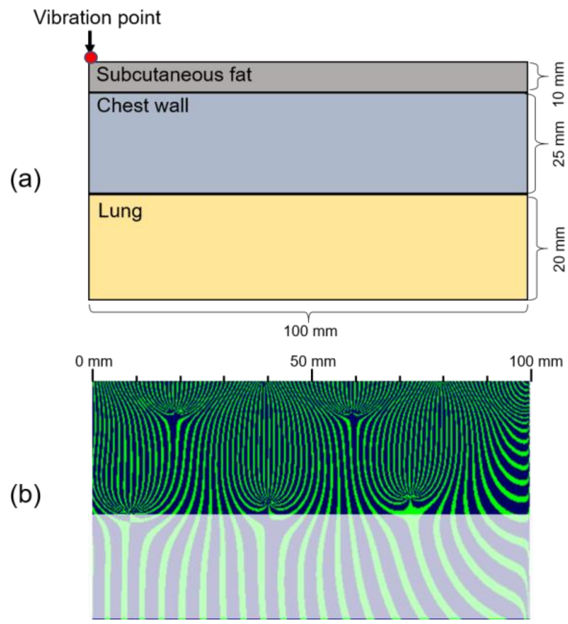

Fig. 1 FDTD simulation result
(a) Model, (b) Shear wave propagation map

E-mail: †*koda@gunma-u.ac.jp

based on the Navier-Stokes equations. The model has a width of 100 mm and a depth of 55 mm, and has a three-layer structure consisting of a subcutaneous fat layer, a chest wall layer and a lung tissue layer, with thicknesses of 10 mm, 25 mm and 20 mm, respectively. Figure 1(b) shows the propagation of shear waves when the subcutaneous fat parameters are v = 2 m/s, ρ = 1000 kg/m^3, the chest wall parameters are v = 4 m/s, ρ = 1000 kg/m^3, and the lung parameters are v = 6 m/s, ρ = 340 kg/m^3. The vibration frequency of the shear waves is 78.1 Hz, and the incidence angle is set to 45 degrees from the horizontal. Since the echo signals in the lung imaging area were considered to be multiple-reflection areas, the shear wave propagation images in those areas were displayed with a mask. A characteristic wavefront propagation was observed at a position about 40 mm from the vibration position, where the wavefront approaches the horizontal direction near the boundary. This characteristic propagation appears to be repeated periodically, approximately every wavelength of the shear wave.

Fig. 2(a) shows an experimental setup for the phantom model. The phantom model was vibrated by a small vibrator and shear waves were observed using a tablet echo device. The konjac with a thickness of approximately 25 mm was placed on the front surface of the ultrasonic probe to simulate the soft tissue of the chest wall. A sponge was placed at the bottom of the konjac to simulate an air-containing lung. Fig. 2(b) shows the propagation of shear waves in the ROI located at 30 - 50 mm x direction distance from the vibration point. It can be seen that the characteristic wavefront propagation similar to the simulation results is observed at 40 - 50 mm from the vibration position.

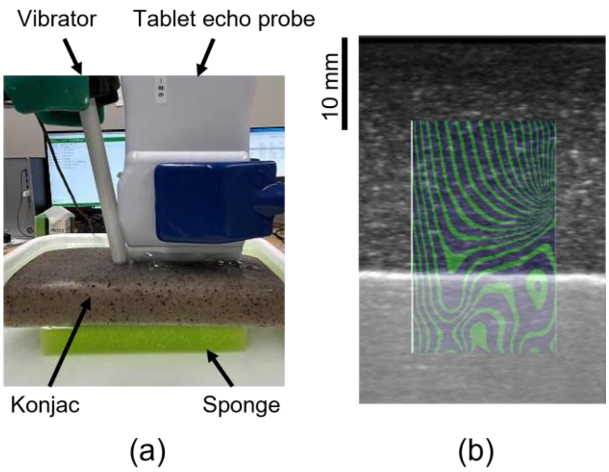

Fig. 2 Experimental results of the phantom model. (a) Experimental setup, (b) Shear wave propagation map in ROI ranging 30 - 50 mm from the vibration position.

Fig. 3(a) shows the experimental system for *in vivo* experiments on volunteers with healthy lungs. Measurements were performed with subjects in a relaxed prone position. The vibrator and ultrasonic probe are were held by an elastic adapter made using a 3D printer. The tip position is was fixed at about 10 mm from the end of the acoustic lens of the probe. The ultrasound probe and the actuator tip were placed between the ribs. Fig. 3(b) shows the shear wave propagation in the ROI located at a distance of 30 - 50 mm in the x direction from the vibration point. At the right end of the ROI (50 mm from the vibration point), the chracterisitic propagation is observed in which the wavefront approaches horizontal near the boundary with the pleura. The reason why the wavefront becomes nearly horizontal is thought to be due to the synthesis of the reflected wave component from the boundary in the thickness direction of the chest wall, i.e., due to the mechanism of guided wave generation [4].

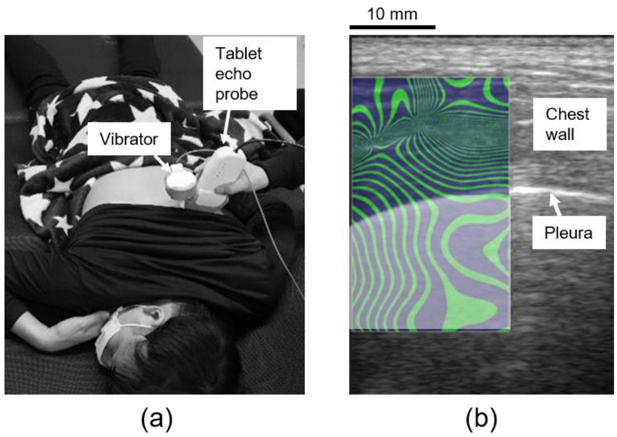

Fig. 3 Experimental results of the *in vivo* lung. (a) Experimental setup, (b) Shear wave propagation map in ROI ranging 30 - 50 mm from the vibration position.

4. Conclusions

Using continuous shear wave imaging, we visualized shear waves propagating through the chest wall, which is a layer that is thin compared to the wavelength of the shear wave, and observed characteristic Lamb wave-like propagation, with the wave front approaching horizontal near the boundary with the lung tissue.

References

1) Y. Yamakoshi, et al. Ultrason Imaging., 37, 323-340 (2015)
2) R. Koda, et al. Ultrason Imaging. 45, 30-41 (2023)
3) X. Zhang, et al. IEEE TUFFC, 64, 1298-1304 (2017).
4) K. Parker, Acoustics, 5, 575-585 (2023)