2E2-3

Proceedings of Symposium on Ultrasonic Electronics, Vol. 37 (2016)
16-18 November, 2016

Ex Vivo Assessment of Porcine Aortic Stiffness based on Leaky Lamb-wave Dispersion Analysis of Shear Wave Propagation

Jun-keun Jang[1†], Kengo Kondo[1], Takeshi Namita[1], Makoto Yamakawa[1], and Tsuyoshi Shiina[1] ([1]Div. Human Health Sciences, Grad. School of Med., Kyoto Univ.)

1. Introduction

The mechanical properties of artery have gained importance as an independent predictor of cardiovascular morbidity and mortality in our aging society. Especially, arterial wall stiffness is a major contributor to stoke, myocardial infarction, and unstable angina [1]. Meanwhile, ultrasound shear wave elastography (SWE) has attracted considerable attention thanks to its quantitativeness, reproducibility, and simplictiy of use. This emerging modality enables the noninvasive and quantitative evaluation of Young's modulus (E) of human soft tissue directly from the estimated shear wave velocity (C_S) (*i.e.*, $E = 3\rho C_S^2$, where ρ is density) [2]. In spite of its advantages, the conventional SWE cannot accurately estimated C_S for thin-layered media (*e.g.*, skin layeres, arterial walls, and corneas) since the shear waves in the media propagate as complex guided waves [3]. To overcome this limitation, leaky Lamb-wave dispersion analysis (LLDA) method has recently proposed. This method modeled the shear waves propagating into the thin media as leaky Lamb waves [4]. In the previous study, we demonstrated that LLDA method can be applied to tubular strucutres by eliminating circumferential waves in the tube phantom and fitting the Lamb-like dispersion curves obtained experimentally to theoretical curves [3]. In this work, we performed *ex vivo* experiments for porcine arota to verify our method for assessing arterial wall stiffness using SWE.

2. Methods

2.1 Leaky Lamb-wave Dispersion Analysis

The most notable characteristic of guided waves is dispersion effects, *i.e.*, their propagation speeds differ at each frequency. This fact makes it difficult to accurately estimate C_S using the conventional SWE which is generally based on the time-of-flight method . The LLDA method estimates C_S by fitting experimental dispersion curves to theoretical curves obtained from $V(k, f)$, dispersion equation of the first antisymmetric mode of leaky Lamb waves as shown in equation (1). C_L is the longitudinal velocity of the medium, C_S is the shear wave velocity of the medium, C_0 is the longitudinal velocity of the surrounding fluid, ρ is the medium density, ρ_0 is the surrounding fluid density, h is the thickness of the medium, k is the wave number, and f is the frequency [3].

$$\begin{aligned} &v(k,f) \\ &= (k^2-k_S^2)^2 \sin\left(\frac{k_L h}{2}\right)\cos\left(\frac{k_S h}{2}\right) \\ &+ 4k^2 k_L\, k_S \cos\left(\frac{k_L h}{2}\right)\sin\left(\frac{k_S h}{2}\right) \\ &+ i\frac{\rho_0 k_L (2\pi f)^4}{\rho k_0 c_S^4}\cos\left(\frac{k_L h}{2}\right)\cos\left(\frac{k_S h}{2}\right) = 0, \qquad (1) \\ &\quad k_0^2 + k^2 = \left(\tfrac{2\pi f}{c_0}\right)^2, \\ &\quad k_L^2 + k^2 = \left(\tfrac{2\pi f}{c_L}\right)^2, \\ &\quad k_S^2 + k^2 = \left(\tfrac{2\pi f}{c_S}\right)^2 \end{aligned}$$

In our previous study, we proposed the elimination of circumferential waves appeared in the axial velocity data and a curve fitting procedure above 600Hz in dispersion curves to apply the LLDA method to tubular phantoms since leaky Lamb waves are originally guided waves that propagate into a plate surrounded by fluids [3].

2.2 *Ex Vivo* Experiment

The excised porcine aorta was immersed in saline solution with no intraluminal pressure, as shown in **Fig. 1**. The IQ (in-phase and quadrature) data were obtained using Aixplorer® system and SL15-4 linear probe. The center frequency was 7.5 MHz; the pushing duration of acoustic radiation (ARF) force was 150 μs; and the frame rate was 10 kHz. A 2D autocorrelator was employed to calculate axial velocity data from the acquired IQ data [5]. The LLDA method estimated Cs, and then Young's modulus was deduced from the estimated Cs.

2.3 Mechanical Test

To evaluate the effectiveness of LLDA over the conventional SWE in the assessment of porcine aortic stiffness, the estimated Young's moduli were compared with the conventional SWE results and

---

jangjunkeun@yahoo.co.jp

mechanical test (Instron® 3342). The stress interval for calculating Young's modulus was selected from 1 kPa to 5 kPa since no intraluminal pressure was applied to the specimens.

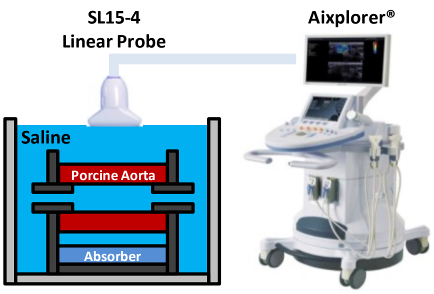

Fig. 1 Experiment Setup

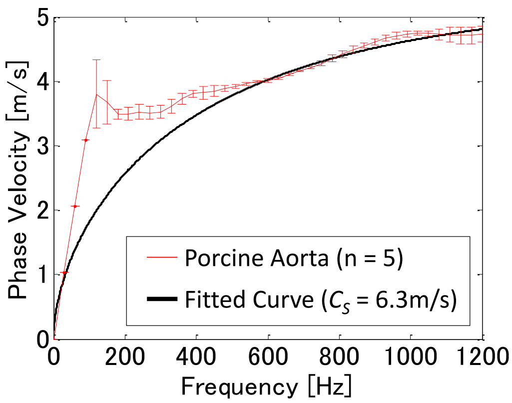

Fig. 2 Dispersion Curves of Specimen 1

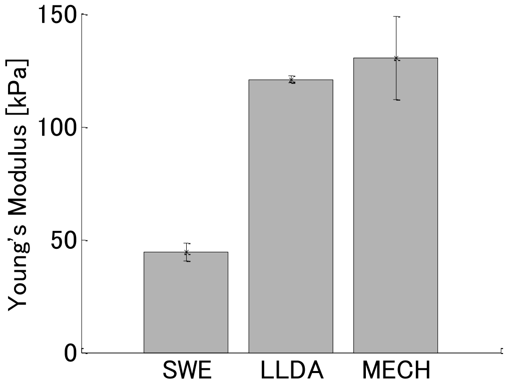

Fig. 3 Young's Moduli for Specimen 1

Table. I Comparsion of Young's Moduli [kPa]

	SWE	LLDA	Mech. Test
Specimen 1	44.6 ± 3.9	125.2 ± 2.1	130.3 ± 18.4
Specimen 2	30.4 ± 3.5	120.5 ± 2.0	111.7 ± 8.8

3. Results and Discussion

Fig. 2 and **Fig. 3** represent the dispersion curves and the Young's moduli of the specimen 1, respectively. The discrepency between porcine aorta and the fitted curve in the lower frequency region was not negligible, so the curve fitting was conducted above 600Hz, as proposed in the previous study [3]. This discrepancy can be attributed to the limitation of leaky Lamb wave model. The estimated shear wave velocity was 6.5 m/s; and the deduced Young's modulus was 119 kPa. From **Fig. 2** and **Table I**, the conventional SWE was proved to be inadequate for the assessment of arterial wall stiffness, while the LLDA method showed a good performance, judging from the negligible differences between the results of LLDA and mechanical test. As a result, the conventional SWE is ineffective for estimating arterial wall stiffenss. In contrast, the LLDA method was confirmed to be effective from *ex vivo* experiments of porcine aorta. Moreover, the proposed method in the previous study was validated to be requried when the LLDA is applied to the assessment of arterial wall stiffness. The limitation of this work is that no intraluminal pressure was considered. The future study should be focused on the effect of the static and dynamic intraluminal pressure on the performance of LLDA.

4. Conclusion

In this work, we applied the LLDA method to the assessment of *ex vivo* procine aortic stiffness. The Young's moduli estimated by LLDA showed a good agreement with mechanical testing under no intraluminal pressure. The future study should focus on assessing the reproducibility of the LLDA method under physiological conditions, *e.g.,* blood pressure and hearbeat, as well as evaluating its clinical feasibility.

Acknowledgment

We would like to express our thanks to Dr. M. Matsukawa, Doshisha University since we received valuable advice on making the vessel phantom for the preliminary study.

References

1. Gary F. Mitchell *et al.*: Circulation, **121** (2010) 505
2. M. Tanter *et al.*: Ultrasound Med. & Biol., **34** (2008) 1373.
3. J. K. Jang *et al.*: Jpn. J. Appl. Phys., **55** (2016)
4. M. Couade *et al.*: Ultrasound Med. & Biol., **36** (2010) 1662
5. T. Loupas *et al.*: IEEE Trans. Ultrason. Ferroelectr. Freq. Control, **42** (1995) 672