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Directional Dependence of Shear Waves in a 3D Blood Vessel Model

3次元血管モデルにおけるせん断波の方向依存性

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1. Introduction

ARFI (Acoustic Radiation Force Impulse) and SSI (Supersonic Shear Imaging) methods enable us to evaluate the mechanical properties of soft tissues noninvasively. Because a locally homogeneous medium is assumed, the shear modulus of the medium can be directly deduced from the shear wave speed. However, shear waves in arterial walls are affected by dispersion effects. The reason is that multiple reflections and mode conversions within the thin wall cause the shear wave propagation much more complex than in the unbounded medium. As a result, the arterial wall serves as a dispersive waveguide, and thus each frequency component propagates at a different speed[1]. A number of methods based on guided waves (e.g., Lamb waves, leaky Lamb waves, etc.) have been proposed to estimate the viscoelastic properties of the arterial wall using 2D plate models[1,2]. The actual structure of the artery, however, is a long tube rather than a thin plate. The cylindrical structure of the artery results in the directional dependence of shear wave propagation: the shear waves in the arterial wall can be mainly divided into longitudinal components and circumferential components. Furthermore, similarly to Lamb waves, there are three different mode types in a hollow cylinder: longitudinal (axisymmetric), torsional (axisymmetric), and flexural mode (non-axisymmetric)[3]. Because the acoustic radiation force is applied orthogonally to the arterial wall, the longitudinal flexural mode, we think, can characterize the mechanical properties of the arterial wall, just like the antisymmetric mode of Lamb waves in a 2D plate as explained in [1].

As a preliminary study, we performed finite element method (FEM) analysis to observe the shear wave propagation in our 2D plate and 3D hollow cylinder models, which means linear elastic materials and vacuum boundary conditions were used. Finally, we could observe (1) the complex propagation of shear waves due to the dispersion effects in both models, (2) the directional dependence in the 3D model.

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2. FEM Analysis

The shear wave propagation in a 2D free plate and a 3D hollow cylinder were simulated with PZFlex® (Weidlinger Associates Inc.). PZFlex® is a time domain finite element analysis package for analyzing piezoelectric materials, NDT (Non Destructive Testing), acoustic wave propagation problems, and nonlinear tissues. Fig. 1 illustrates the geometries of the 2D and 3D simulation models. The driving frequency, grid space, and time step were 1.5 MHz, 0.1 mm, and 2.2 µs, respectively. The mechanical properties were ρ (density) = 1000 kg/m^3, c_L (compressional wave velocity) = 1500 m/s, and c_T (shear wave velocity) = 8 m/s. To reduce simulation run time and memory requirements, only a quadrant of the entire volume of the 3D model was simulated by applying symmetry boundaries at x = 0 and y = 0, respectively.

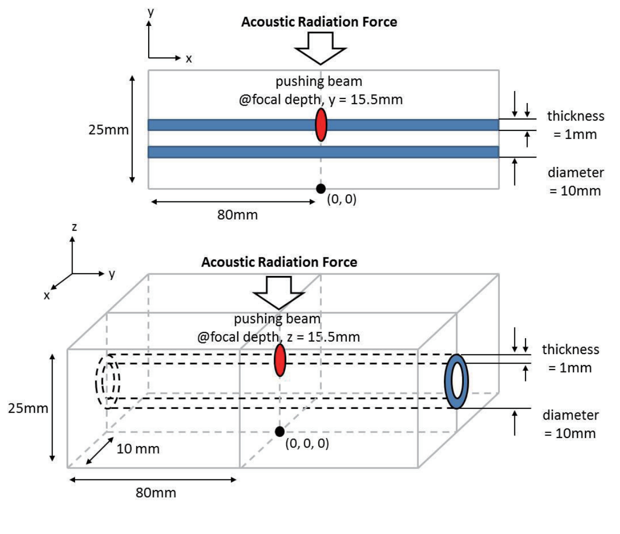

Fig. 1 2D and 3D simulation models

Because PZFlex® employs ARST(Acoustic Radiation Stress Tensor) to generate acoustic radiation force, the ARST need to be prepared at the very beginning of simulation. This tensor is internally calculated from time-averaged pressure of focused acoustic beams[4]. Finally, we could generate shear waves by applying the ARST to an input boundary condition. Fig. 2 shows the calculated ARS fields at the focal depth.

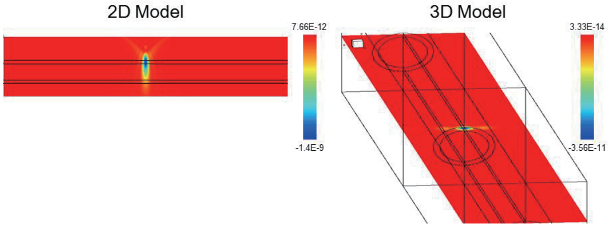

Fig. 2 calculated ARS fields in 2D and 3D models

3. Results and Discussion

Fig. 3 shows the snap shot of the y-direction displacements in the ROI (Region Of Interest) of the 2D model when t = 1 ms, 2 ms, and 3ms (the pushing duration of the acoustic radiation force was set to be 200 μs). With the shear waves propagating in the lateral direction, the aspects of the wave propagation become complex. Because multiple reflections occur at the boundaries, the mechanical energy of the acoustic radiation force tends to be confined within the plate. As a result, the interferences between shear waves exert influence on the shape of shear wave propagation.

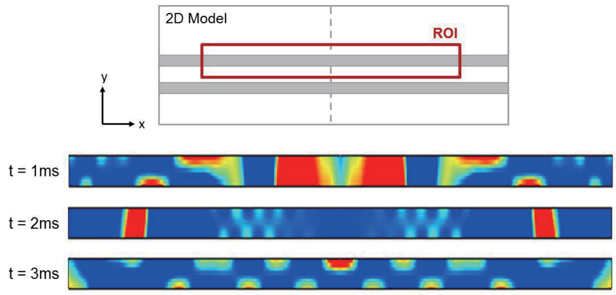

Fig. 3 y-direction displacements on ROI in 2D model when t = 1ms, 2ms, and 3ms

Fig. 4 presents the z-direction displacements on the x-y plane located at the focal depth in the 3D model when t = 0.8 ms and t = 4.5 ms. After the pushing sequence, shear waves propagate in all directions. However, the shear waves in the y-direction propagate mainly as the longitudinal components. The following Fig. 5 illustrates the z-direction displacements on the x-z plane located at y = 0 when t = 0.8 ms and t = 4.5 ms. The result in Fig. 5 shows the propagation of the circumferential components in the hollow cylinder.

These results indicate that the 3D cylindrical structure of the arterial wall causes the directional dependence of shear wave propagation, which is mainly composed of the longitudinal and circumferential components. Therefore, owing to the impact of the two components, the dispersion curve obtained from a simple 2D plate model may be insufficient for accurate assessment of arterial wall mechanical properties.

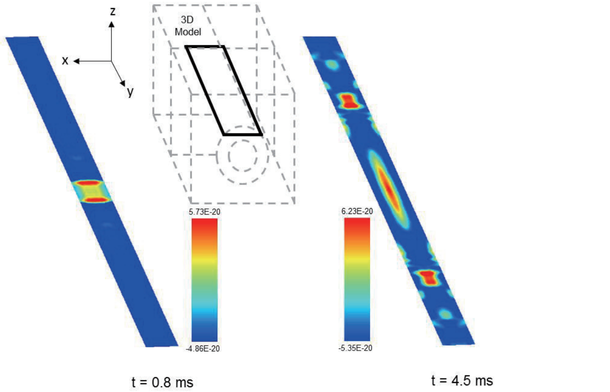

Fig. 4 z-direction displacements on the x-y plane located at the focal depth when t = 0.8 ms and 4.5ms

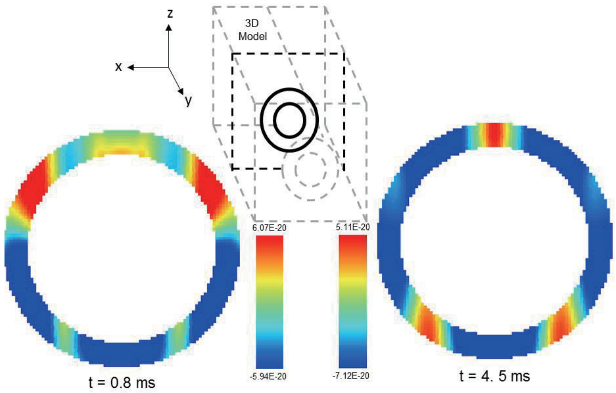

Fig. 5 z-direction displacements on the x-z plane located at y = 0 mm when t = 0.8 ms and 4.5ms

4. Conclusion

In this work, we simulated the shear wave propagation induced by acoustic radiation force in a 3D hollow cylinder model by performing FEM analysis. The directional dependence of shear waves was observed in the 3D hollow cylindrical model, but not in the 2D model. The results under more realistic, practical conditions (e.g., soft tissue/arterial wall/blood boundary condition, viscosity, etc.) and the validation of the simulation model with the longitudinal flexural mode will be discussed in the presentation.

5. References

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