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# Evaluation of Accuracy of Ultrasonic Measurement of Wall Shear Stress at Stenosis by Computational Fluid Dynamics

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## 1. Introduction

Wall shear stress (WSS) is known as an index related to progression of arteriosclerosis, which is a main cause of cardiovascular diseases. In recent years, a medical ultrasound system was employed to estimate WSS and diagnose atherosclerosis. In ultrasound imaging, WSS is obtained by applying spatially differentiation to measured blood flow velocities. However, when WSS was estimated from velocity measured by a diagnostic ultrasound system, WSS tends to be underestimated because velocity profile is smoothed spatially due to the finite spatial resolution of an ultrasound imaging system [1]. Therefore, some studies have tried to correct the underestimation of WSS by approximating a velocity profile in a vessel radial direction as parabolic [1]. However, blood velocity in a stenosed vessel would be complicated and results in an asymmetric velocity distribution.

In this study, we proposed a signal processing method to approximate a measured velocity profile as an asymmetric velocity distribution. A simulation phantom mimicking a stenotic vessel was modeled and fluid flowing in such a model was simulated by the computational fluid dynamics. The accuracy of the proposed method was evaluated based on the results of the computational fluid dynamics.

## 2. Methods

### 2.1. Computational fluid dynamics (CFD)

A commercial software (COMSOL Multiphysics) was used to simulate blood flow as incompressible fluid flowing through a cylindrical tube model. **Figure 1** shows a model used in this study. A three-dimensional model was modeled as a cylindrical tube with a channel diameter of 6 mm and a channel length of 100 mm. A plaque was created at 50 mm in the cylindrical tube as shown in Fig. 1. In this study, we investigated an effect of presence of stenosis on WSS estimation by changing the plaque thickness from 1 mm to 2 mm. Steady-state analysis was performed under a condition such that inflow and outflow boundary conditions were set at flow velocity and pressure of 0.5 m/s and 0 Pa, respectively. No-slip boundary condition was applied to the boundary between the lumen and the outer wall.

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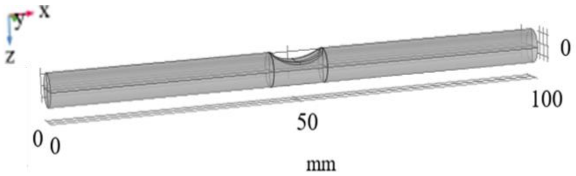


Fig. 1 Model of flow path for finite element analysis.

### 2.2. Simulation setup

The ultrasound simulation software, Field II, was used to simulate received ultrasound waves [2,3]. Simulation was performed by assuming a linear array probe with a center frequency of 7.5 MHz, 192 elements, and an element pitch of 0.2 mm. The 10 scatterers per resolution cell were randomly distributed inside the model shown in Fig. 1, and the scatters were moved based on displacement calculated from the velocity distribution obtained in Sect. 2.1. Using such a procedure, echo images of red blood cells were created.

### 2.3. Model for approximating velocity profile

In this section, we propose a signal processing method for approximating a measured velocity profile with an asymmetric flow velocity distribution. The blood velocity measured by the block matching method is denoted as $V_{\mathrm{BM}}(r,t)$ [4], where $r$ and $t$ are depth position and time, respectively. To approximate $V_{\mathrm{BM}}(r,t)$ with an asymmetric velocity distribution, the root mean square error (RMSE) of velocities were calculated in the interval from the near wall boundary to the center position of the velocity distribution. Also, the RMSE was calculated in the interval from the center position of the velocity distribution to the far wall boundary. These calculations were expressed as

$$\mathrm{RMSE}_1 = \frac{1}{n_1}\sqrt{\sum_{r=r_0-R_1}^{r_0}\{V_{\mathrm{est}}(r,t)-V_{\mathrm{BM}}(r,t)\}}, \quad (1)$$

and

$$\mathrm{RMSE}_2 = \frac{1}{n_2}\sqrt{\sum_{r=r_0}^{r_0+R_2}\{V_{\mathrm{est}}(r,t)-V_{\mathrm{BM}}(r,t)\}}, \quad (2)$$

respectively, where $n_1$ and $n_2$ are the number of data of measured velocity. $V_{\mathrm{est}}(r,t)$ is the velocity distribution model. In this study, parabolic and the Womersley velocity distributions were assumed as the model $V_{\mathrm{est}}(r,t)$ [5]. The center position of the velocity profile is denoted as $r_0$, and $R_1$ and $R_2$ are the distances from the center position $r_0$ to the near and far wall positions, respectively. To approximate the measured velocity profile with the velocity distribution model, $R_1$, $R_2$, and coefficients of the velocity distribution model were altered and optimized so that the RMSEs shown in Eqs. (1) and (2) were minimalized. Finally, the WSS was estimated using spatial differentiation of $V_{\mathrm{est}}(r,t)$ at the zero-crossing positions at $r = r_0 - R_1$ and $r_0 + R_2$.

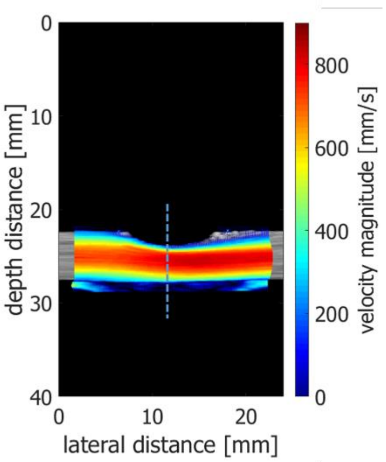


Fig. 2 Velocity magnitudes on B-mode image obtained in simulation at a plaque thickness of 2 mm.

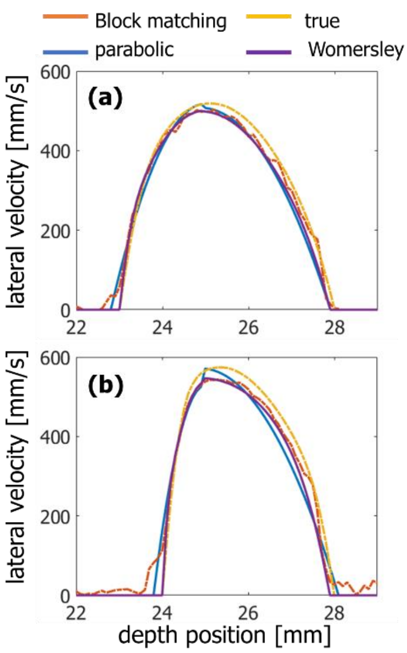


Fig. 3 Velocity profile obtained with plaque thickness of (a) 1 mm and (b) 2 mm, respectively. The yellow line shows true velocity profile. The red, blue and purple lines show velocity profiles estimated with block matching method, fitted with parabolic and Womersley profiles, respectively.

Table I Bias errors of WSS at plaque thicknesses of (a) 1 mm and (b) 2 mm.

| (a) | parabolic | Womersley |
|---|---|---|
| WSS (near wall) | -40.0 % | -4.4 % |
| WSS (far wall) | -26.1 % | -16.1 % |

| (b) | parabolic | Womersley |
|---|---|---|
| WSS (near wall) | -39.7 % | -16.3 % |
| WSS (far wall) | -53.0 % | -23.3 % |

## 3. Results

**Fig. 2** shows a B-mode image (plaque thickness: 2 mm) and the spatial distribution of flow velocity. **Figs. 3(a) and 3(b)** show a 1D velocity profile shown in the dashed line in Fig. 2 with plaque thicknesses of 1 mm and 2 mm, respectively. In Figs. 3(a) and 3(b), the red and yellow lines are the measured velocity $V_{\mathrm{BM}}(r,t)$ and true velocity, respectively. The blue and purple lines are the 1D velocity profiles approximated with parabolic and the Womersley profiles, respectively. In Figs. 3, the gradient of the purple line (Womersley) was more similar to the yellow line (true value) than the blue line (parabolic). **Table I** shows the bias errors of the WSS obtained from the blue (parabolic) and purple (Womersley) lines. As shown in Table I, the bias error of WSS was reduced to less than 30% by fitting to the Womersley distribution.

## 4. Conclusion

In this study, a signal processing method to approximate a measured velocity profile with an asymmetric velocity distribution was proposed to improve the underestimation of WSS and validated by computational fluid dynamics. The experimental results showed that the bias error of WSS was reduced to less than 30% by fitting to the Womersley distribution.

## References


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