3P5-5

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

Wall Shear Stress Measurement Method Based on Novel Flow Model Near Vascular Wall in Echography

血管壁近傍流れモデルに基づく壁面せん断応力の超音波測定

Motochika Shimizu[1†‡], Tomohiko Tanaka[1], Takashi Okada[2], Yoshinori Seki[2], and Tomohide Nishiyama[2] ([1]Research & Development Group, Hitachi Ltd.; [2]Healthcare Business Unit, Hitachi Ltd.)
清水一力[1†‡]，田中智彦[1]，岡田孝[2]，関佳德[2]，西山知秀[2] ([1]株式会社日立製作所　研究開発グループ，[2]株式会社日立製作所　ヘルスケアビジネスユニット）

1. Introduction

Arteriosclerosis is one of the most serious diseases in cardiovascular diagnosis because it triggers other fatal diseases such as myocardial infarction and cerebral infarction. An ultrasonic diagnosis instrument is an effective modality for quickly assessing arteriosclerosis noninvasively. For early diagnosis of arteriosclerosis, wall shear stress (WSS), which is the blood stream stimulation of the vessel wall, has been proposed as a diagnosis index [1-2]. A WSS larger than 1.5 Pa keeps the vessel wall in healthy condition, while WSS smaller than 0.4 Pa promotes arteriosclerosis [1].

For arteriosclerosis progression assessments, conventional methods have insufficient measurement accuracy of WSS in echography. To distinguish the two threshold values (1.5 Pa and 0.4 Pa), the error of WSS should be less than 57%. However, various errors in ultrasonic imaging cause a much larger WSS error. The prievious research [3-4] tried to reduce only the velocity error caused by tissue motion.

The aim of this research is to devise a novel echocardiographic method for measuring WSS with an error less than 57% by reducing the influence of all three main error factors.

2. Materials and methods

2.1 Three error factors in WSS measurements

The definition of WSS is physically described by Equation (1):

$$\sigma_{WSS} = \mu \left. \frac{du}{dy} \right|_{y_w} \tag{1}$$

where σ_{WSS} is WSS, μ is blood viscosity, du/dy is the velocity gradient, and y_w is the vessel wall position. When estimating WSS from the velocity distibution, both the measurement error of the velocity and the wall position affect the WSS error.

A typical velocity distibution measured by an ultrasonic diagnosis instrument is shown in **Fig. 1 (b)**. An accurate WSS cannot be obtained from the simple calculation of Equation (1), because the velocity and wall position have three types of measurement errors: a velocity underestimation error due to the wall filter, a fluctuation error due to velocity measurement variations, and a wall position error due to B-mode image blurring.

2.2 Proposed method

The WSS measurement method proposed in this paper is based on a novel flow model for nearby a vascular wall. We assume that the flow near a wall is along with the vessel wall, which is in turn based on the parallel flow assumption [5]. By solving the Navier-Stokes equations under this assumption, the velocity gradient distribution is obtained as a linear line, shown in **Fig. 1 (c)**. In the figure, point A where the linear line crosses the wall position indicates *du/dy* at the wall. To estimate WSS, point A is calculated from the relation between *u* and *du/dy* (Equation (2)).

$$u(y) = \int_{y_w}^{y} \frac{du}{dy}\,dy = \frac{1}{2}\left(\left. \frac{du}{dy} \right|_{y_w} + \frac{du}{dy} \right)(y - y_w) \tag{2}$$

Equation (2) means, for example, the area of the trapezoid ABCD is equal to the velocity at y_1.

This paper compares two methods for solving Equation (2) to investigate the effect of error influence reduction. Method I only deals with velocity underestimation, while method II reduces the influence of all three errors.

First, method I solves Equation (2) at the maximal point (y_1). Using the measured value at y_1

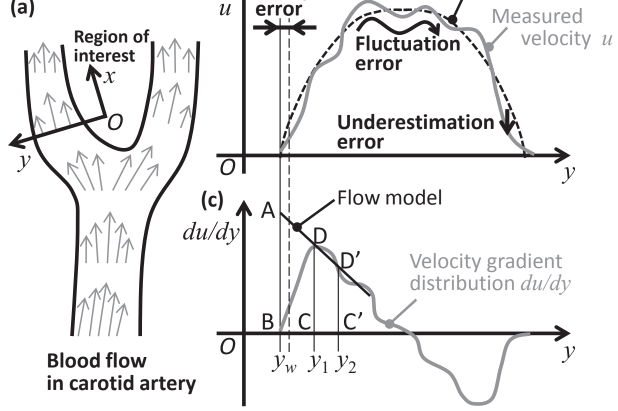


Fig. 1 Velocity distribution and flow model for near a vascular wall.

for the WSS estimation reduces the influence of the velocity underestimation error, because the innner area of y_1 is less underestimated by the wall filter.

Next, method II solves two equations at the maximal point (y_1) and the inflection point (y_2), or of the trapezoids ABCD and ABC'D' in Fig. 1 (c), as simultaneous equations. The measured value at y_2 is less affected by the velocity underestimation error than y_1 is because y_2 is inner. This point is also robust to fluctuation errors, because it is near the center of the wave. Furthermore, the influence of the wall position error is reduced by treating y_w as an unknown quantity. The wall position error due to a blurry wall image is suppressed in the calculation of the simultaneous equations.

2.3 Experimental setup

The experimental setup is shown in **Fig. 2**. The experiment evaluated the measuring performance of the proposed methods. Here, WSS values measured with Particle Image Velocimetry (PIV) were taken to be the ground truth.

An ultrasonic diagnosis instrument (ProSound F75, Hitachi Aloka Medical, Ltd.) was used to collect B-mode data and color Doppler data (5MHz) of the pulsatile flow of polyethylene glycol (Wako Pure Chemical Industries, Ltd.) containing 20-μm glass particles (EMB-20, Potters Ballotini Co., Ltd.) in a carotid artery phantom made of permeable urethane (Tomei Hitohada gel, Exseal corporation, Ltd.). Pulsatile flow at 1 Hz was produced by a combination of a peristaltic pump (7518-12, Cole-Parmer Instrument Company, LLC) and syringe pump (F14-10, Yamaha Motor Co., Ltd.). The collected data was first processed with a Vector Flow Mapping algorithm [6] for calculating the two-dimensional velocity distribution. Next, the velocity distribution on a cross section perpendicular to a highlighted vessel wall was calculated. Finally, the WSS was calculated with the proposed methods.

The PIV system also measured the flow in the carotid artery phantom. The system consisted of a CCD camera (SpeedSense1010, Dantec Dynamics A/S) and a Nd:YAG laser source (5W, 532 nm). The CCD camera recorded the light scattered from the glass particles, and PIV analysis software (Dynamic Studio V3.31, Dantec Dynamics A/S) calculated the two-dimensional flow velocity distribution. The ground truth of WSS was calculated from the velocity distribution measured by PIV.

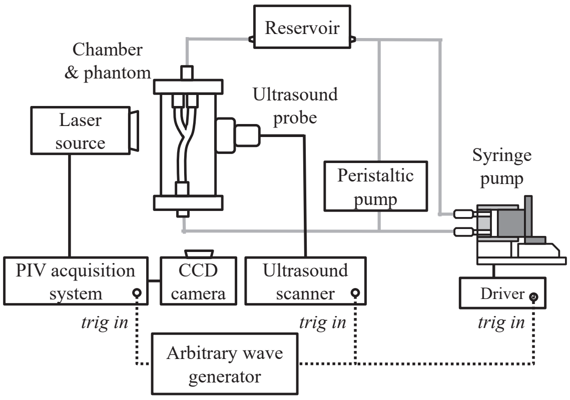
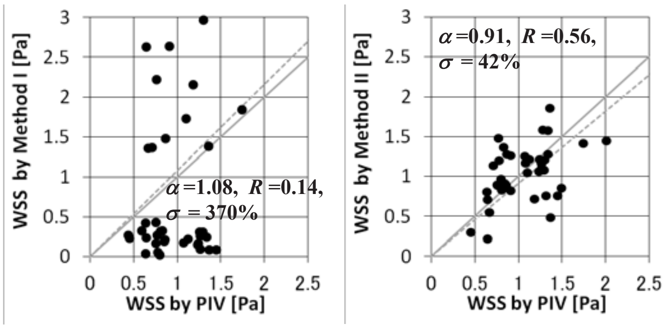


Fig. 2 Experimental setup.

3. Results and Discussion

The measured relations between the PIV and proposed methods are shown in **Fig. 3**. Method I had no correlation with PIV (the correlation coefficient, R, was 0.14), and its standard deviation (SD), σ, was 370%. In the case of using method II, R was 0.56, σ was 42 %, and the slope, α, was 0.91.

Method II had a 42% error, which is within the 57% error required for arteriosclerosis diagnosis. This is because method II reduces the influences of all three main errors, whereas method I only deals with the velocity underestimation error.



(a) Method I (b) Method II

Fig. 3 Measured correlation between proposed methods and PIV.

4. Conclusion

This research proposed a new WSS measurement method using an ultrasonic diagnosis instrument. The method can measure WSS within a 42% SD, which is sufficient to distinguish high-risk vessels of arteriosclerosis.

References

1. A. M. Malek et al.: JAMA **282** (1999) 2035.
2. L. Kornet et al.: Arterioscler Thromb Vasc Biol. **18** (1998) 1877.
3. Y. I. Cho and K. R. Kensey: Biorheology **28** (1991) 241.
4. S. Ricci et al.: IEEE International Ultrasonics Symposium Proceedings (2014) 432.
5. P. K. Kundu and I. M. Cohen: Fluid Mechanics Second Edition (2002) 274.
6. K. Itatani et al.: Japanese Journal of Applied Physics **52** (2013) 07HF16.

---

mailto:motochika.shimizu.bj@hitachi.com