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Evaluation of blood flow velocity waveform in common carotid artery using multi-branched arterial segment model of human arteries

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ABSTRACT

Arteriosclerosis is considered to be a major cause of cardiovascular diseases, which account for approximately 30% of the causes of death in the world. We have recently demonstrated a strong correlation between arteriosclerosis (arterial elasticity) and two characteristics: maximum systolic velocity (S1) and systolic second peak velocity (S2) of the common carotid artery flow velocity waveform (CCFVW). The CCFVW can be measured by using a small portable measuring device. However, there is currently no theoretical evidence supporting the causes of the relation between CCFVW and arterial elasticity, or the origin of the CCFVW characteristics. In this study, the arterial blood flow was simulated using a one-dimensional systemic arterial segments model of human artery in order to conduct a qualitative evaluation of the relationship between arterial elasticity and the characteristics of CCFVW. The simulation was carried out based on the discretized segments with the physical properties of a viscoelastic tube (the cross-sectional area at the proximal and terminal ends, the length, and the compliance per unit area of the tube (C_S)). The findings obtained through this study revealed that the simulated CCFVW had shape similar characteristics to that of the measured CCFVW. Moreover, when the compliance C_S of the model was decreased, the first peak of the simulated-CCFVW decreased and the second peak increased. Further, by separating the anterograde pulse wave and the reflected pulse wave, which form the CCFVW, we found that the decrease in the first peak of the simulated CCFVW was due to the arrival of a reflected pulse wave from the head after the common carotid artery toward the arrival of a anterograde pulse wave ejected directly from the heart and that the increase in the second peak resulted from the arrival of the peak of the reflected pulse wave from the thoracic aorta. These results establish that the CCFVW characteristics contribute to the assessment of arterial elasticity.

1. Introduction

The recent increase in the number of patients with cardiovascular diseases due to lifestyle-related disorders has become a problem in developed countries. According to findings from a survey conducted by the World Health Organization (WHO). Examples of cardiovascular diseases are angina pectoris, myocardial infarction, cerebral thrombosis, and cerebral infarction; the major cause of these diseases is the development of a circulatory failure due to arteriosclerosis in the coronary and cerebral arteries. Therefore, slowing the progression of arteriosclerosis is believed to lead to the prevention of cardiovascular diseases. The risk factors of arteriosclerosis include lifestyle-related diseases such as hypertension, obesity, and dyslipidemia [1]. Arteriosclerosis is accompanied by no subjective symptoms and progresses with age but is said to be preventable through routine exercise and improvement of eating habits.

Nowadays, flow-mediated dilatation (FMD) tests [2] and pulse wave velocity (PWV) tests [3] are, respectively, widely performed in medical institutions as methods for the evaluation of vascular endothelial function and arterial elasticity. However, the device

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used for conducting these tests is large, has many sensors, and requires measurement skills, and is therefore unsuitable for performing measurements at home. Ultrasonotomographic images are analyzed as the diagnostic method of systemic arteriosclerosis. The analysis allows for a real-time visualization of the condition of vascular endothelium, blood circulation, and blood flow velocity waveforms, and it can be adopted for evaluating the arteriosclerosis by visualizing the intima media thickness (IMT) of the carotid arteries and the presence or absence of plaque. The common carotid artery is an important artery that supplies blood to the head, and because it travels relatively close to the skin, measurements can be performed easily. Compared to the measurement of the peripheral pulse pressure in the wrists and ankles, the common carotid artery is believed to allow for an evaluation of such information because of its proximal location to the heart and the aorta.

In order to evaluate the functions of the circulatory system on the basis of the common carotid artery hemodynamics, our research team has recently been working on the development of a small device using an ultrasound Doppler method for the measurement of the blood flow rate. The device allows for a real-time measurement of the common carotid artery flow velocity waveform (CCFVW) on the basis of continuous ultrasound waves radiated on the common carotid artery from a small ultrasound probe. The CCFVW has five characteristics, namely, the minimal end diastolic flow velocity, which is defined as d; the maximum systolic velocity, which is defined as S1; the systolic second peak velocity, which is defined as S2; the notch between systole and diastole, which is defined as I; and the maximum diastolic velocity, which is defined as D. These characteristics appear clearly in most young healthy subjects. Thus far, the results of the measurement of the CCFVW in 368 subjects from a wide range of age groups have shown a moderately negative correlation between S1 and age ($R = -0.688$). Because the decrease in S1 can be improved through daily exercise, it is believed to be related to the deterioration of the cardiac function associated with aging [4–6]. In addition, it was found that S2/S1 showed a strong positive correlation ($R = 0.738$). S2 has virtually no correlation with age ($R = 0.109$), suggesting that it represents the response to the level of cardiac function (S1), in other words, the amplitude of the reflection of the pulse wave from the bifurcation of the artery and from the periphery.

In a recent study, the relationship between the cardio-ankle vascular index (CAVI) and the characteristics of CCFVW was examined in 59 male participants. Unlike the evaluation of arterial elasticity, which only takes into account the PWV, the measured values of the CAVI do not vary depending on blood pressure, and represent artery-specific stiffness [7]. In addition, they have been found to be associated with cardiovascular risks and with other artery evaluation indexes such as the IMT and plaque scores; further, based on comparisons, they have been found to be useful [8–10]. The results of the measurements showed that the CAVI was strongly correlated with age and S2/S1 ($R = 0.812$, $R = 0.738$). Because the elasticity of the aorta decreases with age, CAVI and age are believed to be related. In addition, statistical data also suggested that information on aortic elasticity can be determined not only on the basis of S2/S1 but also on the basis of other indexes obtained from the CCFVW [11]. In other words, the characteristics, namely, S1 and S2, are probably related to aortic elasticity.

However, there is no theory backing the causes of the existence of a relationship between CCFVW and arterial elasticity, or the components of the CCFVW characteristics. The purpose of this study is to conduct a qualitative evaluation of the relationship between artery elasticity and the CCFVW characteristics. Thus far, the changes in blood flow caused by the stenosis of the arteries [12] and the dynamics of blood circulation in the Circle of Willis in the head [13] have been theoretically evaluated through the use of fluid simulation using a one-dimensional systemic arterial segments model of human artery. However, no previous study has examined the relationship between CCFVW and aortic elasticity. Due to a structural/relative position in the arterial system, the left common carotid artery is affected by the arrival of pulse waves from arteries all over the body, such as the Circle of Willis in the head, the part of the aorta after the thoracic aorta, and peripheral arteries in the arms and legs. Therefore, a one-dimensional systemic arterial segments model, reflecting the physical characteristics of major arteries in the human body, can be used as a simulation model [12,14]. In this study, the CCFVW characteristics were established on the basis of an arterial blood flow simulation using a one-dimensional systemic arterial segments model. The relationship between the CCFVW characteristics and the arterial elasticity can be studied by varying the compliance in the model. In addition, the effect of the reflected wave of the pulse wave on the formation of CCFVW, as well as the effect of the reflected pulse wave resulting from a decrease in arterial elasticity, can be examined by decomposing the flow rate/pressure waveform in the left common carotid artery, as determined from the simulation, into anterograde pulse waves and reflected pulse waves.

If the degree of arterial elasticity can be evaluated on the basis of CCFVW measured using a small device for measuring blood flow velocity, a self-check can easily be performed at home or in various facilities such as fitness clubs; this may contribute to an inhibition of the progression of arteriosclerosis.

2. Methods

2.1. Fluid equations

A fluid simulation based on a one-dimensional model was performed by simultaneously solving an equation of continuity with the following one-dimensional Navier-Stokes equations representing the flow of an incompressible viscous fluid inside a viscoelastic tube [15]. These equations assume an absence of outflow from the tube wall, presume a uniformity of the flow velocity distribution, and ignore the influence of gravity.

$$\frac{\partial A}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad (1)$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) + \frac{A}{\rho}\frac{\partial p}{\partial x} + f = 0 \quad (2)$$

Here, x represents the arbitrary position along the axial direction of the tube, t represents time, $A = A(x, t)$ represents the cross-sectional area of the tube, $Q = Q(x, t)$ represents the average flow rate in the cross section of the tube, $p = p(x, t)$ represents the mean pressure in the cross section of the tube, ρ represents the density of the fluid, and $f = f(x, t)$ represents the viscous resistance.

The average flow velocity in the cross section of the tube $V = V(x, t)$ was calculated using the following equation.

$$V = \frac{Q}{A} \quad (3)$$

When the liquid flow inside the tube is presumed to exhibit a laminar flow of a Newtonian fluid, using Womersley's analytical solution, the viscous resistance f in Eq. (2) is expressed by the following equation.

In the arteries with a diameter greater than 1 mm, the margin of error of the viscous resistance would be small even if blood is hypothesized as a Newtonian fluid. In addition, the viscous