The Sixteenth International Symposium on Artificial Life and Robotics 2011 (AROB 16th '11),
B-Con Plaza, Beppu,Oita, Japan, January 27-29, 2011

Blood flow velocity waveforms in the middle cerebral artery at rest and during exercise

T. Matsuo, S. Watanabe, M. Sorimachi, M. Kanda, Y. Ohta, and #T. Takahashi

Kanagawa Institute of Technology, Shimo-ogino 1030, Atsugi, Kanagawa 243-0292, Japan.
(Tel : 81-46-291-3279; Fax : 81-46-291-3262)
(Email address : matuo@rm.kanagawa-it.ac.jp)
#Asahikawa Medical College, Midorigaoka Higashi 2-1-1-1, Asahikawa 078-8510, Japan.

Abstract: The blood flow velocities in the middle cerebral artery were measured under steady-state and incremental cycle exercises using the transcranial Doppler ultrasound velocimeter. The peak-systolic velocity was found to rise markedly under exercise, while the end-diastolic velocity tended to keep a resting value. The fluctuation of velocity and resistance index were calculated in order to evaluate the hemodynamic load on the vessel wall. They also increased markedly under exercise. Such hemodynamic changes in activity might be important in understanding the genesis of vascular diseases as well as physiology of cerebral circulation.

Keywords: Transcranial Doppler, Ultrasound, Middle cerebral artery, Cerebral Circulation, Blood velocity

I. INTRODUCTION

Since the brain tissues are extremely vulnerable in terms of oxygen deficiency, an adequate and continuous supply of oxygenated blood is essential for the function of the brain. The blood flow in the middle cerebral artery (MCA) maintains about 80% of the flow volume arriving at the cerebral hemisphere. Since the blood velocity waveforms are considered to be closely related to the flow disturbances caused by arterial diseases such as stenosis and cerebral aneurysms, blood velocity measurements using transcranial Doppler (TCD) sonography are widely conducted in clinical examination [1][2].

Most of the clinical data of transcranial Doppler have been measured under resting condition. It should, however, be noted that the blood flow would be easily disturbed by daily activity such as work, exercise and posture change, as well as changes in environmental factors such as ambient temperature. In the present study, we measured velocity waveforms in the MCA during cycle exercise in order to understand the dynamics of MCA blood flow caused by physical exercise. Velocity waveforms might contain information concerning the homodynamic load on the vessel wall such as shear stress and velocity fluctuation which are considered to play an important role of the genesis and development of arterial diseases [2].

II. METHOD

1. Subjects

Six healthy young male and 6 healthy young female volunteers participated in the present study. None of the subjects had any history of cardiovascular, cerebrovascular, or respiratory disease. All subjects were fully informed about the procedures, risk, and benefits of the study, and written consent was obtained from all subjects before the study. This study was approved by the university institutional board.

2. Experimental design

Each subject was required to keep his body in an upright, seated position on an electromagnetically-braked cycle ergometer during rest and exercise periods. Two kinks of exercises were conducted as follows;

(A) Steady-state exercise;

The work rate was maintained at 100 W for males and at 50 W for females for 15 minutes exercise. During exercise, the subjects pedaled at a constant rate of 60 rpm paced by a metronome. The exercise intensity corresponds to "moderate exercise".

(B) Incremental exercise;

During 15 minutes exercise, the work rate was increased from 20 to 100 W by a 20 W increment step for males, and from 10 to 50 W by a 10 W step for females. The duration of each step was 3 minutes with keeping a pedaling rate of 60 rpm.

3. Measurement of blood velocity and pressure

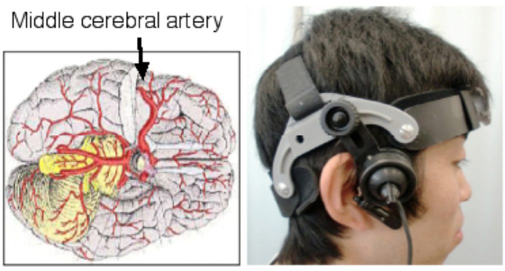

Fig.1 Position for Doppler examination

The blood flow velocity in the right middle cerebral artery was obtained using a 2-MHz pulsed Doppler ultrasound system (Intra-view, Rimed, Israel). Its pulsed probe was located over the temporal bone and the Doppler signal was optimized through a change in the insonation angle. The probe attached to the skull at a fixed angle was held using a headgear with an adjustable positioning system. The blood flow velocity was assessed for 6-10 consecutive cardiac cycle recorded during the last minute before and during exercise. Peak-systolic, end-diastolic, and mean blood flow velocity in MCA were represented by *MCAVs*, *MCAVd*, and *MCAVm*, respectively.

The blood pressure in the brachial artery was sphygmomanometrically measured using a pneumatic arm cuff which was held at heart level. Mean arterial blood pressure (MAP) was calculated as diastolic blood pressure (DBP) plus one-third pulse pressure [3].

III. RESULTS AND DISCUSSION

1. Velocity waveforms

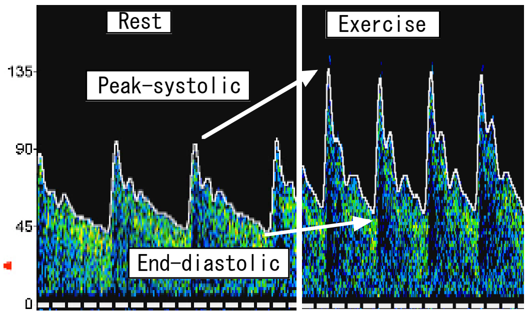

Fig. 2 Measured velocity waveforms in the MCA

In Fig. 2, an example of the obtained velocity waveforms is shown, where the waveform in the exercise is compared with that in the rest. As can be noted in the left panel, the waveform shows substantial variation of flow velocity during one cardiac cycle. The velocity rises sharply at initial systolic phase of heart (peak-systolic velocity), and decreases gradually during diastole. The flow waveform is characterized by a high forward flow at end-diastole, which is as much as half peak-systolic velocity. This feature is characteristic of blood flow in intracranial arteries, and contrasts with the relatively low diastolic flow component in the external carotid artery. This difference is ascribed to the markedly low flow resistance in the cerebral vasculature compared with that in the territory of the external carotid artery [1].

It should be also noted that the peak-systolic velocity (*MCAVs*) markedly increased during exercise, while the end-diastolic velocity (*MCAVd*) showed a trivial change. Accordingly, the difference between *MCAVs* and *MCAVd* was increased.

2. Hemodynamic data during steady-state exercise

Figure 3 shows physiological quantities (blood velocity, blood pressure and heart rate) measured at rest and during steady-state exercise. The measured values given in the graph are average for 12 volunteers (6 females and 6 males). Peak velocity *MCAVs*, systolic blood pressure, and heart rate rise immediately after onset of exercise. On the contrary, the diastolic pressure and end-diastolic velocity *MCAVd* were found to show no statistically significant change during exercise. It is also noted that the heart rate tends to slightly increase during exercise, while *MCAVs* and systolic pressure show slight inclination to decrease.

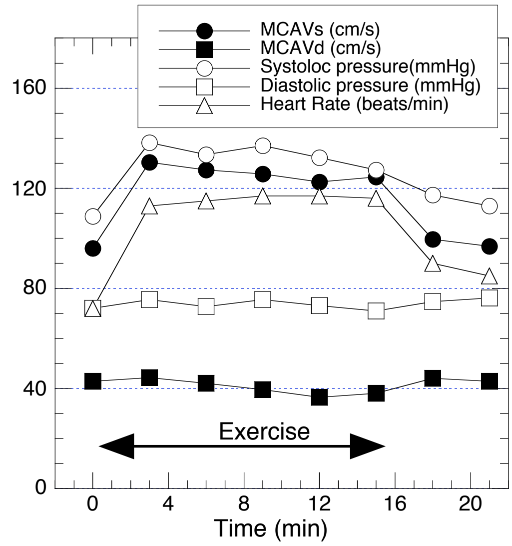

Fig. 3 Physiological quantities measured at rest and during steady-state exercise.

3. Hemodynamic data during incremental exercise

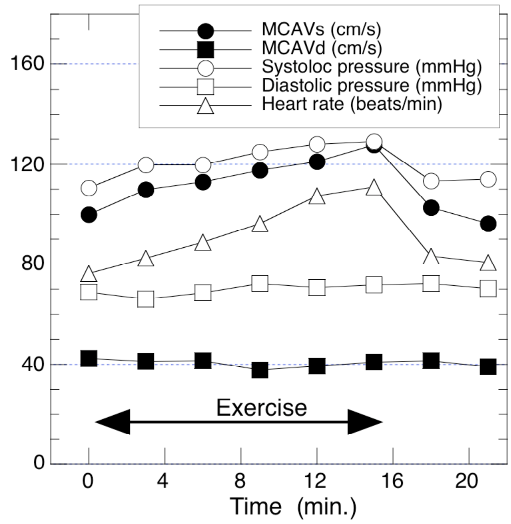

Fig. 4 Physiological quantities measured at rest and during incremental exercise.

The measured physiological quantities under incremental exercise are shown in Fig. 4. The *MCAVs* gradually increases as the degree of exercise increases. After 15 minutes, corresponding work rate being 100 W for male and 50 W for female, *MCAVs* reaches a value (130 m/s) comparable to that in the steady-state exercise. Also the systolic pressure and heart rate are on the increase. As in the steady-state exercise, both *MCAVd* and diastolic pressures show no significant change during exercise.

5. Fluctuation in MCA velocity

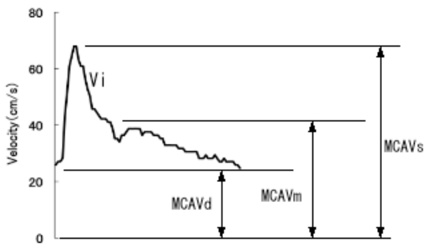

Fig. 5 Indices used in waveform analysis

In order to see the variation in velocity due to exercise, we calculated velocity fluctuation index (*VF*) for measured velocity waveforms, which is defined as,

$$VF = \sqrt{\frac{\sum_{i=1}^{n} (V_i - MCAV_m)^2}{n}} \quad \cdots\cdots\cdots(1).$$

Here, V_i: velocity at time t_i, $MCAV_m$: mean velocity averaged over one cardiac cycle, and n: number of measured velocity data for one cardiac cycle. This index is corresponding to the standard deviation in statistics.

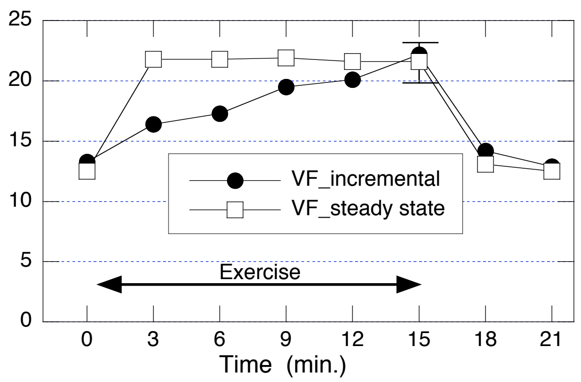

Fig. 6 Velocity fluctuations (VF) of MCA blood flow under incremental and steady-state exercises.

Figure 6 compares *VF* values calculated for steady-state exercise with those for incremental exercise. Velocity fluctuations in steady-state exercise are well constant during exercise. The *VF* values under exercise were found to be about 1.8 times larger than those at rest. In the incremental exercise, *VF* increases as the exercise intensity increases. Such *VF* variations as a function of exercise intensity are quite similar to the *MCAVs* variations shown in Figs. 2 and 3.

5. Resistance index

Pourcelot [4] introduced the "resistance index" to Doppler sonography as a means to characterize the peripheral resistance in the cerebral circulation. Resistance index (*RI*) is defined as following equation,

$$RI = \frac{MCAV_s - MCAV_d}{MCAV_s} = 1 - \left(\frac{MCAV_d}{MCAV_s}\right) \quad \cdots(2).$$

This index describes the ratio of peak-systolic velocity to the end-diastolic velocity. For the normal common carotid artery, *RI* is reported to be between 0.55 and 0.75. In arteries that supply high-resistance musculocutaneous beds, *RI* is known to be greater than 0.75 [4]. The arteries that supply the brain have *RI* index less than 0.75. A low *RI* value is also seen post-stenotically in cases where flow resistance is decreased by reactive dilatation of blood vessels [1].

In Figs. 7 and 8, are shown the obtained *RI* values during exercise, in which results for males and females are indicated individually. Under steady-state exercise shown in Fig.7, although the variance of the data are considerably large, *RI* values tend to increase rather gradually from 0.57 to 0.74 in males and from 0.53 to 0.67 in females, compared with the fluctuation index shown in Fig. 6. These values of *RI* can be well compared with the previous data mentioned above.

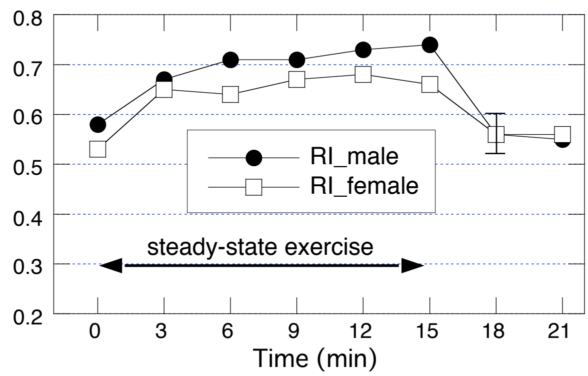

Fig. 7 Resistance index during steady-state exercise

As shown in Fig. 8, in males, the *RI* values in incremental exercise vary increasingly from 0.57 to 0.69 as increase of exercise intensity. Although an increasing trend is seen also in females, the data points show rather scattering. The reason for the difference between female and male is not clear at present, and sophisticated experiment would be necessary.

The index *RI* is not only a function of flow resistance but also influenced by vascular compliance. It is generally known that the velocity waveform changes considerably with aging result from increased resistance due to cerebral atherosclerosis, and decreased compliance of vessel wall [1]. The waveforms of elder subjects were reported to be characterized by high *RI* values and steep decrease of velocity in diastole. The waveform change form rest to exercise shown in Fig. 2 seems to be similar to that due to aging.

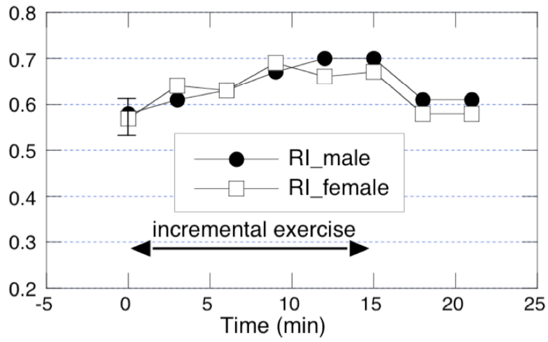

Fig.8 Resistance index during incremental exercise

We also measured velocity waveforms during strong exercise with intensities from 120 to 150 W (data not shown). It was found that above 120 W of exercise intensity, the *MCAVs* values were almost constant, while *MCAVd* values were slightly decreased, resulting in that both velocity fluctuation *VF* and resistance index *RI* were increased.

5. Correlation between hemodynamic variables

Measured hemodynamic variables such as blood velocities, arterial pressures, and heart rate were subjected to correlation analysis each other. Among the results, the relationship between *MCAVs* and systolic blood pressure (*SBP*), and that between *MCAVs* and heart rate *HR* were found to show statistically significant correlation as shown in Figs. 9 and 10. The significant correlation between *MCAVs* and systolic arterial pressure might be supported by the results indicated in Figs. 2 and 3. Although the data are not given here, mean MCA blood velocity *MCAVm* showed significant correlation with mean arterial pressure and heart rate.

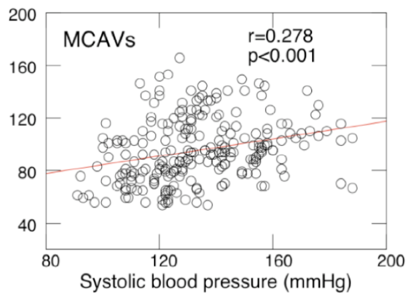

Fig. 9. Correlation between *MCAVs* and systoric arterial pressure

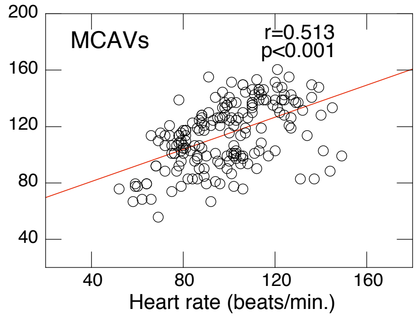

Fig. 10. Correlation between *MCAVs* and heart rate

IV. SUMMARY

The velocity waveforms in the middle cerebral artery in young volunteers were measured under moderate-intensity cycle exercise. The peak systolic velocity *MCAVs* and the end-diastolic velocity *MCAVd* were obtained from measured waveforms. Calculated hemodynamic variables, velocity fluctuation *VF* and resistance index *RI*, showed remarkable increase under exercise. The waveforms in exercise seemed to be similar to those of elder people at rest. A preliminary experiment of high intensity exercise showed nonlinear changes of *MCAVs*, *MCAVd*, *VF* and *RI*, indicating that the influence of exercise on cerebral blood flow is more complicated than thought before. However, the number of volunteers was still limited in the present study and the results are thought to be affected by individual differences in physiological variables. Therefore, further study is required to derive a concrete conclusion. Simultaneous measurements of MCA blood flow waveforms and arterial blood pressure waveforms are under way, since these measurements would provide much information on the regulation of cerebral circulation.

REFERENCES

[1] G-Michael von Reuturn and Hans Joachim von B u e d i n g n (1993), Ultrasound Diagnosis of Cerebrovascular Disease, Georg-Thieme Verlag Stuttgart·Newe York.
[2] Hennerici M G and Stephen P M (2001), Cerebravascular ultrasound: theory, practice and future developments, Cambridge Univ. Press New York.
[3] Watanabe S, Matsuo T, Sorimachi M, et al. (2009), Comparison of blood flow velocity in the middle cerebral artery between men and women at rest and during exercise. Therapeutic Research, 30(4), 537-544.
[4] Pourcelot L (1976), Diagnostic ultrasound for cerebral vascular disease, in Donald JS, Levi S edits: Present and Future of Diagnostic Ultrasound. Kooyker Rotterdam.