Mem. Fac. Educ. Kumamoto. Univ.
Nat. Sci., No.47. 59−64, 1998

Variability of Maximal Amplitude in Carotid Artery Pulse during Exercise: Power Spectral Analysis

Hirotoshi IFUKU, Kohachi TANIGUCHI, Yasuharu OISHI,
Hisahiro MATSUMOTO, and Koji OSHIGE*

(Received September 1, 1998)

Abstract

To determine whether or not the power spectrum of maximal amplitude variability in the carotid artery pulse (CAP) can be used as a noninvasive index of sympathetic nerve activity in exercise, we studied it under various states of activity in the autonomic nervous system in 6 healthy male subjects. In the CAP power spectrum, two components were observed at rest: a high frequency component (HF) at >0.15 Hz and a low frequency component (LF) between 0.05 and 0.15 Hz. Controlled respiration at 0.3 Hz enhanced the HF at that frequency. Increased sympathetic nerve activity induced by cold stress increased the LF, and increased parasympathetic nerve activity by ocular compression increased the HF. During exercise, many peaks appeared in the CAP power spectra, particularly at the LF. The present study suggests the possibility that the LF of the power spectrum in CAP variability can be used as a noninvasive index of sympathetic nerve activity in exercise.

Key words: carotid artery pulse, power spectral analysis, exercise

Introduction

Power spectral analysis of heart rate variability has been used to assess noninvasively the autonomic nervous control of the heart even in exercise (2, 9). In the power spectrum, the amplitude of the component in the high frequency range (HF, >0.15 Hz) has been suggested as an index of vagal activity (10, 11). As an index of sympathetic activity, the ratio of the component in the low frequency range (LF, 0.05-0.15 Hz) against the HF component (LF: HF ratio) was proposed, but this is now considered to be an index of sympatho-vagal balance (8). Moreover, since heart rate variability is smoothed by dynamic exercise, the power spectrum of the variability is markedly decreased (2, 9). Thus, the power spectrum of heart rate variability was found to be a poor index of sympathetic activity in exercise.

The carotid artery pulse (CAP), however, can be used as a noninvasive index of cardiac contractile function because of its proximity to the heart. In a preceding paper, we reported an improved way of fixing the transducer that enables continuous and stable recording of the CAP during moderate exercise (6).

In this study, we recorded the CAP with this improved method during exercise and in stimulated states of autonomic nervous system activity, and then computed the power spectrum of variability of the maximal amplitude in the CAP. We thus attempted to establish two things: 1) that the power spectrum of CAP variability can be used as a noninvasive index of sympathetic nerve activity during increased sympathetic or parasympathetic nerve

---

* Graduate School of Engineering, Kagoshima University, Kagoshima 890-8580, Japan

activities, and 2) that the power spectrum of CAP variability is of practical value even in exercise.

Methods

Subjects. A group of 6 healthy male subjects, aged 21-24 years, volunteered for this study. They had no medical history of circulatory disease, and their CAP contour, electrocardiogram (ECG), and blood pressure were normal. Informed consent was obtained.

CAP and ECG. To record CAP, a pulse transducer (45259, NEC San-ei) fixed on a special apparatus (6) was held over the right carotid artery. The subjects were allowed to swallow to relieve any discomfort from wearing the apparatus. The ECG was recorded using bipolar chest leads. The CAP and ECG were simultaneously recorded on a data recorder (R-61, TEAC) throughout all the experiments.

Experimental procedures. After resting 10-20 min in a supine position, the subjects underwent cold stress, ocular compression, and exercise. They were asked to breathe at 0.3 Hz (18 breaths/min) in synchrony with a metronome or a sine wave on an oscilloscope throughout all the experiments. The cold stress was given according to Hines-Brown's cold pressor test (5), which required the subjects to immerse the right hand in water at 4℃ for 1 min. The ocular compression was done according to Aschner's test (3). With eyes closed and the heart rate being monitored on a tachometer (1321, NEC San-ei), the subjects' left eyeball was compressed three times for 15 s with the experimenter's fingers. The exercise was performed at a work load of 75 W for 4 min in the supine position on a cycle ergometer (Model 864, Monark). Pedal frequency was 50 rpm.

Data processing. The CAP and ECG recorded on the data recorder were reproduced and led to a laboratory-oriented microcomputer (Signal Processor 7T17, NEC San-ei). The sampling rate of the A-D converter was 200 Hz (5 ms). After some artifacts of CAP and ECG were eliminated by a moving average method (5 data points), the maximal amplitude of CAP and the R-R interval of ECG were measured in millimeters of mercury (6) and milliseconds, respectively. To compute the power spectrum of variability in CAP amplitude, we applied the fast Fourier transform (4) to the maximal amplitude of CAP. The power spectral array was employed to examine time-course changes in the power spectrum of CAP amplitude. The instantaneous heart rate was calculated by multiplying the inverse of the R-R interval (per second) by 60 s. The power spectra of variability for the R-R interval were computed the same way as for CAP amplitude.

Results

In the power spectrum of the maximal amplitude in CAP at rest, major components were observed at two frequency ranges: a frequency higher than 0.15 Hz (HF) and a low frequency range between 0.05 and 0.15 Hz (LF). During controlled respiration at 0.3 Hz, the spectrum at the frequency corresponding to respiration was more enhanced in the HF range than during spontaneous respiration.

The power spectral array of variability in CAP amplitude before, during, and after cold stress are shown in Fig.1B. Cold stress markedly decreased the HF component in the power spectra of both CAP and R-R interval variability. However, the LF component was increased in the power spectra of CAP variability but not in R-R variability. These phenomena were observed in all 3 of the tested subjects.

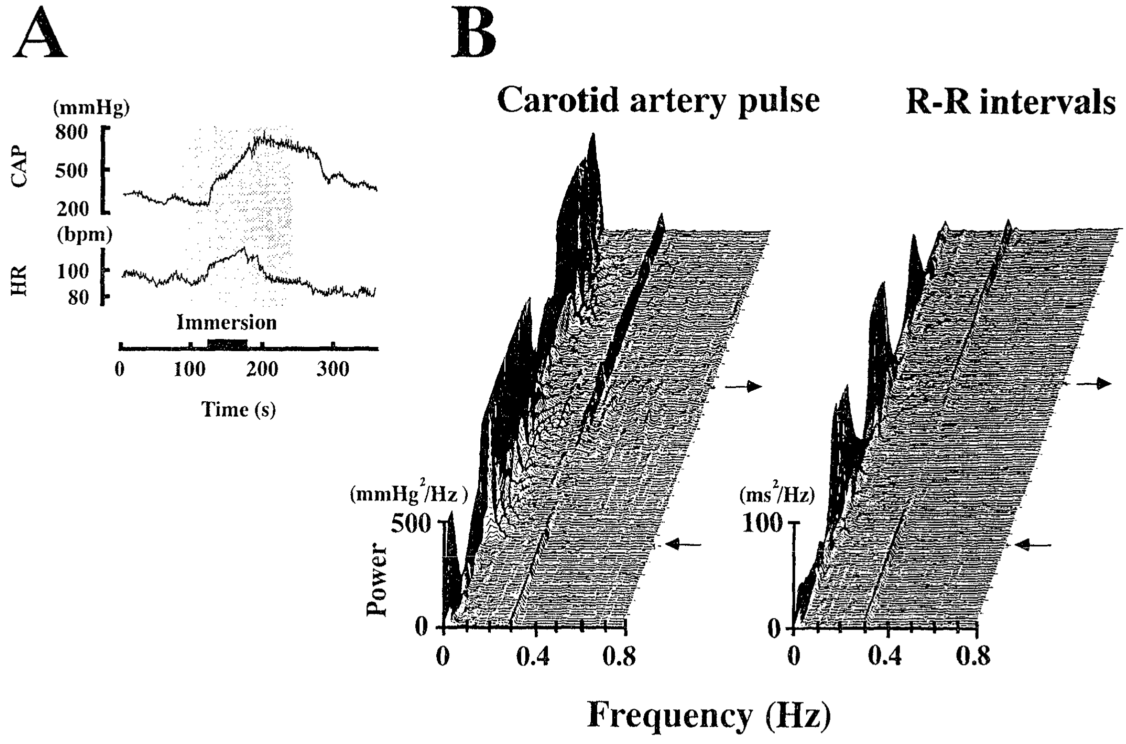

Fig.1 **A**: Time courses of the maximal amplitude in the CAP (CAP) and heart rate (HR) during cold stress. **B**: Power spectrum series of variability in CAP amplitude and R-R interval during cold stress. The period during which the series is shown is indicated by the shaded area in A. Recording period for each spectrum is 63 s. Leftward and rightward arrows indicate the start and the end of cold stress (60 s).

During ocular compression, the power spectra of amplitude variability in the CAP were similar to those observed in the R-R interval. The HF component was increased, and the power peak in synchrony with the rhythm of ocular compression (every 15 s; 0.067 Hz) appeared in the LF. These phenomena were observed in all 3 of the tested subjects.

During exercise, the power spectra of amplitude variability in the CAP were quite different from those observed in the R-R interval. The power spectra of the R-R interval were markedly decreased at all frequency ranges, but many peaks appeared in the power spectra of the CAP, including at the LF (Fig.2B). These phenomena were observed in all 4 of the tested subjects.

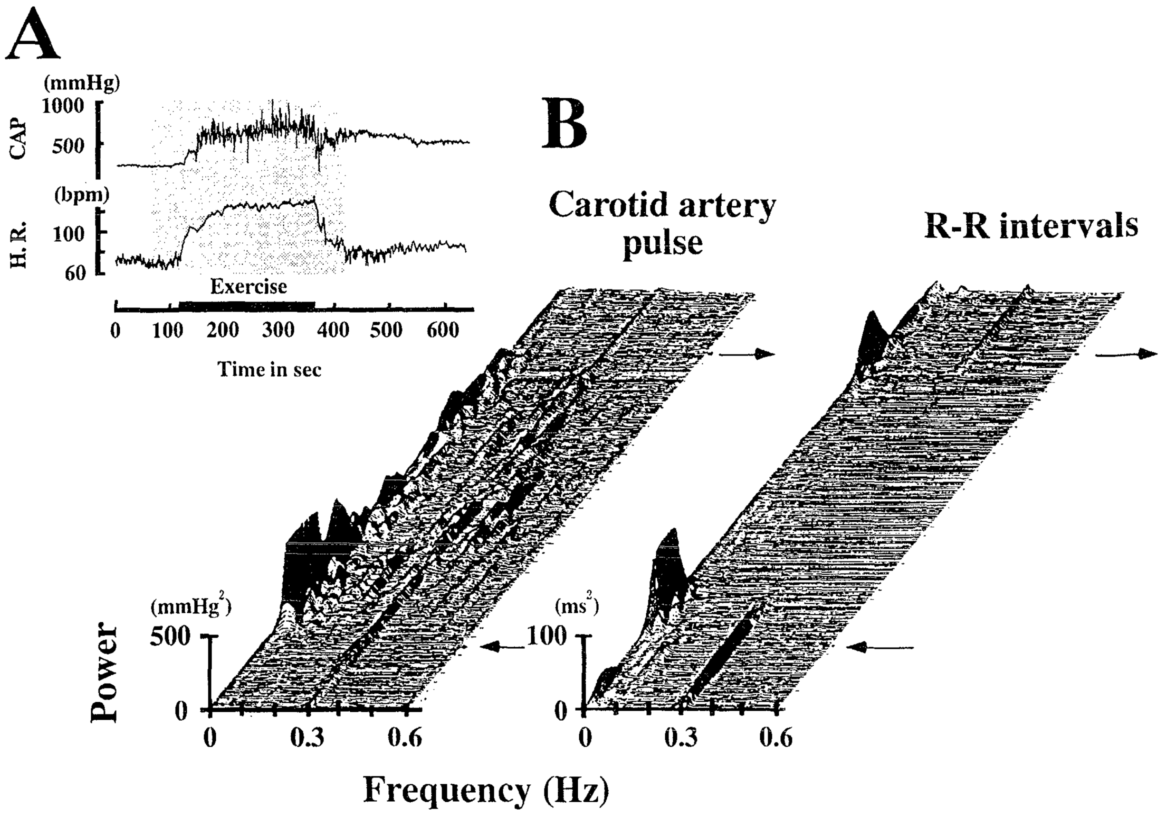

Fig.2 **A**: Time courses of the maximal amplitude in the CAP (CAP) and heart rate (HR) during exercise. **B**: Power spectrum series of variability in CAP amplitude and R-R interval during exercise. The period during which the series is shown is indicated by the shaded area in A. Recording period for each spectrum is 58 s. Leftward and rightward arrows indicate the start and the end of exercise (240 s).

Discussion

Problems of measuring CAP variability

According to the guidelines on standards of measurement for heart rate variability, the requirements for short-term power spectral analysis include a sampling rate of 250-500 Hz and continuous recording of 2-5 minutes made under physiologically stable conditions (11). For the power spectral analysis of CAP variability as well, these standards should be used whenever possible.

In this study, recordings during cold stress, eyeball compression, and exercise could not be made under physiologically stable conditions (Fig.1A and 2A). To deal with this shortcoming, the power spectral array was employed (7) and time-course changes transient in the power spectrum of CAP amplitude were investigated.

Since the recording should last for at least 10 times the wavelength of the frequency bound of the investigated component, recordings of approximately 1 and 2 minutes are needed to address the HF and LF, respectively (11). In this study, the time required for cold stress and ocular compression was about 1 minute. However, if the recording is longer than approximately 1 minute, it becomes complicated to interpret a spectrum in which three stages, i.e. pre-stimulus, stimulus, and recovery, are occasionally included. In the present study, therefore, a recording of approximately 1 minute was adopted so that three stages were not included in a spectrum, though the reliability of LF become poor. Naturally, we did not refer to a very low frequency at$<$0.05 Hz.

To calculate the R-R interval, the R-wave fiducial points need to be estimated. As the R-wave is a sharp spike, a minimum sampling rate of 250 Hz was required to identify the points. In this study, however, the sampling rate was 200 Hz. To calculate the maximal amplitude of the CAP, the beginning point of the upstroke and the highest point during systole need to be estimated. Since the percussion wave, in which both points were included, was much more gentle than the R-wave, the sampling rate of 200 Hz would hardly affect the calculation of the maximal amplitude of the CAP. This was confirmed in preliminary experiments.

CAP variability during increased activities of sympathetic or parasympathetic nerves

Since the maximal amplitude of the CAP represents relative changes in pulse pressure, power spectral analysis of the amplitude variability in the CAP can be considered the same as that of the relative variability in the blood pressure.

It has been interpreted that the HF component in the power spectrum of arterial pressure variability is a mechanical result of respiration (1). In the present study, controlled respiration and ocular compression, a method of evoking bradycardia by stimulating the vagus nerve, enhanced the HF power component in both CAP and R-R interval variability. These findings suggest that the HF power component in the CAP reflects a mechanical effect of respiration, as it does in arterial pressure (8).

In a previous study, it has been reported that the LF in the power spectrum of arterial pressure variability increased significantly when sympathetic nerve activity was enhanced by tilting (8). In the present study, cold stress known to enhance sympathetic nerve activity (12) yielded an increase of the LF, in agreement with Pagani et al. (8). This increase is probably due to variability in the vasomotor activity induced by cold stress.

These findings suggest that the power spectrum in CAP variability reflects the states of activity of the autonomic nervous system in the heart; in particular, the LF power component reflects the state of sympathetic nerve activity.

CAP variability during exercise

Arai et al. (2) and Perini et al. (9) have reported that dynamic exercise markedly decreased the power spectrum of heart rate variability. In the present study, the power spectra of R-R interval variability were markedly decreased during exercise, as previously reported. On the other hand, many peaks appeared in the power spectra of CAP variability, particularly at the LF. This appearance of the LF suggests that increased sympathetic nerve activity induced numerous changes such as an increase in cardiac output, an enhancement of cardiac contractility, and a decrease in peripheral vascular resistance during exercise. These changes probably caused the LF variability in CAP.

In conclusion, the present study indicates the possibility that the LF of the power spectrum in CAP variability can be used as a noninvasive index of sympathetic nerve activity during exercise. Detailed calculations of each component of the power spectrum in CAP remain to be done.

Acknowledgments. We are grateful to Prof. Hisashi Ogawa for his advice and editorial help, and to Dr. Alan Rosen for his reading of the English used in this manuscript.

References

1) Akselrod, S., D. Gordon, L. B. Madwed, N. C. Snidman, D. C. Shannon, and R. J. Cohen. Hemodynamic regulation: investigation by spectral analysis. *Am. J. Physiol.* 249: H867-H875, 1985.

2) Arai, Y., J. P. Saul, P. Albrecht, L. H. Hartley, L. S. Lilly, R. J. Cohen, and W. S. Colucci. Modulation of cardiac autonomic activity during and immediately after exercise. *Am. J. Physiol.* 256: H132-H141, 1989.

3) Aschner, B. Uber einen bisher noch nicht beschriebenen Reflex vom Auge auf Kreislauf und Atmung. Verschwinden des Radialis-Pulses bei Druck auf das Auge. *Wien. Klin. Wochenschr.* 21: 1529-1530, 1908.

4) Cooley, G. W., and J. W. Tukey. Algorithm for the machine calculation of complex Fourier series. *Math. Comput.* 19: 297-301, 1965.

5) Hines, E. A., and G. E. Brown. The cold pressor test for measuring the reactivity of the blood pressure: data concerning 571 normal and hypertensive subjects. *Am. Heart J.* 11: 1-9, 1936.

6) Ifuku, H., K. Taniguchi, and H. Matsumoto. Continuous record of carotid artery pulse during exercise. *Jpn. J. Physiol.* 43: 111-116, 1993.

7) Kunitake, T., and N. Ishiko. Power spectrum analysis of heart rate fluctuations and respiratory movements associated with cooling the human skin. *J. Auton. Nerv. Syst.* 38: 45-56, 1992.

8) Pagani, M., F. Lombardi, S. Guzzetti, O. Rimoldi, R. Furlan, P. Pizzinelli, G. Sandrone, G. Malfatto, S. Dell'Orto, E. Piccaluga, M. Turiel, G. Baselli, S. Cerutti, and A. Malliani. Power spectral analysis of heart rate and arterial pressure variabilities as a marker of sympatho-vagal interaction in man and conscious dog. *Circ. Res.* 59: 178-193, 1986.

9) Perini, R., C. Orizio, G. Baselli, S. Cerutti, and A. Veicsteinas. The influence of exercise intensity on the power spectrum of heart rate variability. *Eur. J. Appl. Physiol.* 61: 143-148, 1990.

10) Pomeranz, B., R. J. B. Macaulay, M. A. Caudill, I. Kutz, D. Adam, D. Gordon, K. M. Kilborn, A. C. Barger, D. C. Shannon, R. J. Cohen, and H. Benson. Assessment of autonomic function in humans by heart rate spectral analysis. *Am. J. Physiol.* 248: H151-H153, 1985.

11) Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Heart rate variability: standards of measurement, physiological interpretation, and clinical use. *Circulation* 93: 1043-1065, 1996.

12) Yamamoto, K., S. Iwase, and T. Mano. Responses of muscle sympathetic nerve activity and cardiac output to the cold pressor test. *Jpn. J. Physiol.* 42: 239-252, 1992.