Continuous Record of Carotid Artery Pulse during Exercise

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Summary The fixing apparatus for a pulse transducer was improved to record continuously and stably the carotid artery pulse (CAP) during exercise on a bicycle ergometer. The CAP changed largely at the onset and at the end of exercise, oscillating during exercise. The contour of the CAP at exercise was different from that at rest in several respects. During exercise, the incisura were lower, and/or the tidal wave occasionally exceeded the percussion wave. The present method proved to be applicable to exercise on both supine and upright bicycle ergometers with a heart rate lower than approximately 160 beats/min.

Key words: carotid artery pulse, exercise, continuous recording.

In mechanocardiography, the carotid artery pulse (CAP) is as critical as the apexcardiogram and the phonocardiogram, and is used to measure the left ventricular ejection time (LVET). Moreover, the first derivative of the CAP is of clinical value in estimating cardiac contractile velocity [1]. However, since a pulse transducer is held either by hand, by an air-filled neck cuff [2], or by a transducer platform [3], it is easily moved due to neck movements during exercise. Consequently, the CAP is extremely unstable during exercise and cannot be recorded continuously. To deal with this shortcoming, recordings have been made during the interruption of exercise or after its completion [4, 5]. Van der Hoeven *et al.* [6] reported, however, that the LVET on cessation of exercise was different from that during exercise because of an almost immediate drop. In some cases, an ear densitogram and its derivative have been used as substitutes for the CAP [7]. However, the LVET thus derived were not equivalent to the values obtained from the CAP [8]. In studies of systolic time intervals in exercise, it has been emphasized that the CAP should be recorded during uninterrupted exercise [2, 6]. Therefore, invention of a method to record continuous and stable CAP has been long awaited.

We developed our fixing apparatus for the pulse transducer by improving the

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Fig. 1. Left: Fixing apparatus for the pulse transducer (arrow) used in the present experiment. Right: Fixing apparatus attached to a subject. Head is tilted back to show the apparatus more clearly.

previous ones, and obtained a stable CAP and its first derivative during moderate, uninterrupted exercise.

A pulse transducer (45259, NEC San-ei) was fixed on an improved version of the S.O.M.I. brace (A08-920-0000, US Manufacturing), which was originally a brace to fix the cervical vertebrae (Fig. 1); it was then held over the carotid artery monitoring the contour of the CAP on an oscilloscope (2G47, NEC San-ei). In this way, the pulse transducer slipped much less than in other manual or mechanical methods [2, 3] because the brace limited neck movements and moved together with the body during exercise. When the contour of the CAP was abnormal or when the pulse transducer slipped with light exercise on a bicycle ergometer, we tried to record it again. Although body movement is extremely restricted with conventional methods [2, 3], the present method allowed the subject a certain degree of movement. However, since the apparatus can be uncomfortable to wear, the autonomic nervous system might be affected. The subjects in the present study complained of restricted swallowing ability. In experiments lasting more than a few minutes, subjects were allowed to swallow from time to time at the expense of a stable contour.

The output of the pulse transducer, which yields an amplitude of 0.7 V per 100 mmHg, was led to a Bioelectric amplifier (1253A, NEC San-ei). To measure the

Fig. 2. Record showing the carotid artery pulse (CAP P), the first derivative of the carotid artery pulse (CAP dP/dt), and the heart rate at exercise. Paper speed was 1 mm/s. Downward and upward arrows indicate the onset and offset of exercise on the upright bicycle ergometer (750 kpm/min). Although the base line moves heavily during exercise, the CAP P was recorded continuously. The CAP dP/dt was also stably recorded, as shown.

first derivative of the CAP, the output of the amplifier was fed to a Pressure pulse wave differentiation unit (1323, NEC San-ei). Recordings were made on a Rectigraph (8K11ME, NEC San-ei).

To obtain a significant amplitude of CAP, calibration is critical. Despite one study's effort to devise a calibration method [9], no definitive method has yet been established. We calibrated CAP amplitude as follows: Because the upstroke time (the interval from the beginning of the upstroke to the highest point in the CAP during systole) was approximately 0.1 s [2], we used a 5 Hz triangular wave whose interval from the lower peak to the upper peak was 0.1 s. This wave, with a peak-to-peak amplitude of 0.7 V, was derived from a Function generator (FG-330, IWATSU) and led to the Bioelectric amplifier. By adjusting the amplifier gain, we obtained the 5 Hz triangular wave with a peak-to-peak amplitude of 1 V. We then got a calibration value of $\pm 1,000$ mmHg/s/V from the Pressure pulse wave differentiation unit. When measured by this method, the peak wave of the CAP at rest ranged from 59.2 to 314.9 mmHg, and its first derivative from 1,105.0 to 4,692.0 mmHg/s in seven subjects. The wide range of the control value is probably due to the fact that amplitudes of the pulsation to be touched over the carotid artery varied with individuals, resulting in a large individual variation in the holding pressure of the pulse transducer. The present method, therefore, does not give the absolute amplitude of the CAP but rather an index of the holding pressure.

Figure 2 shows the CAP, its first derivative, and the heart rate recorded during exercise on an upright bicycle ergometer (750 kpm/min). The amplitudes of the

Fig. 3. Record showing the CAP P , the CAP dP/dt , and the electrocardiogram (ECG) at rest (A) and during exercise on the supine bicycle ergometer yielding a heart rate of approximately 150 beats/min (B). Paper speed was 50 mm/s. The contour of the carotid artery pulse at exercise differed in several respects from that at rest. The incisura (a) became lower and was occasionally located below the beginning of the upstroke. The tidal wave (b) also occasionally exceeded the percussion wave.

CAP were almost constant at rest, but they increased abruptly after the onset of exercise and decreased progressively after cessation. The CAP changed largely at the onset and at the end of exercise, and oscillated during exercise. In spite of this oscillation, the CAP was able to be recorded continuously. The first derivative of the CAP was also stably recorded.

Figure 3 indicates the contours of the CAP, the first derivative of it, and the electrocardiogram at rest (A) and during exercise on a supine bicycle ergometer at the heart rate of approximately 150 beats/min (B). The contour of the CAP during exercise differed in several respects from that at rest. The incisura (marked "a" in

the figure) became lower and were occasionally located below the beginning of the upstroke [10]. We confirmed that this point was really the incisura by using the peak points in the first and the second derivative (not shown), which enabled measurement of the LVET. The tidal wave (marked "b") occasionally exceeded the percussion wave [2]. Since the latter finding is often seen in elderly or hypertensive individuals whose vessels are stiff and less compliant [11], it is suggested that this phenomenon reflects a state of vasoconstriction during exercise.

By increasing the loads of the bicycle ergometer, we were able to record a stable CAP from subjects with heart rates less than approximately 160 beats/min. However, the CAP obtained during exercise was more stable on a supine bicycle ergometer than on an upright one, because the upper part of the body could be better fixed and neck movement was limited. To obtain a stable CAP during exercise on an upright bicycle ergometer, subjects had to be careful not to move the upper part of the body, thereby restricting exercise. The heavier the exercise beyond a heart rate of 160 beats/min, the more difficult it became to record the CAP because the pulse transducer slipped or the contour of the CAP scaled out. This was probably due to the intensive body movement necessitated by the heavier loads. In particular, during pedaling a supine bicycle ergometer, the body moved greatly toward the head. Although it was difficult to record a stable CAP, recordings of the CAP were possible during heavier exercise in the upright position. In one subject, for example, the CAP could be recorded until a heart rate of approximately 160 beats/min in the supine position and 170 beats/min in the upright position. It was very difficult to apply the present method to exercise on a treadmill; many artifacts in synchrony with the rhythm of locomotion contaminated the CAP recordings.

Although this method is limited to submaximal exercise on a bicycle ergometer, it allows measurement of systolic time intervals such as the LVET continuously during moderate exercise in combination with the first and the second derivative of the CAP. Moreover, it can be used for non-invasive observation of cardiac function during clinical exercise testing of patients with heart disease.

In conclusion, we improved the fixing apparatus for the pulse transducer so that a stable CAP could be continuously recorded for the first time during exercise on both supine and upright bicycle ergometers at a heart rate of less than approximately 160 beats/min. The present method is applicable to continuous measurement of the LVET during exercise. Thus, it can be expected to estimate cardiac contractile function during exercise, which creates a new possibility for cardiac physiology.

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