

Changes of Cardiac Output During Treadmill Exercise by Impedance Cardiography

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Nine athletes and ten nonathletes were selected randomly to study the changes of cardiac function during exercise by impedance cardiography. The speed of the treadmill was maintained at 3.4 mph, and its grade was increased by 1% (Balke protocol). The exercise was continued until the target heart rate (THR), 85% of maximum oxygen uptake (VO_{2max}). The measured parameters for pre-and post-exercise were stroke volume (SV), heart rate (HR), and cardiac output (CO). Average stroke volume of athletes at pre-exercise, 71.1 ml, was higher than that of nonathletes, 64.6 ml, and stroke volume of the former at post-exercise, 97.0 ml, was also higher than that of the latter, 85.2 ml. Therefore, despite the lower heart rate, cardiac outputs of athletes at pre-and post-exercise, 4.98 and 16.3 L/min, were higher than those of nonathletes, 4.87 and 14.2 L/min. For the second phase of the study, cardiac outputs of three subjects were measured during the continuous treadmill exercise with newly developed electrodes and shoes for minimizing motion artifact. Though there were several studies measuring cardiac output during continuous bicycle exercise, this is thought to be the first study in the world measuring cardiac output during continuous treadmill exercise without aid of ensemble averaging.

Key Words: Cardiac output, treadmill exercise, impedance cardiography, athletes, oxygen uptake.

Measurement of cardiac output during continuous exercise by noninvasive technique is very necessary in the field of sports medicine. However, there are only two noninvasive techniques, one of which is CO₂ rebreathing technique and the other is impedance cardiography. While the CO₂ rebreathing technique needs special breathing and blood sampling, impedance cardiography has a motion artifact problem due to body movement.

Denniston *et al.* (1976) had difficulties in analyzing the impedance waveforms due to the significant motion artifact during arm exercise, which is far less noisy than treadmill exercise. Kobayashi *et al.* (1978)

and Hatcher and SRB (1986) measured cardiac output on a bicycle ergometer within 5 seconds after exercise to avoid the motion artifact. Hwang *et al.* (1989) successfully measured cardiac output during continuous bicycle ergometer. The motion artifact during treadmill exercise is much more severe than that during bicycle exercise. It was the aim of this study to estimate cardiac output during continuous treadmill exercise by reducing the motion artifact with the newly developed electrodes and shoes.

METHODS AND PROCEDURE

Subjects were nine athletes including five marathoners and ten nonathletes for the pre-and post-exercise measurement, and three nonathletes for estimation of cardiac output during continuous treadmill exercise. Mean age, height, and weight were 24.5yr, 173cm, and 71kg for nonathletes, and 21.2yr, 175cm, and 68kg for athletes, respectively. Balke and Ware protocol (1959) was adopted using the treadmill (model 1800, Marquette Co). The exercise load was increased until the target heart rate

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based on the following Karvonen's formula (1957).

$$HR_{target} = 0.85 * (HR_{max} - HR_{rest}) + HR_{rest}$$

where $HR_{max} = 220 - Age$

Stroke volume was measured for five stages: standing at rest, on the treadmill just before exercise, 1, 3, and 6 minute recovery for the pre-and post-exercise measurement (the first phase of this study). Cardiac functions were measured for ten stages: on the treadmill just before exercise, 1, 3, 6, 9, and 12th. minute during exercise, immediately after exercise, 1, 3, 6, and 9 minute recovery for the second phase of this study.

Thoracic impedance data was obtained using an impedance cardiograph developed by one of the authors (DWK) with the newly developed elastic band electrodes and shoes. An elastic band was put inside the tubular meshed brass band electrode (3M) to provide firm contact with the body surface and sweat absorption. Silicon rubber and sponges were attached to the soles of shoes for absorbing the impact of each step. The new band electrodes were applied to the forehead and neck and the other two to the xyphoid and approximately 10 cm lower around the abdomen, respectively as shown in Fig. 1. The outer electrodes (1 & 4) provided an electrical current of $3mA_{rms}$ with a frequency of 100kHz. The impedance change waveform was measured between the two inner electrodes (2 & 3). The impedance change waveform, its first derivative (dZ/dt), and EKG were recorded on a four channel chart recorder (8K-21, San-Ei) at a speed of 50 mm/s.

Stroke volume (SV) was calculated according to the following Kubicek's formula(1966) except blood resistivity (ρ).

$$SV = \rho * (L/Z)^2 * dZ/dt_{max} * LVET$$

Where ρ = electrical blood resistivity ($\Omega \text{ cm}$)
 L = distance between the electrode 2 and 3 in Fig. 1 (cm)
 Z = total impedance between the electrode 2 and 3 (Ω)
 dZ/dt_{max} = peak amplitude of dZ/dt waveform in Fig. 2 (Ω/sec)

In Kubicek's formula ρ was assumed constant value, $150\Omega\text{cm}$. However, it varies among the subjects depending on their hematocrits (Hct) which increase with exercise level. Thus the blood resistivity was calculated for each subject using the equation below as proposed by Tanaka et al.(1970):

$$\rho = 66(3 + 1.9\text{Hct}) / (3 - 3.8 \text{Hct})$$

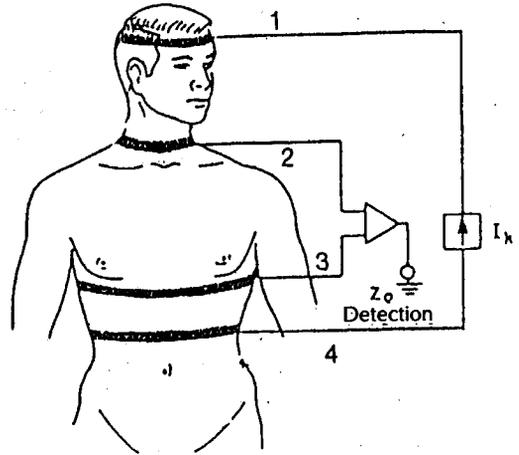


Fig. 1. Four-terminal system for the measurement of cardiac output by means of electrical impedance. A constant sinusoidal current (3 mA, 100 kHz) was applied to electrodes 1 and 4. Voltage reflecting thoracic impedance changes was picked up from electrodes 2 and 3.

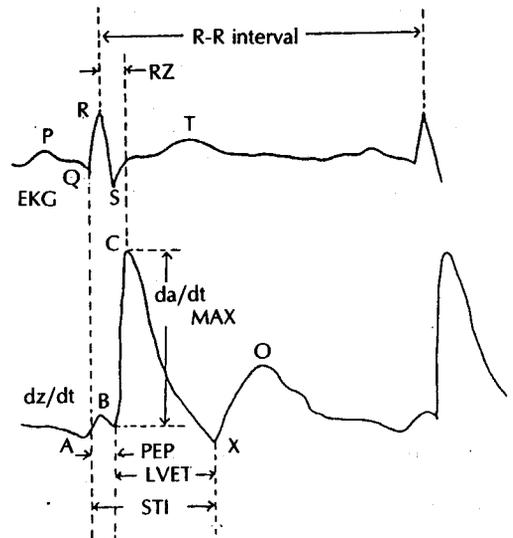


Fig. 2. Typical waveforms of ECG and dZ/dt by impedance cardiography.

Systolic time interval (STI) was measured as the summation of preejection period(PEP) and left ventricular ejection time (LVET) as shown in Fig. 2. PEP was measured between Q wave of ECG and B

point of dZ/dt waveform, which corresponds to the opening of aortic valve. LVET was measured between B point and X point, which corresponds to the closing of aortic valve. Heather index (HI) as a cardiac contractility was calculated by dividing dZ/dt_{max} by R-Z interval (time interval between R wave of ECG and C-point of dZ/dt waveform) as shown in Fig. 2

RESULTS

Fig. 3 shows changes in the average cardiac output and stroke volume of the athletes and nonathletes for pre-and post-exercise. The average stroke volume of athletes and nonathletes at rest was 71.1 ± 3.5 (mean \pm S.E.) and 64.6 ± 5.6 ml, respectively, and it decreased to 66.7 ± 4.0 and 56.3 ± 5.2 ml just before exercise on the treadmill. The average stroke volume during recovery of athletes was higher than nonathletes, and that of the former and the latter especially at 1 min recovery was 90.7 ± 3.2 and 75.1 ± 4.2 ml, respectively.

Heart rate of athletes and nonathletes at rest were 70.1 ± 3.3 and 75.4 ± 3.6 , respectively, and 75.0 ± 4.5 and 81.9 ± 3.9 min^{-1} just before exercise on the treadmill, respectively as shown in Fig. 4. Athletes and nonathletes continued exercise until heart rate of 167.9 ± 4.7 and 167.1 ± 2.5 min^{-1} , respectively, with a corresponding 85% of VO_{2max} . Heart rate of athletes and nonathletes at 1 min. recovery was 107.7 ± 6.2 and 133.2 ± 3.2 min^{-1} , respectively, indicating that recovery of the former is faster than that of the latter.

Cardiac output of athletes and nonathletes was 4.98 ± 0.22 and 4.87 ± 0.22 at rest, and 5.0 ± 0.18 and 4.61 ± 0.20 L/min just before exercise, respectively. Cardiac output of the former and the latter was 16.3 ± 0.7 and 14.2 ± 0.7 L/min at 85% of VO_{2max} respectively as shown in Fig. 3 since stroke volume of the former is larger than that of the latter during exercise as well as at rest. Fig. 5 shows the relationships of cardiac output and stroke volume to heart rate. Correlation coefficient of heart rate (HR) and cardiac output is 0.999 and 0.98 for the athletes and nonathletes, respectively. Correlation coefficient of heart rate and stroke volume is 0.956 and 0.946 for the athletes and nonathletes, respectively.

Fig. 6 shows the relationships of LVET and Heather Index(HI) to heart rate. Correlation coefficient of heart rate and LVET is -0.953 and -0.978 for the athletes and nonathletes, respectively. Heather Index is an indicator for cardiac contractili-

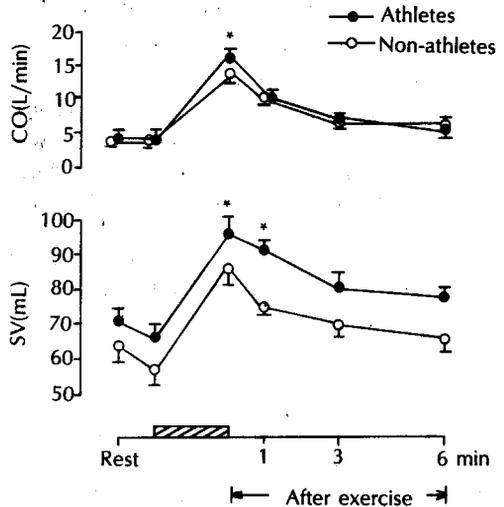


Fig. 3. Changes of cardiac output(CO) and stroke volume (SV) after progressive treadmill exercise by impedance cardiography in nonathletes and athletes. Significantly different from nonathletes * $p < 0.05$

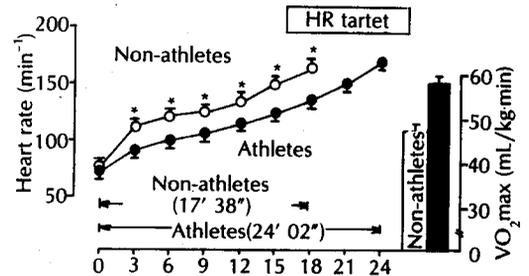


Fig. 4. Changes of heart rate and VO_{2max} during progressive treadmill exercise in nonathletes and athletes.

ty. Vanfraechem (1979) found that the correlation coefficient of HR and HI was 0.90. In this study they are 0.968 and 0.788 for the former and the latter, respectively. As shown in Fig. 6 Heather indices of the athletes are higher than those of the nonathletes for the same HR. Therefore, it can be said that the cardiac contractility of the athlete is higher than that of the nonathlete.

Fig. 7 shows the changes of HR, SV, and CO for three normal adults during the continuous treadmill exercise. Stroke volume varied depending on the posture. Stroke volume was 74.0 ± 10.0 in supine,

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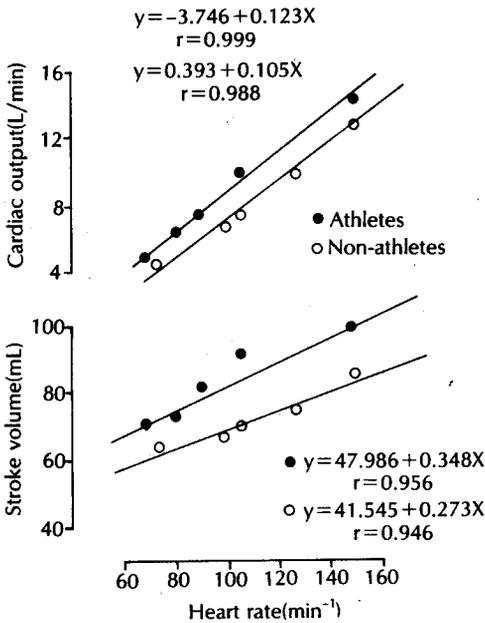


Fig. 5. Stroke volume and cardiac output in relation to heart rate by impedance cardiography in nonathletes and athletes.

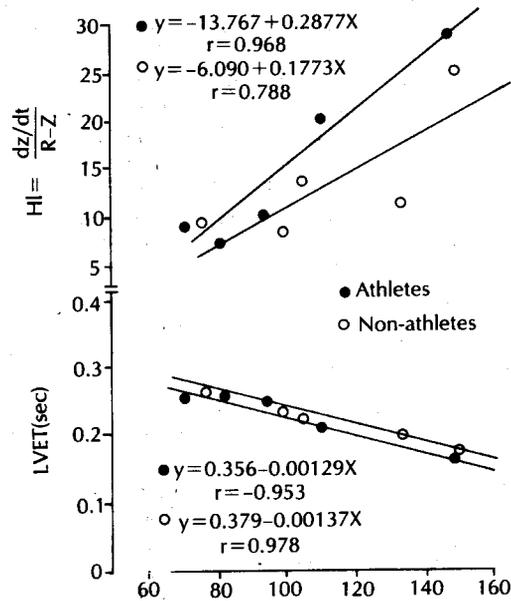


Fig. 6. Left ventricular ejection time(LVET) and Heather index(HI) in relation to heart rate by impedance cardiography in nonathletes and athletes.

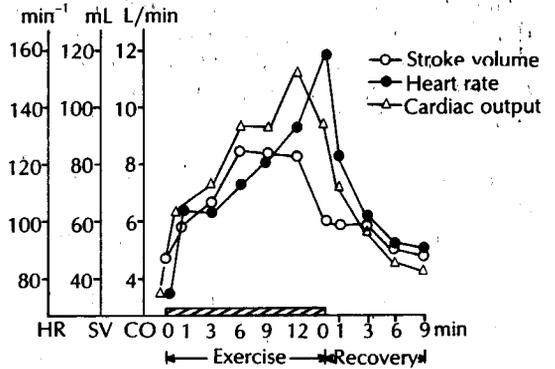


Fig. 7. Changes of stroke volume(SV), heart rate(HR) and cardiac output(CO) during progressive treadmill exercise by impedance cardiography in three nonathletes

61.7 ± 7.5 in sitting, 58.9 ± 7.3 in standing, and 47.7 ± 10.1 ml on treadmill just before exercise, respectively. It increased to 59.4 ± 4.4, 67.6 ± 5.4, and 84.8 ± 4.8 ml, the maximal value, during 1, 3, and 6 minute exercise, respectively. Stroke volume did not increase and reached a steady-state from 6 min. into exercise to the end of exercise. It decreased to 59.8 ± 5.3 ml immediately after stopping exercise and returned to 48.0 ± 3.8 ml, about the same value as that just before exercise, at 9 min into recovery. Cardiac output was 4.79 ± 1.01 in supine, 4.20 ± 0.78 in sitting, 3.75 ± 0.88 in standing, and 3.38 ± 0.51 L/min just before exercise. It increased to 6.47 ± 0.76 and 11.13 ± 1.01 L/min in 1 and 12 min exercise, respectively. It returned to 4.20 ± 0.28 L/min at 9 min into recovery.

DISCUSSION

Blomqvist and Saltin (1983) indicated that cardiac function is dependent on the degree of aerobic capacity. VO_{2max} of athletes and nonathletes in this study was 58.2 and 47.5 ml/kg/min, respectively, as shown in Fig. 4. According to Astrand and Saltin (1961) maximal exercise ability is determined by VO_{2max}; therefore, it can be said that athletes are superior to nonathletes in exercise ability.

Impedance cardiography is one of the convenient techniques in cardiac output measurement. Many studies including Kim et al. (1988) showed that it had high correlation(0.90) with thermodilution tech-

nique for cardiac patients at rest. Thermodilution technique is inaccurate for patients with left-to-right shunt, and its accuracy varies greatly depending on measurement skill. While impedance technique is also not accurate for patients with fluid accumulation in the thorax such as plural edema or valvular diseases (Schieken et al. 1981), it is noninvasive, simple, has good reproducibility, and gives beat-by-beat information including contractility and systolic time interval.

Measurement of cardiac output during treadmill exercise is currently possible by impedance cardiography and CO₂ rebreathing technique. Simultaneous measurement of cardiac output showed a good correlation coefficient, 0.96 (Zhang et al. 1986). However, thermodilution method is not suitable for measuring cardiac output during exercise since it is very complex to measure and dangerous.

Stroke volume is dependent on end-diastolic volume and cardiac contractility (Simmons et al. 1971, Hartley et al. 1968). In this study, stroke volume of athletes at rest, 71.1 ml, was significantly higher than that of nonathletes, 64.6 ml. Clausen (1977) reported that stroke volumes at rest were 90 for athletes and 70 ml for nonathletes, and maximal stroke volume was 150 for the former and 125 ml for the latter. The difference in stroke volumes between this study and Clausen's study is thought to be due to the difference of physical dimensions. He also suggested that the reason why the heart rate of athletes who have trained long time is so low is due to increased stroke volume not to decreased heart rate.

While cardiac outputs of athletes and nonathletes at rest and during moderate exercise are not significantly different, cardiac output of the athlete in maximal exercise is significantly higher than that of nonathletes (Blomqvist et al. 1983). In this study cardiac output at rest was 4.98 and 4.87 L/min for athletes and nonathletes, respectively. Although cardiac outputs of both groups are approximately the same, the heart rate is lower and stroke volume is higher for athletes. Cardiac output of athletes (16.3 L/min) during exercise is significantly higher than that of nonathletes (14.2 L/min) due to the fact that stroke volume of the former is higher.

In conclusion, cardiac function was successfully measured using impedance cardiography without stopping exercise using newly developed electrodes and shoes on the treadmill. However, an ensemble average technique is needed for more accurate measurement in the future study.

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