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Approximation Equation for Oxygen Uptake Kinetics in Decrement-load Exercise Starting from Low Exercise Intensity

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Abstract The purpose of the present study was to determine the degree of fitting an approximation equation for oxygen uptake ($\dot{V}o_2$) in decrement-load exercise (DLE). Work rate was started from 120 watts and was decreased by a rate of 15 watts per min. The initial work rate of DLE corresponded to 72±10% of the work rate at anaerobic threshold determined in incremental-load exercise (ILE). $\dot{V}o_2$ in DLE increased rapidly, reached a peak, and decreased linearly until the end of the exercise. $\dot{V}o_2$ in DLE was higher than that in ILE at the same work rate except in the early periods in ILE and DLE. This difference ranged from 300 to 400 ml/min. This difference is a result of repayment of oxygen debt in DLE and from the oxygen deficit induced by the delay of response of $\dot{V}o_2$ in ILE. As work rate in DLE can be obtained by the difference between work rates in constant-load exercise (CLE) and ILE, we postulated that the approximation equation for $\dot{V}o_2$ kinetics in DLE could be expressed by a combination of approximation equations in CLE and in ILE. When time delay was taken into consideration in this equation, the fitting of data obtained by using the equation was better than that of data obtained by using the equation without a parameter of time delay. The degree of fitting ranged from 94 to 98% (r^2). Thus, it seems that $\dot{V}o_2$ including oxygen debt in DLE can be approximated by the equation used in this study. *J Physiol Anthropol 22 (1): 7–10, 2003* http://www.jstahge.jst.go.jp/en/

Keywords: decrement-load exercise, oxygen uptake, approximation equation

Introduction

The responses of oxygen uptake ($\dot{V}o_2$) kinetics to work load have been examined using various work modes, such as constant-load exercise (CLE), incremental-load exercise (ILE) and so on (Whipp et al., 1981; Casaburi et al., 1977; Miyamoto and Niizeki, 1992, Yano et al., 2000). Approximation equations for responses of $\dot{V}o_2$ kinetics to these work loads have also been proposed. Based on these equations, the division of $\dot{V}o_2$ kinetics (Whipp et al., 1982), the effect of exercise intensity on $\dot{V}o_2$ kinetics (Barstow and Mole, 1991) and the association of $\dot{V}o_2$ kinetics with other physiological functions (Rossiter et al., 1999; Scheuermann et al., 2001) have been discussed. Thus, an accurate approximation equation is the first step towards elucidation of $\dot{V}o_2$ kinetics in exercise.

Recently, $\dot{V}o_2$ kinetics in decrement-load exercise (DLE) has been examined (Whipp et al., 1992; Horiuchi and Yano, 1997). The characteristic of $\dot{V}o_2$ kinetics in this work mode is that $\dot{V}o_2$ includes repayment of oxygen debt during exercise. We simulated $\dot{V}o_2$ kinetics in DLE starting from 120 watts and being reduced at a rate of 15 watts per minute to examine the oxygen debt kinetics (Yano et al., 2003). We found that oxygen debt increases soon after the start of exercise and reaches a steady state in the simulation (described in detail in Discussion). However, kinetics of oxygen debt in DLE has not been adequately examined using real measurements. An approximation equation for $\dot{V}o_2$ kinetics in DLE has not even been derived.

In the present study, therefore, we made an approximation equation for $\dot{V}o_2$ kinetics in DLE by combining approximation equations in CLE and in ILE. Since the work rate in DLE is the difference between work rates in CLE and ILE, we postulated that the approximation equation for $\dot{V}o_2$ kinetics in DLE could be expressed by the combination of approximation equations in CLE and in ILE. We tested the degree of fitting of data obtained using the equation to actually measured $\dot{V}o_2$ in DLE. Furthermore, we tried to separate the factors consisting in $\dot{V}o_2$ kinetics in DLE by referring to the above-mentioned simulation (Yano et al., 2003).

Methods

Six healthy males participated in this study. Their mean (±SD) age, height and weight were 24±3.1 years, 171±5.7 cm and 64±5.6 kg, respectively. After the objective and procedure of the experiment and the risks associated with the experiment were explained, written consent to participate in the study was obtained from each subject. This study was approved by the local ethics committee.

A bicycle ergometer in which the load can be adjusted by a computer (232C, Combi) was used. On the first day, each subject performed ILE after a 5-min rest period to determine his maximal $\dot{V}o_2$ ($\dot{V}o_2$max). After cycling at a work rate of zero watts for 4 min, the work rate was increased in ramp mode by 15 watts per min until the subject could no longer maintain a rotation rate of 60 rpm. On separate days, a DLE test with a peak work rate of 120 watts was performed. After cycling at a work rate of zero watts for 4 min, the work rate was suddenly increased to the peak value, and then the work rate was reduced in ramp mode at a rate of 15 watts/min until it reached zero watts.

O_2 uptake and CO_2 output ($\dot{V}co_2$) were measured breath-by-breath using a respiratory gas analyzer (AE-280S Minato Medical Science). The flow volumes of inspiration and expiration were determined using a hot-wire respiratory flow meter. The flow signals were integrated electrically for each breath and converted to ventilation per minute. The respiratory flow meter was calibrated using a 2-liter syringe. The results of measurement with this instrument were linear with ventilation in the range of 0–600 l/min. The O_2 and CO_2 concentrations were analyzed using a zirconium sensor and infrared absorption analyzer, respectively. The data of $\dot{V}o_2$ and $\dot{V}co_2$ were outputted every 15 sec.

Anaerobic threshold (AT) was determined by the V-slope method (Beaver et al., 1986). $\dot{V}$o2 was plotted against $\dot{V}$co2 in an ILE test. Two regression lines were drawn, one at low exercise intensity and one at high exercise intensity. The intercept of the two regression lines was defined as AT. $\dot{V}o_2$max was taken as the highest 15-sec average achieved during the ILE test.

The difference between $\dot{V}o_2$ at breath level in DLE and at zero watts ($\Delta\dot{V}o_2$) was approximated using commercially available computer software (KaleidaGraph ver. 3.0) by the following equation (model 1):

$$\Delta\dot{V}o_2 = A_1 \cdot (1-\exp(-t/\tau_1)) - A_2 \cdot (t-\tau_2 \cdot (1-\exp(-t/\tau_2))), \quad (1)$$

where A is the amplitude of the system and τ is the time constant of the system. The first term in Eq. (1) is the approximation equation for $\dot{V}o_2$ in CLE and the second term is the approximation equation for that in ILE (See Whipp et al., 1981.). There is a time delay (TD) from the active muscle to the lung in $\dot{V}o_2$. This may be evaluated by introducing TD into Eq. (1) (model 2).

$$\Delta\dot{V}o_2 = A_1 \cdot (1-\exp(-(t-TD)/\tau 1)) - A_2 \cdot (t-TD-\tau_2 \cdot (1-\exp(-(t-TD)/\tau_2))). \quad (2)$$

In this approximation, the first $\dot{V}$o2 for 15 sec after DLE was excluded from the approximation data to minimize the effect of cardiodynamic phase.

Closeness of the association between an independent variable and the dependent variable was expressed as Pearson's simple correlation coefficient. Significant differences between mean values of parameters obtained from equations (1) and (2) were examined by Student's paired t-test. The level of significance was set at $p<0.05$. The results are expressed as means and standard deviations (SD).

Results

$\dot{V}$o2max obtained in ILE was 2.95±0.32 l/min. $\dot{V}o_2$ at AT was 1.90±0.30 l/min. The work rate at AT was 167±22.6 watts. Initial work rate in DLE was below the work rate at AT and corresponded to 72±10% of the work rate at AT.

An example of a comparison of $\dot{V}o_2$ in ILE and that in DLE is shown in Fig. 1. $\dot{V}o_2$ in DLE increased after the start of the exercise, reached a peak, and then decreased linearly until the end of the exercise. From around the peak until the end of DLE, $\dot{V}o_2$ in DLE was higher than that in ILE. These differences showed minus values at a higher work rate due to $\dot{V}o_2$ response at the onset of DLE and showed smaller values at a lower work rate due to $\dot{V}o_2$ response at the onset of ILE. Except for these periods, the differences ranged from 300 to 400 ml/min.

An example of $\Delta\dot{V}o_2$ is shown in Fig. 2. Peak of $\Delta\dot{V}o_2$ appeared at around 2 min and its value was 1.07±0.08 l/min. The data were approximated by equations without (model 1) and with time delay (model 2). As shown in the figure, a fitting

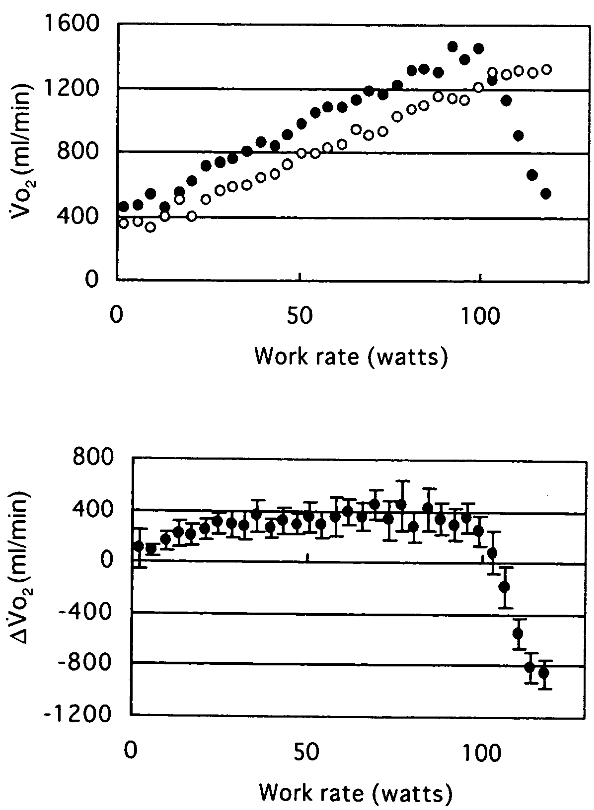

Fig. 1 The upper panel shows a comparison of oxygen uptake in decrement-load exercise (●) and that in incremental-load exercise (○) in one subject. The lower panel shows differences between oxygen uptake in decrement-load exercise and that in incremental-load exercise.

curve obtained by model 1 showed higher values than data until 1 min after the start of exercise and lower values at 2 min after the start of exercise.

Table 1 shows the values of parameters obtained by models 1 and 2. There were significant differences between the values of parameters obtained using equations with and without time delay. Fitting of data obtained by the equation with time delay was better, and the degree of fitting ranged from 94 to 98% (r^2). When amplitude in CLE (A_1) was divided by the work rate in CLE (120 watts), gain could be obtained. This value was 10.3 ml/min/watt in model 2. When A_2 was divided by decrement rate of work rate, gain could also be obtained. This value was 11.7 ml/min/watt in model 2. Time constants in CLE (τ_1) and in ILE (τ_2) obtained in model 2 were about half of those in model 1.

Discussion

The first term of Eq. (2) is equivalent to that proposed for $\Delta\dot{V}o_2$ kinetics in CLE. The time constant obtained in this term coincides with that reported in CLE at lower exercise intensity. The gain can be calculated by dividing the amplitude obtained in this term by initial work rate in DLE. This value is 10.3 ml/min/watt, which is within the reported range (Henson et al., 1989).

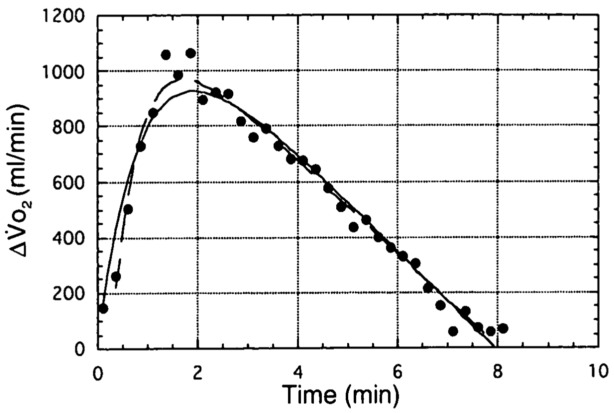

Fig. 2 Examples of fittings by models 1 (–) and 2 (– –). In model 2, the first $\Delta\dot{V}o_2$ was excluded from the fitting data in order to eliminate the effect of the cardiodynamic phase.

The second term of Eq. (2) is equivalent to that proposed for $\Delta\dot{V}o_2$ kinetics in ILE. In a previous study, $\Delta\dot{V}o_2$ kinetics was examined in a work mode in which DLE is carried out after ILE, and it was found that the time constant becomes faster in DLE than in ILE (Miyamoto and Niizeki, 1992). Although the reason is not known, the present result is not near to one in DLE but in ILE. Gain in DLE without ILE has been reported (Whipp et al., 1992). Although a method to determine the linear part in $\dot{V}o_2$ decrement has not been described, this gain was obtained by dividing the slope of $\dot{V}o_2$ by the decrement rate of work rate. In the present study, the gain was obtained from the approximation equation, which is not an arbitrary method. The value (11.7 ml/min/watt) is slightly higher than the previously reported one.

The difference between $\dot{V}o_2$ in DLE and that in ILE is associated with the repayment of oxygen debt (Whipp et al., 1992; Horiuchi and Yano, 1997). Oxygen deficit is produced at the onset of DLE, and the deficit is repaid during DLE. This is known as oxygen debt. In ILE, $\dot{V}o_2$ increases after a time lapse, and this causes the oxygen deficit. Therefore, the difference between the values of $\dot{V}o_2$ in the two work modes includes the oxygen debt in DLE and oxygen deficit in ILE.

Yano et al. (2002) simulated $\Delta\dot{V}o_2$ kinetics in DLE. In their simulation, work rate in DLE was separated into some steps. The steps were regarded as CLEs. $\Delta\dot{V}o_2$ kinetics was assumed at the onset and offset of the CLEs. $\Delta\dot{V}o_2$ increases at the onset of CLEs at the same time and becomes the recovery phase step by step corresponding to the decrement of work rate. The sum of $\Delta\dot{V}o_2$ at the onset of CLEs at a given time corresponds to $\Delta\dot{V}o_2$ excluding oxygen debt in DLE (net $\Delta\dot{V}o_2$). The sum of $\Delta\dot{V}o_2$ at the offset of CLEs at a given time corresponds to $\Delta\dot{V}o_2$ related to oxygen debt (debt $\Delta\dot{V}o_2$). The total of net and debt $\Delta\dot{V}o_2$ is equivalent to $\Delta\dot{V}o_2$ actually observed in DLE (gross $\Delta\dot{V}o_2$). In this simulation, debt $\Delta\dot{V}o_2$ started to increase soon after the exercise and showed a steady state. When the time constant of $\Delta\dot{V}o_2$ kinetics at the offset of CLEs was assumed to be 1.0 min, the steady state value became 150 ml/min, and it became 75 ml/min when the time constant was assumed to be 0.5 min (The time constant is nearly within the range reported for CLE at low exercise intensity (Ozyener et al., 2001; Rossiter et al., 1999).). Furthermore, net $\Delta\dot{V}o_2$ was

Table 1 Model parameters for $\dot{V}o_2$ responses to decrement-load exercise starting from low exercise intensity

	A_1	τ_1	A_2	τ_2	TD	r
	l/min	min	ml/min/min	min	min	
Model 1						
Means	1.35	1.11	197	1.11		0.95
SD	0.08	0.13	14	0.13		0.02
Model 2						
Means	1.24*	0.60*	175*	0.59*	0.36	0.98*
SD	0.07	0.04	10	0.04	0.05	0.01

* Significant differences between values of parameters in models 1 and 2.

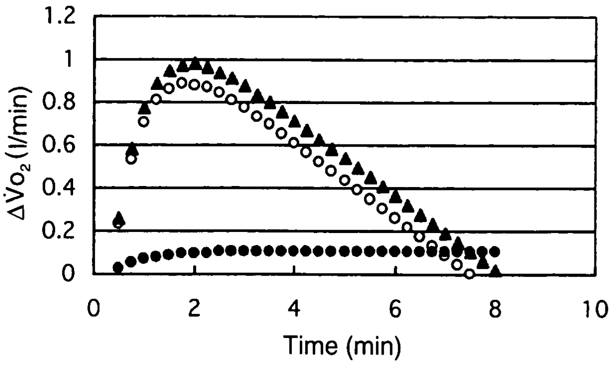

Fig. 3 Structure of oxygen uptake kinetics in decrement-load exercise. Approximation equation (2) was divided into two parts: equations (3) and (4) (see text for details). These values were calculated using parameters shown in Table 1 at a given time from equation (2) (▲), from equation (3) (○) and from equation (4) (●).

lower than gross $\Delta\dot{V}o_2$ but showed similar kinetics to that of gross$\Delta\dot{V}o_2$.

Thus, $\Delta\dot{V}o_2$ in DLE includes debt $\Delta\dot{V}o_2$. Therefore, the approximation equation employed in the present study should include the effect of debt $\Delta\dot{V}o_2$ in order for the data to have good fitting. Then we separate Eq. (2) into the following equations,

$$A_1 \cdot (1-\exp(-(t-TD)/\tau_1)) - A_2 \cdot (t-TD), \quad (3)$$

$$A_2 \cdot \tau_2 \cdot (1-\exp(-(t-TD)/\tau_2)). \quad (4)$$

$\Delta\dot{V}o_2$ calculated from Eqs. (2), (3) and (4) is shown in Fig. 3. These calculated kinetics were similar to the simulation results. The steady-state value of debt $\Delta\dot{V}o_2$ was about 100 ml/min, which is in the range of the steady-state values obtained in the simulation.

Thus, fitting of the approximation equation having a parameter of time delay became better. The obtained values of parameters did not extensively deviate from reported ones. The degree of fitting ranged from 94 to 98%. It seemed that $\dot{V}o_2$ including oxygen debt in DLE could be approximated by the present designed equation used in the present study.

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