Effect of Prolonged Exercise on Pulmonary Gas Exchange during Decremental-Load Exercise.

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Abstract

HORIUCHI, M. and YANO, T. Effect of Prolonged Exercise on Pulmonary Gas Exchange during Decremental-Load Exercise. Adv. Exerc. Sports Physiol., Vol.3, No.1 pp.23-28, 1997. The effects of prolonged exercise on pulmonary gas exchange during decremental-load exercise were investigated. Eight healthy male subjects participated in two experiments. In the first experiment, maximal incremental-load exercise (ILE) was used to determine the maximal work rate and peak oxygen uptake (peak $\dot{V}O_2$). In the second experiment, subjects exercised for one hour following a first decremental-load exercise (DLE1) starting from the maximal work rate determined by the first experiment and then again following a second decremental-load exercise (DLE2). $\dot{V}O_2$, measured every ten minutes during the prolonged exercise, was around 50% of the peak value at 10min, increasing to around 60% at 60min. Total O_2, the sum of O_2 uptake ($\dot{V}O_2$) from the start to the end of the exercise, was significantly lower during DLE2 than DLE1. Total CO_2, the sum of CO_2 output ($\dot{V}CO_2$) was significantly lower during DLE2 than DLE1. Although $\dot{V}CO_2$ tended to be lower during DLE2 than DLE1 at almost all work rates, this difference was only significant at high work rates. The results for $\dot{V}O_2$ and $\dot{V}CO_2$ suggested a smaller increase in lactate during DLE2 than DLE1. The ventilatory equivalent for CO_2 at a higher work rate was significantly higher during DLE2 than DLE1. This increase was thought to be related to muscle glycogen depletion induced by DLE1 and prolonged exercise. In conclusion, after prolonged exercise, pulmonary gas exchange kinetics during decremental-load exercise changed as follows; total O_2 uptake and CO_2 output decreased, the ventilatory equivalent for CO_2 at a higher work rate increased. The mechanism by which excess CO_2 is removed without increasing pulmonary ventilation remains to be elucidated.

Key words: decremental-load exercise, prolonged exercise, total O_2 uptake, total CO_2 output, ventilatory equivalent for CO_2

Introduction

To date, several studies have been carried out on pulmonary gas exchange using different load methods. One method, incremental-load exercise has provided useful results on the increase in lactate during exercise (2). However, to improve the relation between O_2 kinetics and increase of lactate, Whipp et al. (18) developed a new load method: decremental-load exercise. With previous load methods, i.e. incremental-load exercise and steady-state exercise, lactate production exceeded lactate oxidation above the anaerobic threshold. Thus, the kinetics of lactate oxidation during exercise could not be examined. But in decremental-load exercise, the O_2 kinetics includes the repayment phase of the O_2 deficit and lactate produced at the beginning of the exercise. Furthermore, we consider this exercise a useful tool because the kinetics of other pulmonary gas exchanges are involved (6).

Although there have been many studies on the biochemistry and circulation of pulmonary gas exchange during prolonged exercise (1, 4, 9), few have examined the kinetics of pulmonary gas exchange (10, 11). This is because pulmonary gas exchange changes more in the early stage of prolonged steady state exercise than in the later stage. Prolonged decremental-load exercise can provide new insights into pulmonary gas exchange. However if the duration of the decrease in the work rate is too long, distinguishable changes in the pulmonary gas exchange become vague.

To avoid this, in the present study, decremental-load exercises were carried out before and after prolonged exercise, and the kinetics of pulmonary gas exchange between the two compared.

Methods

1. Subjects

The subjects included eight healthy male college students, three undergraduates and five post-graduates. All the subjects were untrained, but familiar with the ergometer in our laboratory. Consent was obtained after explaining the purpose of the experiment, the procedure, and possible risks. The physical characteristics of each subject are shown in Table 1.

2. Loaded experiments

Exercise was performed using a bicycle ergometer (Combi) at 50 rpm. In the first experiment, incremental-load exercise (ILE) was carried out to determine the maximal work rate and peak oxygen uptake (peak $\dot{V}O_2$). In the second experiment, each subject performed prolonged exercise for one hour following the first decremental-load exercise (DLE1) and then again following the second decremental-load exercise (DLE2).

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In the first experiment, each subject exercised on the ergometer for four minutes at 0 watt after five-minutes rest. This was followed by incremental-load exercise of 15 watts/min until exhaustion.

One week later, the second experiment was carried out. Each subject exercised on the ergometer for four minutes at 0 watt after five-minutes rest. This was followed by a decremental-load exercise of 15 watts/min from the maximal work rate determined by the first experiment. Then, after a sitting rest of twenty minutes, subjects performed prolonged exercise for one hour at a work rate of 50% of the peak $\dot{V}O_2$ obtained from the first experiment. The subjects were again rested, this time for thirty minutes, and after O_2 uptake and heart rate had recovered to resting levels, performed DLE2 (the same procedure as for DLE1). In total, the second experiment took 155 ~163 min. (Table1 and Fig. 1).

3. Measurements

Expired gas was analyzed during rest and exercise in a mixing chamber with a capacity of six liters. The volume of expired gas was measured with a respiratory flow meter (Minato Medical Science: RF-H). O_2 and CO_2 fractions were measured with an expired gas monitor (NEC-Sanei: 1H-21A). These

Table 1 Physical characteristics and aerobic work capacity of the subjects

Subjects	Age (yrs)	Height (cm)	Weight (kg)	Peak $\dot{V}O_2$ (ℓ/min)	Work max (watts)	Time in incremental and decremental-load exercise (min)
K.F	23	161.5	62.4	2.49	260	17.33
T.H	26	178.3	69.0	2.34	240	16.00
M.H	29	174.0	68.0	3.51	300	20.00
N.M	26	168.2	63.5	2.62	240	16.00
S.O	22	164.5	64.6	2.60	245	16.33
T.Y	25	164.7	59.5	2.50	240	16.00
K.N	25	172.1	61.5	2.86	260	17.33
S.M	25	174.2	65.9	2.31	240	16.00
mean ±SD	25 ±2.1	169.7 ±5.9	64.3 ±3.2	2.65 ±0.39	253 ±21	16.87 ±1.39

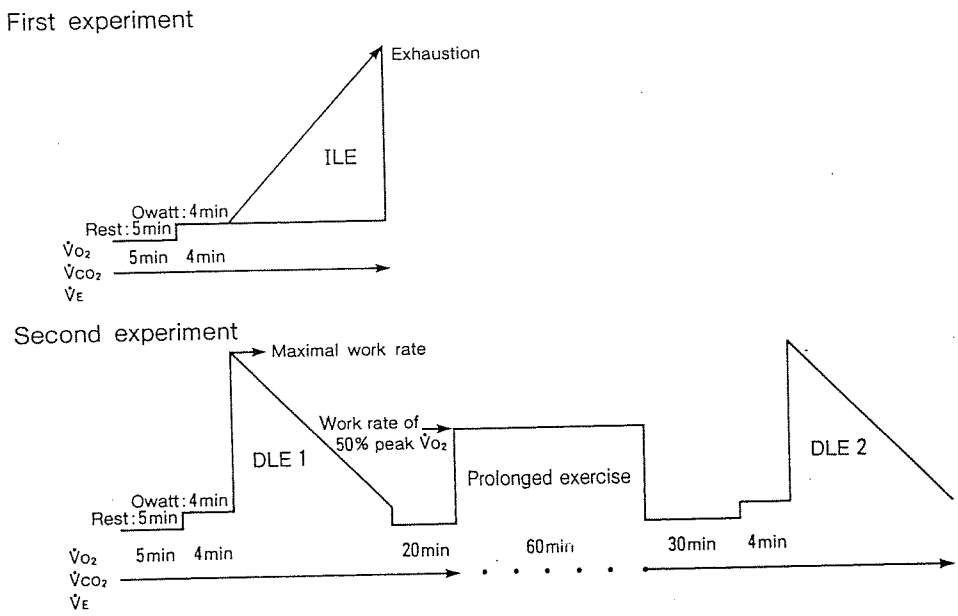

Fig. 1 Protocol of the experiment.
ILE: Incremental-load exercise, DLE1: First decremental-load exercise, DLE2: Second decremental-load exercise.

values were transmitted through an AD converter into a personal computer (NEC: PC 9801m), allowing continuous measurement of O_2 uptake ($\dot{V}O_2$), CO_2 output ($\dot{V}CO_2$), respiratory gas exchange ratio (RER) and ventilation ($\dot{V}_E$) every 20 seconds during ILE and DLE. During the one hour of prolonged exercise, expired gas was also analyzed every 20 seconds at 9～10, 19～20, 29～30, 39～40, 49～50, and 59～60 min. The expired gas monitor was checked by known gases before and after the experiments.

Heart rate (HR) was measured by a heart rate monitor (Cannon: Vantage XL) during experiments.

4. Statistics and management of values

The paired Student's t-test was used and differences at levels of 5%, 1%, and 0.1% were considered significant. Total volumes of $\dot{V}O_2$ and $\dot{V}CO_2$ from the beginning to the end of the exercise (not including the first four minutes at a work rate of 0 watt) were expressed as total VO_2 and total VCO_2. The relationship between $\dot{V}O_2$ and work rate was approximated by a single regression line.

Results

Work rate at exhaustion in ILE ranged from 240 to 300 watts and performance time in ILE and DLE ranged from 16 to 20 min. (Table 1). $\dot{V}O_2$ measured every ten minutes during prolonged exercise was around 50% of peak $\dot{V}O_2$ at 10 min, increasing to around 60% at 60 min. RER significantly decreased from 0.88±0.09 (mean±SD) at 10 min to 0.80±0.06 at 60 min in the prolonged exercise.

Levels of $\dot{V}O_2$ corresponding to the work rate in the incremental and the two decremental exercises of one representative subject are shown in Fig. 2 (the time course in decremental-load exercise proceeds from right to left while that in ILE proceeds from left to right). $\dot{V}O_2$ in ILE linearly increased except during of the beginning and end of the exercise.

In decremental-load exercise, $\dot{V}O_2$ increased rapidly, reaching a peak within 1～2 minutes, then plateaued and later decreased. $\dot{V}O_2$ corresponding to the work rate minus the increasing and plateau phase during decremental-load exercise was approximated by a single regression line. Its slope ($\Delta\dot{V}O_2/\Delta W$) was 9.34±0.70 ℓ /min/watts in ILE. The $\Delta\dot{V}O_2/\Delta W$ was 10.54±0.81 ℓ /min/watts in DLE1 and 10.08±1.03 ℓ /min/watts in DLE2. The $\Delta\dot{V}O_2/\Delta W$ in DLE1 and DLE2 were significantly higher than that in ILE ($p<0.05$). $\dot{V}O_2$ tended to be lower in DLE2 than DLE1, but the difference was not significance. Total VO_2, the sum of $\dot{V}O_2$ from the beginning to the end of exercise, was 24.9±5.9 ℓ in ILE. Total VO_2 was decreased in DLE2 compared to DLE1 in six subjects

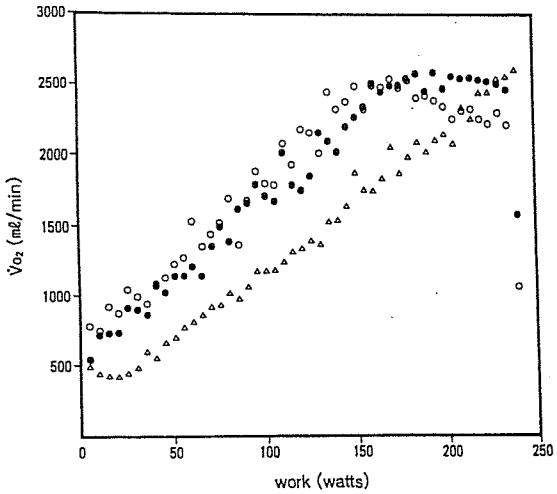

Fig. 2 Kinetics of O_2 uptake during incremental-load exercise (△),the first decremental-load exercise (○), and the second decremental-load exercise (●) for a single subject (N. M).

and almost the same in two subjects. Total VO_2 values in DLE1 and DLE2 were 29.4±4.6 ℓ and 28.1±5.0 ℓ, respectively. Total VO_2 values were significantly higher in DLE1 and DLE2 than ILE ($p<0.05$), and lower in DLE2 than DLE1 ($p<0.05$).

$\dot{V}CO_2$ in decremental-load exercise increased rapidly, reaching a peak within 2～3 minutes, and then decreased (Fig. 3: the subject is the same as in Fig. 2). As $\dot{V}CO_2$ appeared to be lower in DLE2 than in DLE1, the $\dot{V}CO_2$ values were compared at all work rates. It was found that $\dot{V}CO_2$ was significantly lower in DLE2 than DLE1 from 105 to 230 watts with exceptions for 140, 145, and 225 watts ($p<0.05$, $p<0.01$ and $p<0.001$, respectively). Total VCO_2, the sum of $\dot{V}CO_2$ from the beginning to the end of DLE1 and DLE2, was 29.9±2.7 ℓ and 26.9±3.0 ℓ, respectively. Total VCO_2 was significantly lower in DLE2 than DLE1 ($p<0.01$).

$\dot{V}_E$ in decremental-load exercise increased rapidly within a few minutes of exercise, reached a peak at 3～5 minutes, and then decreased (Fig. 4: the subject is the same as in Fig. 2). The $\dot{V}_E$ level in DLE2 in six subjects was higher than that in DLE1 for the first three minutes of exercise, but the level decreased after 3 min. In two subjects, $\dot{V}_E$ was higher in DLE1 than DLE2. No significant differences were found between DLE1 and DLE2.

$\dot{V}_E/\dot{V}CO_2$ in decremental-load exercise decreased rapidly within the first 1～2 minutes of exercise and then increased (Fig. 5: the subject is the same as in Fig. 2). Although $\dot{V}_E/\dot{V}CO_2$ during the decrease and increase phases appeared to be higher

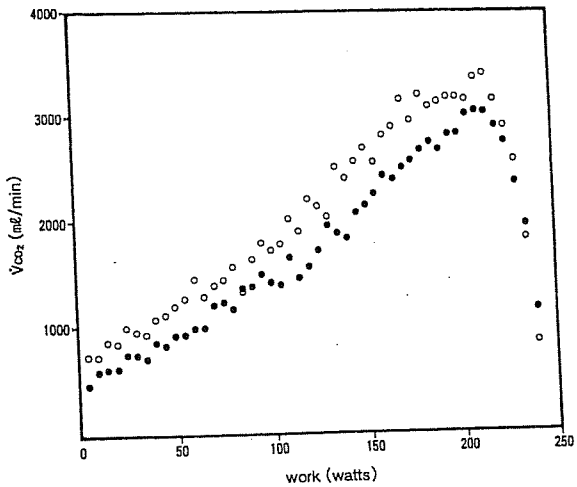

Fig. 3 Kinetics of CO_2 output during the first (○) and second (●) decremental-load exercise for a single subject (N. M).

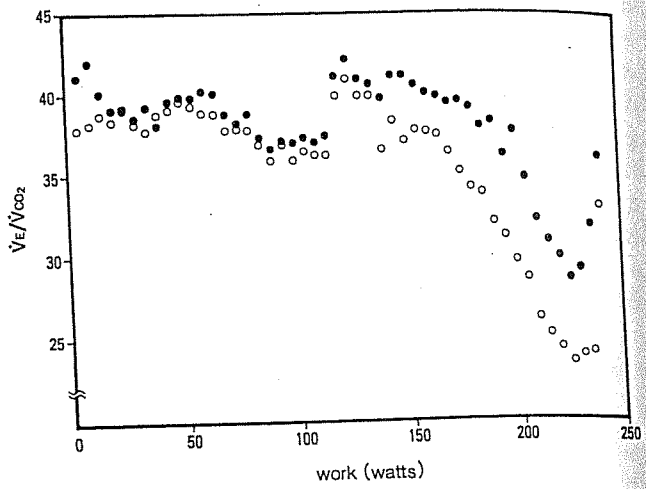

Fig. 5 Kinetics of ventilatory equivalent for CO_2 during the first (○) and second (●) decremental-load exercise for a single subject (N. M).

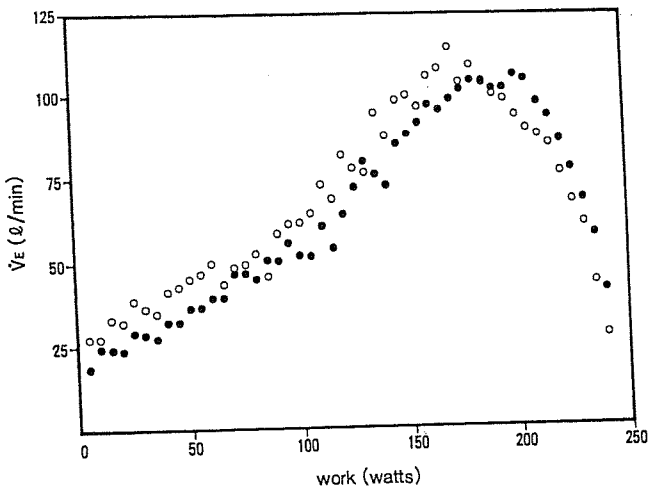

Fig. 4 Kinetics of ventilation during the first (○) and second (●) decremental-load exercise for a single subject N. M).

in DLE2 than DLE1, significant differences were only found from 185 to 235 watts with an exception for 200 watts ($p<0.05$ and $p<0.01$).

Discussion

In the present study, subjects exercised for one hour following the first decremental-load exercise and then again following the second decremental-load exercise. The kinetics of pulmonary gas exchange were compared between DLE1 and DLE2. It was found that total VCO_2, the sum of $\dot{V}CO_2$ from the beginning to the end of exercise, decreased from DLE1 to DLE2. This could be due to a decrease in $\dot{V}CO_2$ at a higher work rate. While total VO_2 significantly decreased from DLE1 to DLE2, $\dot{V}O_2$ did not differ at any work rate. This suggests that prolonged exercise affects $\dot{V}O_2$ at the overall work rate, but not at any specific work rate. Moreover, $\dot{V}_E/\dot{V}CO_2$ in DLE2 increased at higher work rates.

Lactate was thought to increase from the beginning of decremental-load exercise, since in the present study this exercise was performed at the maximal work rate determined by the ILE. It has been reported that when high-intensity, prolonged exercises were repeated several times, the peak blood lactate level decreased during exercise at higher work rates (1). This increase in lactate is partly buffered by a rightward shift of the bicarbonate system, $\ulcorner H^+ + HCO_3^- \leftrightarrows H_2O + CO_2 \lrcorner$ (8). Elmination of the shifted CO_2 by lung ventilation, results in an excessive expiration of CO_2. Yano et al. (21) observed excess CO_2 expiration associated with an increase in the blood lactate level during incremental-load exercise at a high work rate. This indicates that lactate kinetics can be estimated from CO_2 kinetics. Therefore, in the present study, it is suggested that the increase in the lactate level at higher work rates is lower during DLE2 than DLE1.

The lactate concentration in the blood is regulated by a balance between production and oxidation of lactates (15). We next discuss the lactic oxidation based on the kinetics of $\dot{V}O_2$.

Whipp et al. (18) reported that the changing rate of $\dot{V}O_2$ corresponding to the work rate ($\Delta\dot{V}O_2/\Delta W$) was higher in decremental than incremental-load exercise, as was $\dot{V}O_2$ at the same work rate. Horiuchi et al. (6) confirmed that $\dot{V}O_2$ was significantly higher

in decremental than incremental-load exercise, as was the total VO_2 obtained by summing $\dot{V}O_2$ during exercise. It was suggested that total VO_2 is higher in decremental-load exercise due to the repayment of the O_2 deficit produced at the early phase.

The respiratory quotient (RQ) is know to generally decrease during prolonged exercise(4). This is due to not an increase of $\dot{V}CO_2$ but an increase in $\dot{V}O_2$, because O_2 is needed more for the production of ATP in fatty turnover than in carbohydrate turnover(5). However, as the increase in the lactate level observed at higher work rates restrains fatty mobilization(13), the effect of the fatty metabolism may be less on O_2 uptake during DLE2.

The kinetics of $\dot{V}O_2$ and $\dot{V}CO_2$ suggest that the lactate level is lower in DLE2 than in DLE1 at higher work rates, and therefore, the repayment of the O_2 deficit would decrease in DLE2.

Thus, the increase of the CO_2 derived from the energy metabolism and buffer of lactic acid during exercise must be expired by an increase of pulmonary ventilation. The relationship between $\dot{V}CO_2$ and $\dot{V}_E$ should be discussed.

$\dot{V}_E / \dot{V}CO_2$ has been reported to be higher under conditions of depleted muscle glycogen due to diet control and exercise than under normal conditions(5, 7). In the present study, the muscle glycogen might have been depleted immediately before DLE2 by the lactate production during DLE1 because the subjects started from the maximal work rate determined by ILE. Since decremental-load exercise and prolonged exercise were performed aerobically, these exercises would also have affected the value of muscle glycogen. The results of previous studies(5, 7), therefore, suggest that the increase in $\dot{V}_E / \dot{V}CO_2$ in the present study is related to the depletion of muscle glycogen.

A depletion of muscle glycogen is known to lead to a lower blood lactate level during exercise(5, 7, 14). Generally, a change in the lactate level affects pulmonary ventilation, and excess CO_2 is expected to be expired by hyperventilation(16). Thus the decrease of CO_2 in the present study may have been accompanied by a decrease in hyperventilation. However, this was not confirmed by the present results. Therefore, other factors must relate to the output of excess CO_2, as Whipp et al.(17) and Casaburi et al.(3) have already suggested.

Nakamura et al. (12) suggested that the bicarbonate system in venous blood affects the output of excess CO_2. That is, in this buffer, HCO_3^- shifts to CO_2 and the fractions of CO_2 increase. The difference in CO_2 fractions between pulmonary and venous blood increases and may result in excess CO_2 being expired. However, the kinetics of mixed venous CO_2 pressure are reported to be unaffected by an increase in the lactate level in both incremental-load and constant-load exercise (19, 20).

In conclusion, after prolonged exercise, pulmonary gas exchange kinetics during decremental-load exercise changed as follows; total O_2 uptake and CO_2 output decreased, the ventilatory equivalent for CO_2 at a higher work rate increased. The mechanism by which excess CO_2 is removed without increasing pulmonary ventilation remains to be elucidated.

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