THE EFFECT OF DIFFERENT WORK INTERVAL DURATIONS AND WORK:RECOVERY RATIOS ON OXYGEN CONSUMPTION, BLOOD LACTATE AND HEART RATE DURING EXERCISE

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ABSTRACT

The purpose of this study was to determine and compare the acute effect of varied interval lengths and work:recovery (W:R) ratios on the ability to reach and maintain high aerobic power levels. 8 trained female rowers completed 1 continuous and 7 interval sessions on a Concept II rowing ergometer. The intensity was set at 100% VO_{2max} power output ($VO_{2max}PO$) and work was terminated when PO remained below 90% $VO_{2max}PO$ for 15 seconds(s). The interval protocols utilized a 1:0.5 W:R ratio for work intervals of 30 s, 1, 2, and 3 minutes(min) and a 1:1 W:R ratio for work intervals of 1, 2, and 3 min. Blood samples taken from an antecubital vein after the first 3 min or 4 min of work (RLACTATE) and 2 min post exercise (PELACTATE) were analyzed for plasma lactate. Total Working Time (TWT) was greater ($p \leq 0.05$) with an interval protocol when compared to continuous exercise and decreased both when work intervals lengthened and when the W:R ratio changed from 1:1 to 1:0.5. Time working at VO_{2max} was greatest with 3 min intervals and continuous work. The Average Work VO_2 ($AVEVO_2$) was highest in the continuous condition and both 3 min intervals provided the greatest $AVEVO_2$ of the interval sessions. The greatest PELACTATE was observed after the continuous work and in the intermittent sessions the RLACTATE and PELACTATE increased as work intervals were lengthened. RLACTATE and PELACTATE did not differ significantly except that in the 30s:15s and 1min:1min intervals RLACTATE was less than PELACTATE. Heart rates at the end of recovery periods were greatest in the 30s:15s session and in the 1:0.5 W:R protocols when compared to 1:1 W:R conditions. The continuous exercise and both 3 min interval sessions provided the most time spent at VO_{2max} (TVO_2MAX) but the 3min:3min interval design elicited the greatest TWT of these 3 conditions. Therefore, of the protocols studied, the 3min:3min design may be optimal for reaching and maintaining high aerobic power levels when working at 90-100% $VO_{2max}PO$. The 1min:1min TWT was the greatest of all sessions and would therefore elicit the highest caloric expenditure of the protocols studied.

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DEDICATION

This thesis is dedicated to my mother and father, and to my Aunt Ruth, who have always shown their support in so many different ways during my education.

INTRODUCTION

The ability of the aerobic energy production system to produce ATP via the oxidation of glycogen and fat stores is crucial in activities or sporting events which require maximal intensity longer than approximately 2 1/2 minutes(min) (Gollnick and Hermansen, 1973). To improve the rate at which the aerobic system provides energy (aerobic power) the organism should be repeatedly exposed to low oxygen availability (hypoxia). Prolonged exercise can provide this hypoxic environment since chronic exposure to high altitude produces muscular changes similar to those caused by endurance training (MacDougall & Sale, 1981). Also, hypoxia is high when the work demands maximal oxygen consumption (VO_{2max}) (MacDougall and Sale, 1981). Thus, work intensities should approach VO_{2max} to maximize the hypoxic stimulus and therefore the rate of improvement of aerobic power.

Continuous work at VO_{2max} intensity can be maintained for approximately 9 min (Astrand et al., 1960a). The introduction of recovery periods between the work loads in which work and recovery intervals were equal in duration, allowed about 30 min of work to be performed but VO_{2max} during work was attained only when intervals of 3 min duration were used (Astrand et al., 1960a). Shorter intervals even at maximal loads produced submaximal responses such as a low degree of glycogen depletion and lactate accumulation, a respiratory exchange ratio of less than 1, and submaximal values for oxygen consumption and heart rate (Astrand et al., 1960a; Christensen et al., 1960; Edwards et al., 1973; Essen et al., 1977). Increasing the length of the work intervals demanded proportionally greater responses with a concommittant increased lactate accumulation (Astrand et al., 1960a). This indicated that in the longer intervals both aerobic and anaerobic systems were challenged to provide energy. Lactic acid generated from anaerobic glycolysis during long intervals dissociates to lactate and H^+ which accumulates and contributes to fatigue (Sahlin, 1983; Wenger and Reed, 1976). During the recovery intervals the muscle must then remove and/or metabolize the lactate and H^+ if high intensity work is to continue (Belcastro and Bonen, 1975; Boileau et al., 1983; Dodd et al., 1984).

Sprint training has been shown to increase intramuscular buffering capacity and VO_{2max} (Bell and Wenger, 1986). Assuming that lactate and H^+ accumulation is the stimulus that causes muscular adaptations to deal with these metabolites, intervals can be used to enhance aerobic power and increase lactate and H^+ tolerance and/or removal.

It has been demonstrated that more high intensity work can be performed by working intermittently rather than continuously (Astrand et al., 1960a; Christensen et al., 1960), but it has not been shown that varying interval lengths and work:recovery ratios will affect the total amount of overload put on the aerobic energy system.

Since many activities require high aerobic power it is necessary to determine the work:recovery ratios which maximally tax the aerobic energy production system and therefore provide the optimal stimulus for enhanced aerobic power.

Statement of the Problem

The purpose of this study was to determine and compare the acute effect of varied interval lengths and work:recovery ratios on the ability to reach and maintain high aerobic power levels.

The specific purposes were:

1. To determine and compare the effects of continuous and intermittent exercise of different work:recovery ratios on the amount of work that can be performed at 90-100% VO_{2max} intensity.
2. To determine and compare the effects of continuous and intermittent exercise of different work:recovery ratios on the amount of time spent working within 0.1 $l \cdot min^{-1}$ of VO_{2max}.
3. To determine and compare the effects of continuous and intermittent exercise of different work:recovery ratios on average working VO_2 relative to VO_{2max}.
4. To determine and compare the effects of continuous and intermittent exercise of different work:recovery ratios on blood lactate during and after intermittent exercise.
5. To determine and compare the effects of continuous and intermittent exercise of different work:recovery ratios on heart rate immediately after exercise and recovery.

OPERATIONAL DEFINITIONS

Active Recovery - exercise performed between work intervals on the rowing ergometer at approximately one-third of the power output that elicited VO_{2max}.

Continuous Work - exercise performed on the rowing ergometer at 90 - 100% of the power output that elicited VO_{2max} without rest periods or other interruptions until cessation of exercise.

Hypoxia - a lowering of the partial pressure of oxygen (pO_2) in the working muscle tissue during exercise.

Intermittent Work - work is interrupted regularly with recovery periods.

Passive Recovery - the pause between work intervals which consists of sitting quietly on the rowing ergometer.

Respiratory Exchange Ratio (R) - the ratio between the volume of CO_2 produced and the volume of O_2 consumed, measured through expired air.

Work Interval - the portion of a training session that consists of exercise performed at 90-100% of the power output that elicits VO_{2max} on the rowing ergometer.

Work:Recovery Ratio - the ratio between the duration of work interval and duration of recovery interval. For example, a work:recovery ratio of 1:2 implies that the recovery interval is twice the length of the work interval.

METHODS

Subjects

Eight trained female rowers from the University of Victoria signed informed consent and volunteered to act as subjects. Physical characteristics are shown in Table 1. All subjects were familiarized with testing procedures before testing commenced.

Testing Procedure

The testing procedure is presented in Figure 1. Anthropometric measures were weight and the sum of six skinfolds (triceps, biceps, subscapular, suprailiac, front thigh, and medial calf). Aerobic power (Vo_2max) was determined from open circuit spirometry during a single, continuous multistage test on the Gjessing rowing ergometer outlined as follows:

a) initial warm-up at approximately 125 watts.

b) subjects rowed at a rate of about 30 strokes per minute(min) or 600 revolutions per m (rpm) of the flywheel.

c) the first four loads were increased by approximately 25 watts every 2 min and subsequent loads were increased by 25 watts every min.

d) the test continued until 2 of the following 3 Vo_2max criteria were observed:

1) plateau or decline in Vo_2 with increasing loads (< 100 ml per min increase).

2) volitional exhaustion of the subject.

3) $R > 1.15$

Table 1

Physical characteristics of the subjects

Subject	Age (year)	Height (cm)	Weight (kg)	VO_{2max} ($l \cdot min^{-1}$)	Sum of Skinfolds* (mm)
CD	22	170.0	66.6	3.92	75.4
KA	22	175.4	72.3	3.55	85.6
KB	19	177.0	75.0	3.65	79.8
SC	22	176.5	72.0	3.27	89.0
SR	19	169.8	70.4	3.43	75.8
SE	20	180.0	66.0	3.22	78.8
KT	19	179.5	73.5	3.30	81.5
KD	18	178.0	71.6	3.36	76.9
$\bar{x}$	20.1	174.7	70.9	3.46	79.0
SE	0.2	2.5	1.1	0.08	1.8

* sum of skinfolds = triceps + biceps + subscapular + suprailiac + front thigh + medial calf.

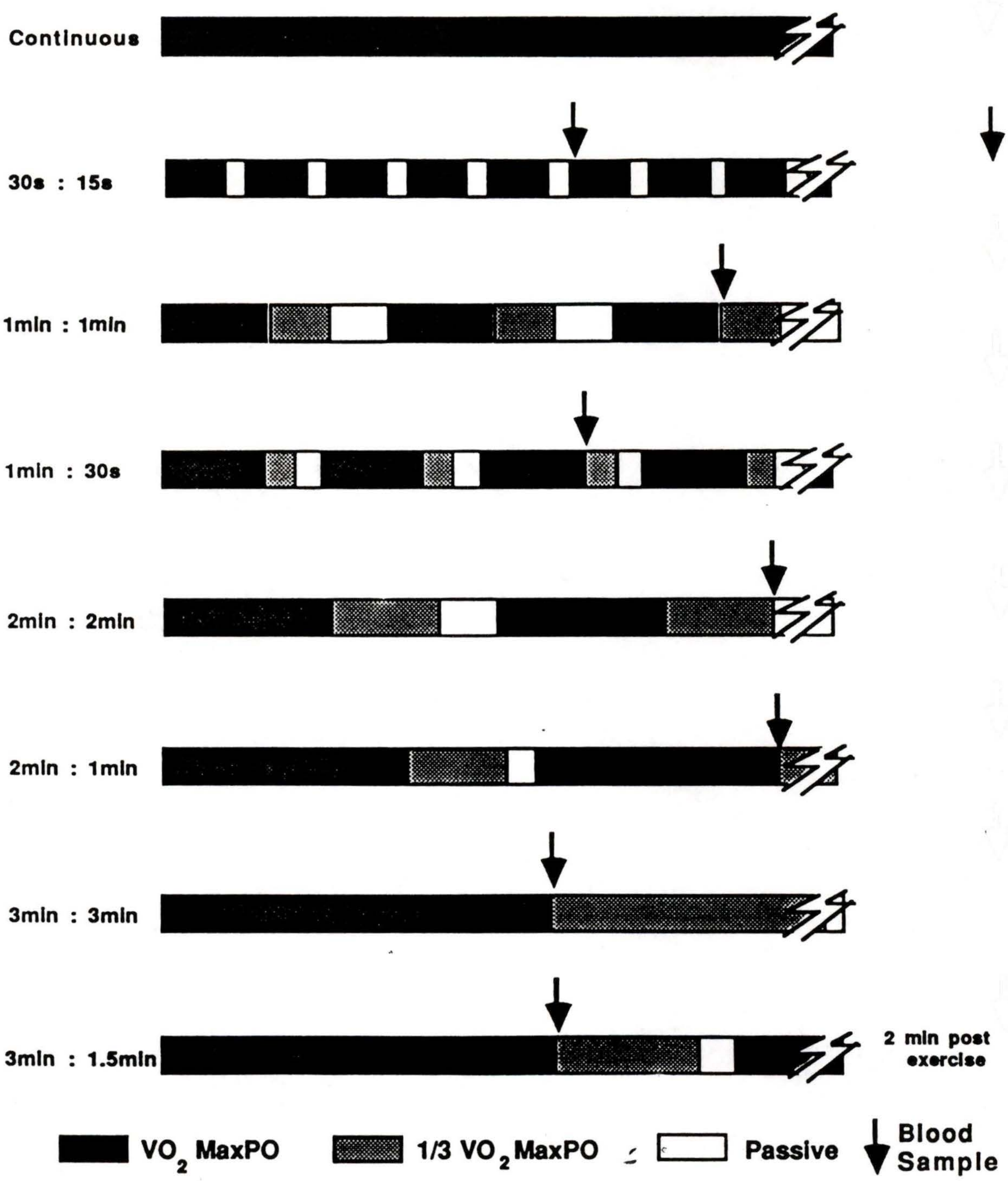

Figure 1. A schematic diagram illustrating the work at 90-100 % VO_2 MaxPO, active recovery, and passive recovery during the exercise conditions

Respiratory gases were collected and analyzed every 30 seconds(s) with a Beckman Metabolic Measurement Cart (MMC) and heart rate was recorded every min throughout the test with a Quantum XL Fitness Monitor. The MMC was calibrated with known concentrations of gases immediately before and after each test. Power outputs (PO) (watts) were calculated by recording rpm every 30 s and PO at VO_{2max} (VO_{2max}PO) was determined graphically by plotting VO_2 vs. PO.

All subsequent exercise sessions were performed at 90 - 100% VO_{2max}PO on a Concept II rowing ergometer. Average 30 s PO was measured by the digital monitor on the Concept II rowing ergometer and the subjects were encouraged to maintain 100% VO_{2max}PO. Each session was terminated when average PO remained below 90% VO_{2max}PO for 15 s.

During the second week, subjects completed a continuous session preceded by a 5 min warm up. The continuous session began with each subject rowing at one-third VO_{2max}PO for 3 min, then the PO was immediately increased to 100% VO_{2max}PO and the session ceased when the termination criterion was met.

Over the following weeks, subjects performed intermittent exercise in which the work:recovery ratio (W:R) was 1:1 and 1:0.5 for work interval lengths of 30 s, 1, 2, and 3 min. The type of recovery between work periods was active except for the last 30 s of recovery in the 1:1 sessions and the last 15 s in the 1:0.5 sessions, which was passive. Water was made available ad libitum during the passive phases of recovery. Respiratory gases were collected and measured every 15 s during work and active phases of recovery using the MMC.

Weekly sessions were randomly assigned so that each condition was not performed during the same week by all subjects. The study was conducted during the training season of the rowers and the coaches considered it as part of the training program.

Total Work Time (TWT) was measured as the total time spent working between 90-100% $VO_{2max}PO$ during one session.

Time at VO_{2max} (TVO_2MAX) was determined by summing all 15 s MMC measurement intervals in which the VO_2 recorded was no more than 0.1 $l \cdot min^{-1}$ below VO_{2max} during one session.

If a session produced a higher VO_2 than the determined VO_{2max} of the subject, this VO_2 value would be used as VO_{2max} for that session and subsequent sessions.

Average Work VO_2 ($AVEVO_2$) was determined by calculating the mean of all VO_2 measurements recorded while working at 90-100% $VO_{2max}PO$ during one session and expressed as a percentage of VO_{2max}.

Blood sampling

All sessions included a blood sample taken from an antecubital vein 2 min after the termination of the session (PELACTATE). Interval sessions included a recovery blood sample (RLACTATE) taken immediately after the first 3 min of work at 90-100% $VO_{2max}PO$ was completed or immediately after the first 4 min of work at 90-100% $VO_{2max}PO$ in the case of 2 min work intervals. The blood samples were immediately added to ice cold 4% perchloric acid to be subsequently centrifuged and analyzed spectrophotometrically according to Sigma method 826-UV (Sigma Chemical Company, 1981) for blood lactate.

Work Heart Rate (WHR) was recorded at the end of each work interval and the mean of these measures was expressed as a percentage of maximum heart rate for each session.

Recovery Heart Rate (RHR) was recorded at the end of each recovery interval and the mean of these measures was expressed as a percentage of maximum heart rate for each session.

Data analysis

Paired Student's t-tests were used to determine if statistical differences existed between the various exercise conditions. The level of significance was set a priori at $p \leq 0.05$.

RESULTS

Total Work Time (TWT) (Figure 2). The TWT with continuous effort at $VO_{2max}PO$ was significantly less ($p < 0.05$) than the TWT of all interval conditions whereas the 1min:1min TWT was significantly greater than all others. The 1min:30s TWT was significantly greater than the 30s:15s, 2min:1min, 3min:3 and 3min:1.5min. The TWT with the 2min:2min and 3min:3min intervals was significantly greater than the 3min:1.5min.

Time at VO_{2max} (TVO_2MAX) (Figure 3). The TVO_2MAX during the 3min:3min condition was significantly greater than the TVO_2MAX of the 30s:15s, 1min:1min, 1min:30s, and 2min:2min, and 2min:1min intervals. The continuous TVO_2MAX was significantly greater than the 30s:15s, 1min:1min, 1min:30s and 2min:2min TVO_2MAX while the 3min:1.5min TVO_2MAX was significantly greater than that of the 30s:15s, 1min:1min, and 1min:30s protocols.

Average Work VO_2 ($AVEVO_2$) (Figure 4). The $AVEVO_2$ across the continuous exercise was significantly greater than all other $AVEVO_2$. The 3min:3min $AVEVO_2$ was the highest of the interval protocols and was significantly greater than the $AVEVO_2$ of all other intervals except the 3min:1.5min condition which in turn showed a higher $AVEVO_2$ than the 30s:15s, 1min:1min, and 2min:2min sessions.

Post Exercise Lactate (PELACTATE) (Figure 5). The PELACTATE following the continuous session was significantly greater than the PELACTATE following all intervals except the 3min:1.5min condition, which showed a significantly greater PELACTATE than the 30s:15s, 1min:1min, 1min:30s and 2min:2min sessions.

Recovery Lactate (RLACTATE) (Figure 5). The RLACTATE during the 3min:1.5min intervals was significantly greater than the 30s:15s, 1min:1min, 1min:30s and 2min:2min RLACTATE. The 30s:15s RLACTATE was significantly less than all other RLACTATE except that of the 1min:1min session, which was significantly less than the 2min:1min, 3min:3min and 3min:1.5min RLACTATE. RLACTATE was significantly less than PELACTATE for the 30s:15s and 1min:1min protocols.

Work Heart Rate (WHR) (Figure 6). In all interval sessions, WHR was significantly greater than the recovery hear rate (RHR). The WHR during the 3min:3min exercise was significantly greater than that of the 3min:1.5min and 1min:30s intervals.

Recovery Heart Rate (RHR) (Figure 6). The RHR following recovery during the 1min:30s intervals was significantly greater than the RHR of the 1min:1min, 2min:2min, 2min:1min, 3min:3min, and 3min:1.5min sessions. The 2min:1min RHR was significantly greater than the 1min:1min, 2min:2min, 3min:3min, and 3min:1.5min RHR, whereas the 3min:1.5min RHR was significantly greater than the RHR of the 3min:3min protocol.

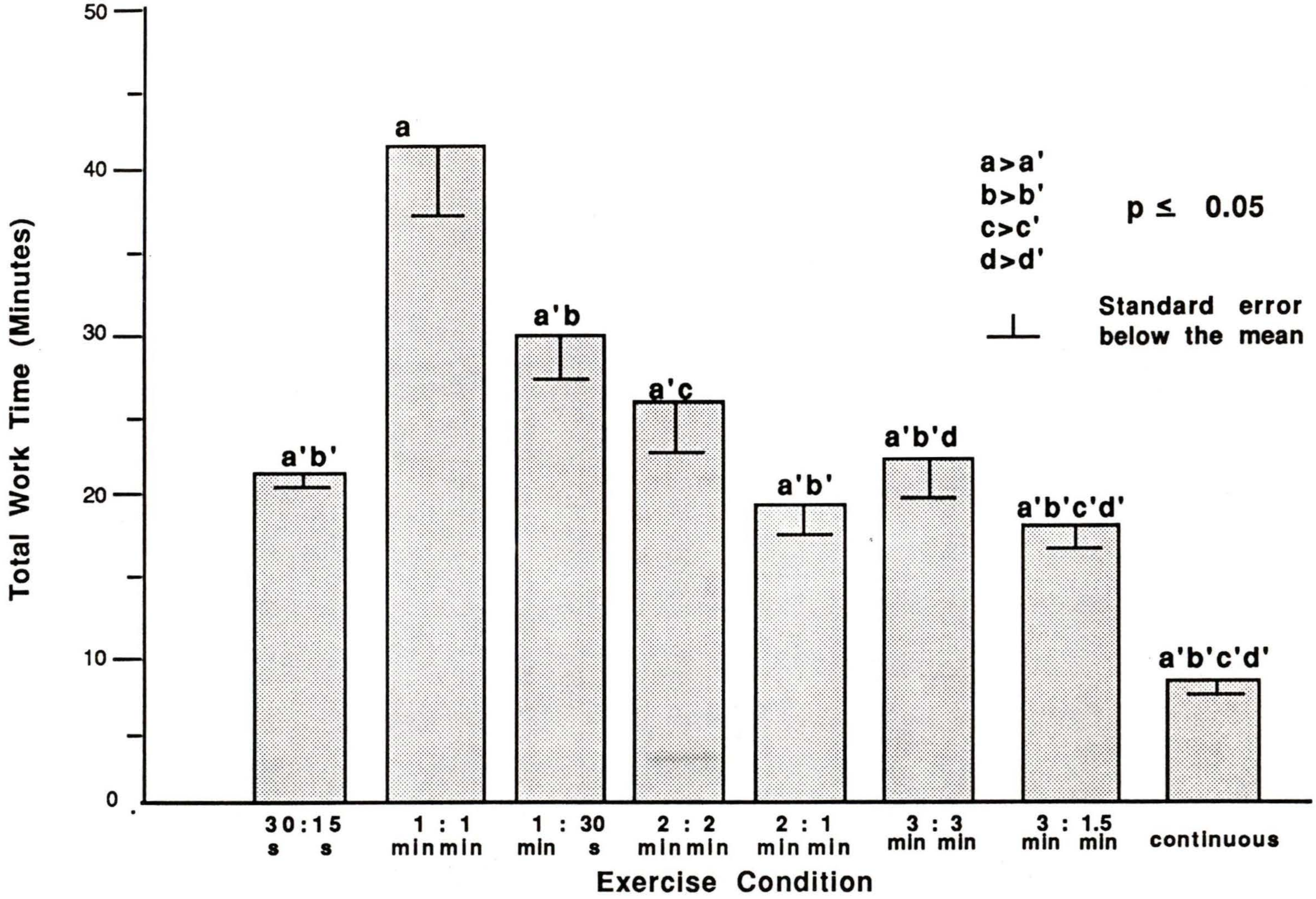

Figure 2. Total work time during the exercise conditions

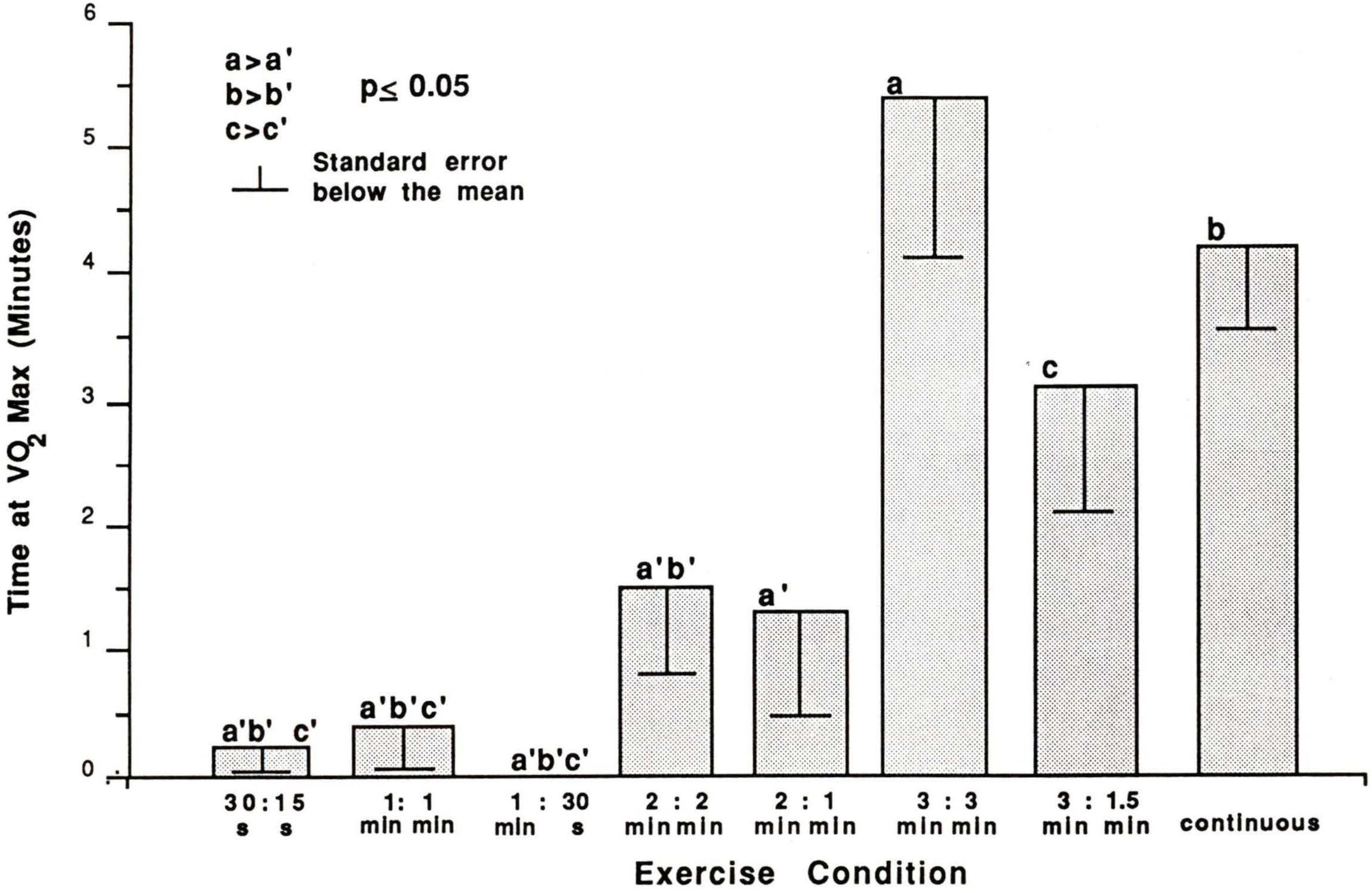

Figure 3. Time at VO_2 max during the Exercise conditions

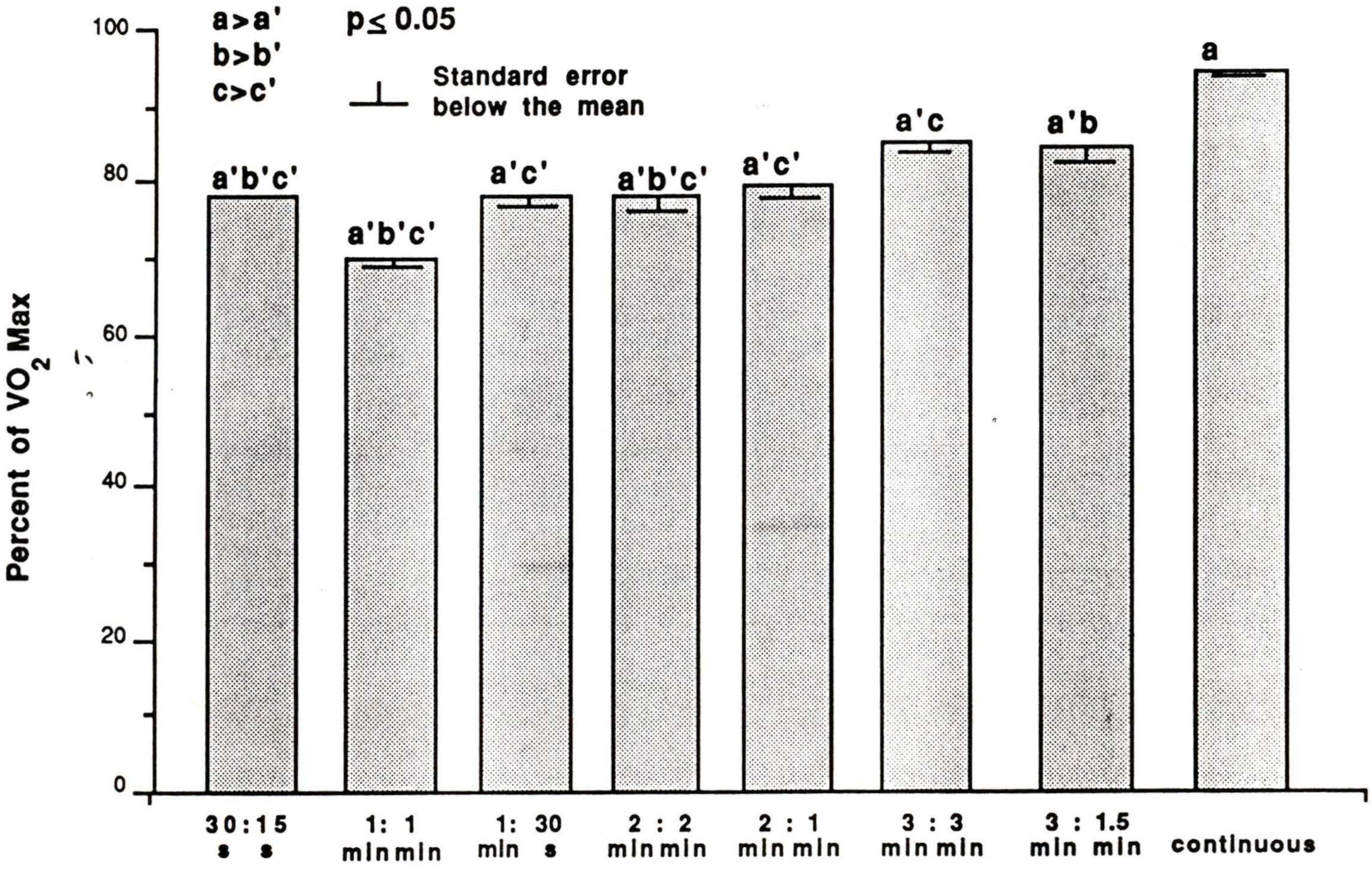

Figure 4. Average work VO_2 during the exercise conditions

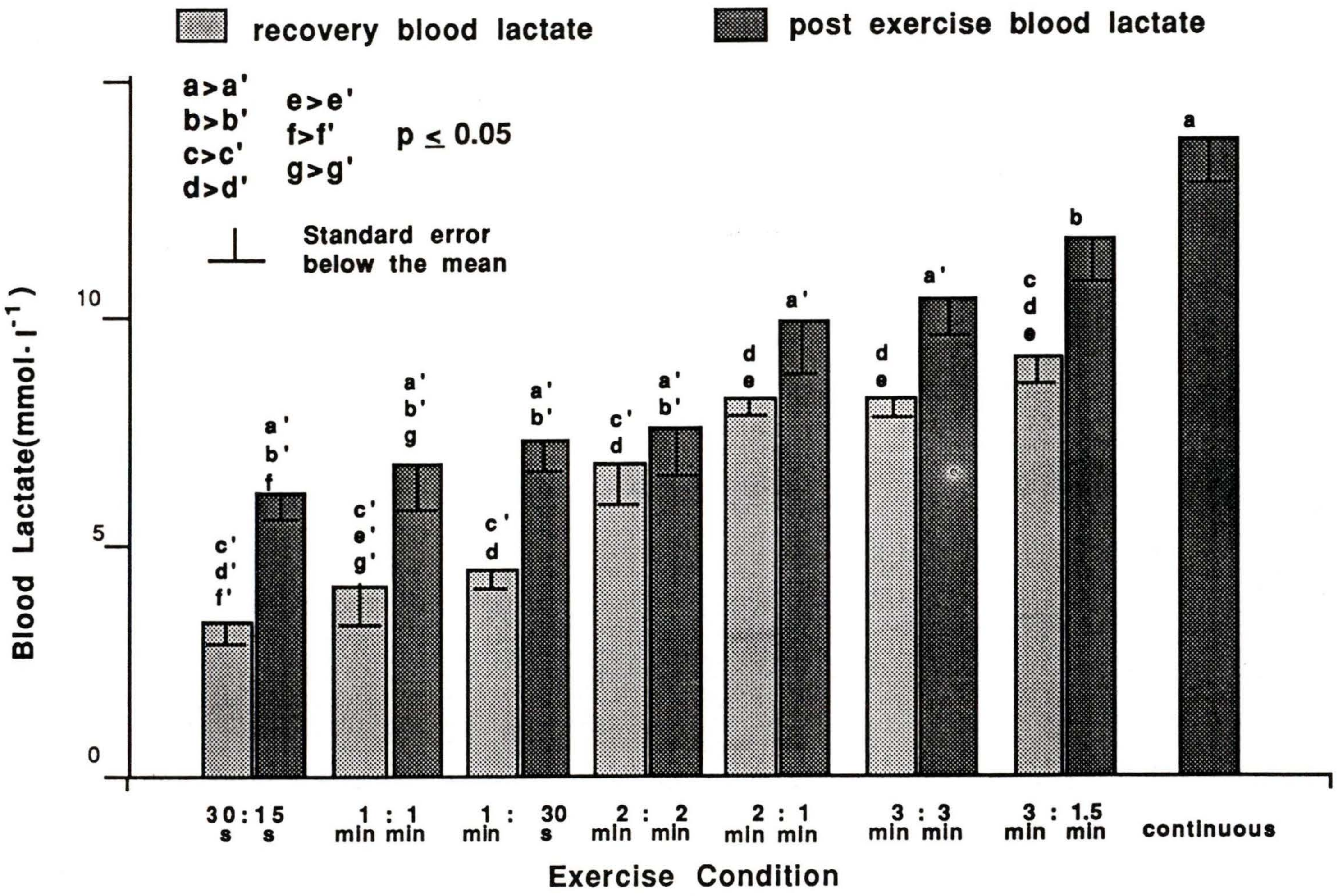

Figure 5. Post exercise blood lactate and recovery blood lactate during the exercise conditions

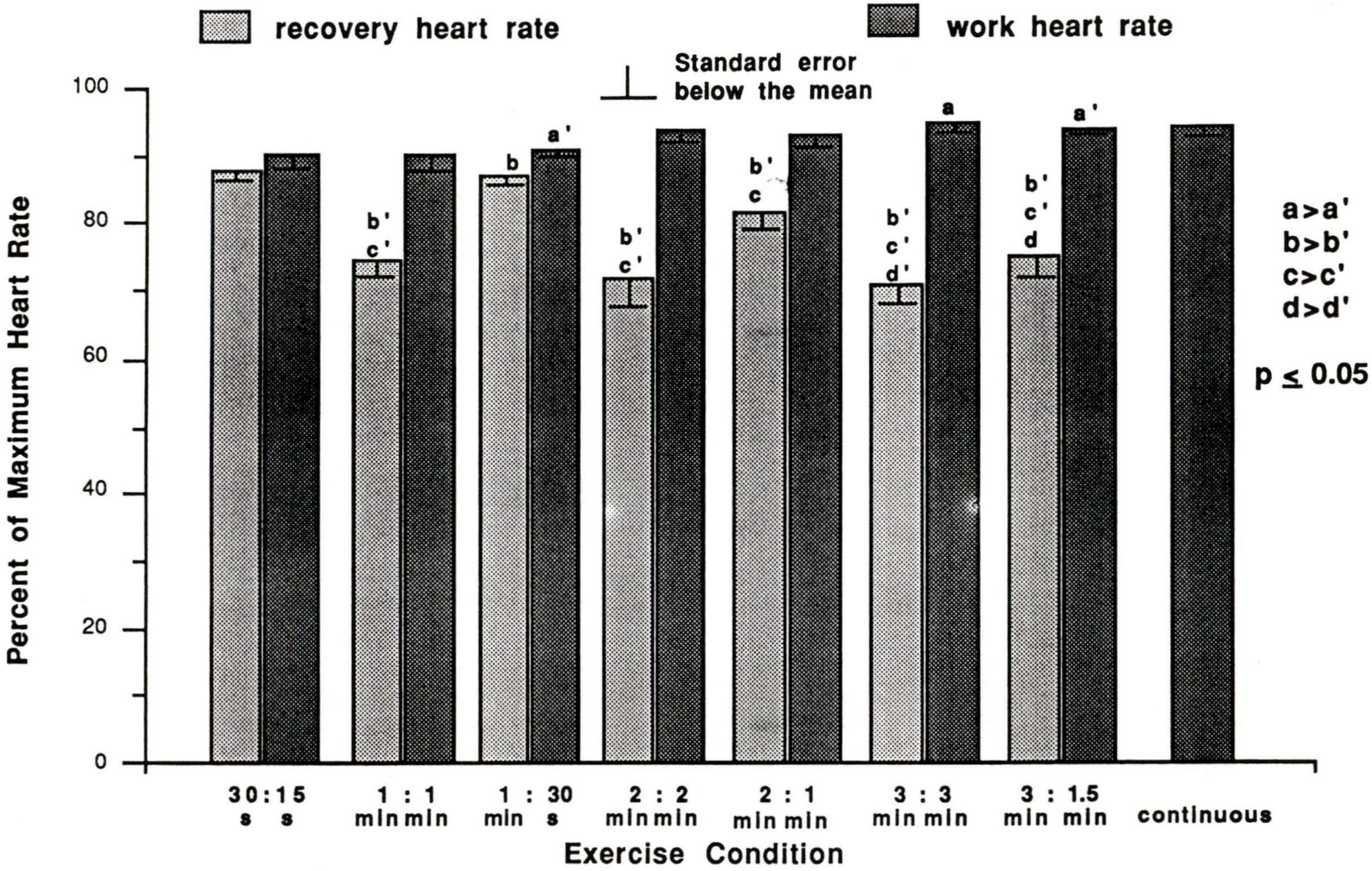

Figure 6. Work heart rate and recovery heart rate during the exercise conditions

DISCUSSION

The mean Total Work Time (TWT) was 8.4 minutes (min) for continuous exercise at VO_{2max} intensity on the rowing ergometer. This was similar to the 9 min on a cycle ergometer observed by Astrand and co-workers (1960a). The continuous TWT was greater than the mean of 3.8 min reported by Lavoie and Mercer (1987) for trained female rowers (mean VO_{2max} of 61.4 $ml \cdot kg^{-1} \cdot min^{-1}$) on a cycle ergometer at $VO_{2max}PO$ but the subjects in the present study tested on the more training specific rowing ergometer and this may have produced the greater TWT. Although Higgs (1973) reported a mean of 4.6 min of continuous running on a treadmill at the workload that elicited VO_{2max}, the higher mean VO_{2max} of the trained female rowers in the present study (48.8 $ml \cdot kg^{-1} \cdot min^{-1}$) compared to that of the female physical education majors (41.3 $ml \cdot kg^{-1} \cdot min^{-1}$) tested by Higgs probably extended the work time. Differences in termination criteria make comparisons difficult. Only Lavoie and Mercer (1987) described the ending criteria. Subjects worked at 60 revolutions per min and stopped when the pedalling cadence remained at 4 revolutions per 5 seconds(s) for 3 consecutive 5 s readings.

At the onset of work, energy demands are met by the intramuscular stores of adenosine triphosphate (ATP) and creatine phosphate (CP). However, these sources cannot maintain high intensity work for longer than approximately 20 s (Green, 1982) so continuation of high intensity work necessitates the anaerobic and aerobic breakdown of glycogen. Lactate and H^+ accumulate and the resultant drop in pH contributes to fatigue (Sahlin, 1983; Wenger and Reed, 1976).

The introduction of any interval protocol significantly increased TWT in comparison to the continuous effort (Figure 2), indicating that the recovery intervals may allow for at least partial repletion of ATP and CP stores and the removal and/or metabolism of accumulated lactate and H^+. Hultman and colleagues (1967) showed that phosphagen restoration is 70% complete within 30 s. It has been suggested that muscle myoglobin plays an important role in maintaining oxygen consumption in working muscle (Astrand et al., 1960b; Cole, 1982) and recovery periods may allow for the oxygenation of the myoglobin since turnover of oxygen in myoglobin is very rapid (Millikan, 1939). Therefore, a large proportion of short term energy requirements can be met by intramuscular phosphagens and oxymyoglobin so that maximal aerobic responses are not elicited with short intervals. When work intervals are lengthened, aerobic and anaerobic glycolysis provides an increasingly greater fraction of the ATP supplied to the working muscle so fatigue will occur sooner as muscle glycogen stores are depleted and H^+ accumulates. Therefore, as work intervals are lengthened, TWT should decrease. Astrand and associates (1960a) found that 30 min of work at $VO_{2max}PO$ could be completed with a 1min:1min session but 2min:2min and 3min:3min sessions meant a nearly maximal or maximal response and strong motivation was necessary to complete 30 min of work. The results of the present study showed a mean of 42 min of work can be completed with a 1:1 W:R protocol but only 26 and 22 min were completed with 2min:2min and 3min:3min protocols, respectively. The termination criteria was not described by Astrand and colleagues (1960a) but in the present study, work was stopped when the power output remained below 90% $VO_{2max}PO$ for 15 s. Perhaps the rigid termination criteria contributed to the difference in TWT between the studies.

When comparing 1:1 to 1:0.5 W:R ratios, TWT was significantly greater when using the 1:1 protocol for the 1 and 3 min intervals. The 1:0.5 W:R ratio allows less time for phosphagen repletion and for the removal and/or metabolism of lactate and H^+. Both 1 min interval conditions produced a higher TWT than the

30s:15s intervals, but this result can be explained by the 15 s rest periods providing only minimal recovery.

The 3 min intervals and the continuous exercise provided the greatest TVO_2MAX (Figure 3) as VO_{2max} was reached and maintained with these conditions but TWT was decreased as lactate and H^+ accumulated, evidenced by the higher PELACTATE in these protocols. The resultant lowering of the muscle pH would enhance the unloading of oxygen at the working muscle due to the Bohr effect (Smith and Kampine, 1984), thus enhancing the attainment of VO_{2max}. The 2 min intervals elicited a lower TVO_2MAX as VO_{2max} could be achieved but not maintained for extended periods with 2 min of work. In the present investigation, during repeated intervals, approximately 1 min of high intensity work was required before VO_2 was within 0.1 $l \cdot min^{-1}$ of VO_{2max}. The time required to attain VO_{2max} would explain the minimal TVO_2MAX values for the 30s:15s, 1min:1min and 1min:30s sessions. It should be noted that methodological limitations can exist when determining oxygen consumption during intermittent work. When measured with the fastest methods to determine pulmonary oxygen uptake, oxygen consumption is always delayed in comparison to the actual turnover in the working muscle because of circulatory time and diffusion velocities. The delay may be several s (Saltin et al., 1976). Astrand and co-workers (1960a) demonstrated that VO_{2max} could be reached in 3 min intervals, but the highest VO_2 attained in the last 30 s of repeated 2 and 1 min intervals were 96% and 64% of VO_{2max}, respectively. Mahler and colleagues (1984) demonstrated that elite rowers can reach VO_{2max} within 1 min and maintain that VO_2 for the duration of a 6 min all-out test, while Astrand and Saltin (1961) showed that with very heavy exercise, trained subjects can reach VO_{2max} in approximately 2 min. Horvath and Michael (1970) found that continuous work at $VO_{2max}PO$ produced higher VO_2 than an incremental VO_{2max} test while Lavoie and Mercer (1987) showed that VO_{2max} was not attained during continuous effort at $VO_{2max}PO$ maintained for a mean of 3.8 min. The subjects studied by Lavoie and Mercer (1987) may not have reached VO_{2max} because 3.8 min at $VO_{2max}PO$ may not be sufficient time to allow for a maximal aerobic response, as continuous exercise at $VO_{2max}PO$ in the present study elicited VO_{2max} at about 4.2 min of work. Repeated intervals maintain a higher muscle temperature, pCO_2 and H^+ concentration to enhance oxygen unloading which should permit VO_{2max} to be reached sooner.

The continuous exercise elicited the highest Average Work VO_2 ($AVEVO_2$) (Figure 4) as VO_{2max} was maintained for half of the work duration. The $AVEVO_2$ of the 3 min conditions was the highest of the intervals because more time was spent working at VO_{2max}. The 1 min work intervals in this study provided almost no time at which VO_{2max} was measured but the $AVEVO_2$ in the 1min:30s session was not significantly different from that of the 2 min protocols because the 30 s recovery did not give sufficient time for ATP-CP repletion or for aerobic metabolism to slow, so the VO_2 between work periods was not markedly reduced. This would also explain the high $AVEVO_2$ for the 30s:15s session. With short work and recovery periods, the oscillations in VO_2 are decreased (Saltin et al., 1976) so that the physiological response is similar to that of continuous work at a lower intensity (Saltin and Essen, 1971; Edgerton et al., 1975). Saltin and co-workers (1976) suggested a possible control mechanism for substrate utilization with short work intervals of high intensity. The high energy phosphagens are consumed during work leading to stimulation of glycolysis and Krebs cycle activity but during recovery ATP and CP are resynthesized so glycolysis, Krebs cycle and oxidative phosphorylation are retarded. Early in recovery when Krebs cycle activity is still high, citrate level is low but as Krebs cycle is slowed, citrate will accumulate. The citrate will penetrate the mitochondrial membrane and inhibit both phosphofructokinase and pyruvate dehydrogenase in the cytosol, thus inhibiting glycolysis.

The sessions with the higher AVEVO$_2$ also had the higher PELACTATE (Figure 5) as the anaerobic lactic system provides energy for work, lowering the muscle pH and enhancing the unloading of oxygen at the working muscle due to the Bohr effect (Astrand and Saltin, 1961). The contribution of anaerobic glycolysis was evident in continuous exercise as the highest PELACTATE (13.7 $mmol \cdot l^{-1}$) was observed which was lower than the 16.7 $mmol \cdot l^{-1}$ recorded by Astrand and associates (1960a). The difference in post exercise blood lactates could be related to sampling time since blood samples were extracted immediately after exercise in the work of Astrand and co-workers (1960a) and 2 min post exercise in the present study. The 2 min may allow for delivery of lactate to sites such as skeletal muscle, heart, and liver to be metabolized so that blood lactate levels would decrease. The 30s:15s and 1min:1min sessions were the only sessions in which PELACTATE was significantly greater than RLACTATE. The low RLACTATE with these short intervals may be explained by the substrate utilization control mechanism proposed by Saltin and colleagues (1976). The PELACTATE was higher because ATP-CP is not 100% resynthesized until about 3-5 min (Hultman et al., 1967; Harris et al., 1976) so that both anaerobic and aerobic glycolysis played a greater role in energy supply as the sessions progressed because ATP-CP stores became less repleted after recovery. Also, ATP and CP concentrations are reduced in relation to the metabolic activity in the cell (Karlsson et al., 1971) and metabolic rates were high even during recovery. Another factor could be that any decrease in pH favors a shift to the right in the reaction

Creatine Phosphate <----> Creatine + Phosphate

(Harris et al., 1976) so during recovery, repletion of CP is limited as muscle pH levels decrease with work. RLACTATE increased with the longer intervals as anaerobic glycolysis played a significant role in energy production in the initial intervals (Figure 5). Blood lactate then plateaued as PELACTATE was not significantly greater than RLACTATE in the longer intervals. This finding would agree with the results of others that showed that blood lactate tends to level off after 5 to 10 min of intermittent exercise (Christensen et al., 1960; Essen et al., 1976; Saltin et al., 1976).

Saltin and colleagues (1976) report that heart rate is closely related to the oxygen uptake in intermittent as well as continuous exercise. The results of the present study may not support this as the only significant differences in the WHR were that the 3min:3min session was greater than both the 3min:1.5min and 30s:15s (Figure 6). Caution must be exercised in comparing WHR with AVEVO$_2$ in the present study because AVEVO$_2$ is the mean VO$_2$ of all work while WHR is the mean of heart rates at the end of each work interval. However, the 1min:1min session had an AVEVO$_2$ of only 70%, TVO$_2$MAX of only 0.3 min and a WHR of 90.7% while the 3min:3min session had an AVEVO$_2$ of 85.3%, TVO$_2$MAX of 5.4 min and a WHR of 95.2%. The difference in end heart rate was only about 5% of maximum heart rate, suggesting that heart rates at the end of work intervals may not be accurate indicators of oxygen consumption during work. High WHR may be caused by increased sympathetic drive due to increases in blood temperature, pCO$_2$ and H$^+$ concentration (Smith and Kampine, 1984).

Heart rates at the end of recovery seem to indicate that the length of recovery is more important in allowing recovery than the length of the work interval. The 30s:15s RHR was the highest and the RHR of the 1min:30s session was significantly higher than all other interval sessions even though AVEVO$_2$ was not as high as other sessions. With short work and recovery intervals, the variations in work and recovery VO_2 are reduced (Saltin et al., 1976). Aerobic metabolism did not slow significantly with short recoveries so the demand for oxygen in the working muscles was not greatly reduced. Therefore, heart rates remained high to ensure that oxygenated blood was delivered to the working muscles. When comparing 1:1 to 1:0.5 W:R ratios, RHR was significantly higher in the 1:0.5 sessions. The shorter recovery did not provide adequate time for phosphagen repletion or for aerobic metabolism to slow, so heart rates decreased only as oxygen demands in the working muscles were reduced.

The continuous and both 3 min designs provided the greatest TVO_2MAX. The 3min:3min intervals were not significantly different from the 3min:1.5min and continuous sessions in TVO_2MAX but the 3min:3min protocol provided the greatest TWT of these 3 sessions. Therefore, of the protocols studied, the 3min:3min design would be the optimal work session for reaching and maintaining high aerobic power levels when working at 90-100% $VO_{2max}PO$. The 1min:1min TWT was the greatest of all sessions and would therefore elicit the highest caloric expenditure. Thus the 1min:1min intervals at 90-100% $VO_{2max}PO$ would be the interval session best suited for high caloric expenditure of the protocols studied.

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Appendix A

PHYSIOLOGICAL PARAMETERS DURING THE EXERCISE CONDITIONS

Physiological Parameters During the Exercise Conditions

Condition	TWT (min)	AVEVO_2 (%VO_2max)	TVO_2MAX (min)	PELACTATE (mmol·l^{-1})	RLACTATE (mmol·l^{-1})	WHR (% HRmax)	RHR (% HRmax)
30s:15s	20.7±0.9	78.3±1.9	0.2±0.2	6.1±0.7	3.3±0.6 (n = 7)	90.3±1.2 (n = 3)	87.7±1.3 (n = 3)
1min:1min	41.6±4.8	70.0±1.7	0.3±0.3	6.7±1.2 (n = 7)	4.1±1.1 (n = 5)	90.7±1.5 (n = 7)	74.9±2.3 (n = 7)
1min:30s	28.9±3.2	78.5±1.5	0.0	7.3±0.9	4.5±0.4 (n = 5)	91.7±0.8 (n = 6)	87.2±0.9 (n = 6)
2min:2min	25.9±3.7	78.3±2.1	1.5±0.7	7.5±1.2 (n = 6)	6.7±1.1 (n = 6)	93.5±0.9 (n = 6)	72.0±3.2 (n = 6)
2min:1min	19.2±2.8	79.4±1.9	1.3±0.8	9.8±1.2 (n = 5)	8.1±0.4 (n = 6)	93.3±1.0 (n = 7)	81.7±2.2 (n = 6)
3min:3min	22.0±3.0	85.3±0.9	5.4±1.3	10.3±1.0 (n = 5)	8.2±0.8 (n = 6)	95.2±0.7 (n = 6)	70.5±2.0 (n = 6)
3min:1.5min	17.6±1.9	84.4±2.2	3.1±1.0	11.6±1.1	9.0±0.5 (n = 7)	93.4±0.4	75.0±2.1 (n = 7)
Continuous	8.4±0.7	94.0±0.5	4.2±0.6	13.7±1.1	——	94.1±1.0 (n = 7)	——

Note. mean ± SE. n = 8 unless specified otherwise

Appendix B

INFORMED CONSENT FOR RESEARCH ON THE EFFECT OF DIFFERENT WORK INTERVAL DURATIONS AND WORK:RECOVERY RATIOS ON OXYGEN CONSUMPTION, BLOOD LACTATE AND HEART RATE DURING EXERCISE

INFORMED CONSENT

Purpose: To investigate the effects of different work interval protocols on the metabolic response to exercise.

Procedure: You will be asked to perform ten exercise tests over the course of ten weeks. The first test will be a VO_{2max} test. All subsequent tests will be performed at the intensity that elicited VO_{2max}. One test will be continuous, lasting for approximately ten minutes, and eight tests will be performed as intermittent exercise, lasting for approximately one hour.

Risk: Blood samples obtained by venupuncture will be performed by a qualified nurse, and finger prick blood samples will be taken by an experienced technician. Both procedures are considered safe with little risk of complication although with any laceration there is some risk of infection.

Consent: I have read the above and agree to participate in this research project at my own risk. I am nineteen years of age or older and regularly take part in strenuous physical activity at least as intense as these tests. I realize that I may expect a thorough explanation and/or demonstration of any procedures and that I may terminate participation at any time in any or all procedures of my own volition.

Having voluntarily assumed participation and risks thereof in the project, I hereby disclaim and release the University of Victoria, its agents, servants or employees, including all personnel involved in the research project, from any and all liability that might otherwise arise as a result of my participation as a research subject in this study.

Name:________________________________Date:________________________

Signature:____

Appendix C

REVIEW OF LITERATURE

REVIEW OF LITERATURE

The Energy Production Systems

Three distinct energy systems in skeletal muscle are integrated to supply chemical energy for muscular contraction during work. This energy is released through the hydrolysis of adenosine triphosphate (ATP). The intensity and duration of the activity determines the relative input of each system in meeting the energy demands of the working muscle (MacDougall et al., 1982).

During high intensity work of short duration, two anaerobic energy systems supply the muscle with ATP. The anaerobic alactic system utilizes immediate muscle stores of ATP as well as resynthesizing ATP from energy released by the breakdown of creatine phosphate (CP) to creatine (Cr) and inorganic phosphate (P_i). Two reactions are involved (Hultman and Sjoholm, 1983):

$$\text{ATP} \longleftrightarrow \text{ADP} + P_i + \text{energy}$$

$$\text{ADP} + \text{CP} \longleftrightarrow \text{ATP} + \text{Cr}$$

This system produces energy at a very high rate but a low capacity allows for only about 20 seconds (s) of high intensity work (Green, 1982).

The anaerobic lactic system can supply energy for high intensity exercise for about 90 s at approximately one-half of the rate of the anaerobic alactic system (Fox and Mathews, 1981), as glycogen and/or glucose are broken down to release energy via anaerobic glycolysis. Lactic acid is produced, which dissociates to lactate and hydrogen ions (H^+). The summary equation of this system is (Hultman and Sjoholm, 1983):

$$\text{ADP} + \text{glucose (glycogen)} \longleftrightarrow \text{ATP} + \text{lactate} + H^+$$

Lactic acid dissociates to lactate and H^+, which at fatigue can cause muscle pH to decrease by 0.5 pH units from resting levels (Sahlin, 1983). The increased H^+ concentration reduces muscle energy production by inhibiting PFK activity (Sahlin, 1983; Wenger and Reed, 1976), phosphorylase activation (Sahlin, 1983), and free fatty acid mobilization (Sahlin, 1983; Wenger and Reed, 1976). Muscle force generation is also negatively affected as H^+ competes with calcium for binding sites on troponin (Wenger and Reed, 1976), calcium release from the sarcoplasmic reticulum is inhibited (Sahlin, 1983), the cell becomes hyperpolarized (Wenger and Reed, 1976), and myosine ATP-ase activity is decreased (Sahlin, 1983). Thus the impaired energy production and force generation of muscle will result in fatigue.

During activity of low to moderate intensity and long duration, the aerobic system is almost solely utilized for energy production (Wenger and Reed, 1976). Also, as high intensity exercise increases in duration, the aerobic system is called upon to supply energy to the muscle. Oxygen is used in the process of converting carbohydrates, fats and sometimes proteins to energy through Krebs cycle and the electron transport system in the mitochondria. The by-products of this system are carbon dioxide (CO_2) and water (H_2O). This system is condensed by the following equation (Hultman and Sjoholm, 1983):

$$\text{ADP} + O_2 + \text{substrate} \text{ <-----> } \text{ATP} + CO_2 + H_2O$$

Aerobic Power

In maximal activities that last longer than approximately 2 1/2 minutes(min), the aerobic energy system produces most of the energy (Gollnick and Hermansen, 1973). Endurance performance is directly related to maximal aerobic power (Costill et al., 1973; Karlsson and Saltin, 1971; Secher et al., 1982) which is measured by maximal oxygen consumption (VO_{2max}), or the greatest rate at which oxygen can be taken into the body, then transported to and utilized by the working muscles. VO_{2max} is considered the criterion measure of aerobic power (deVries, 1980; MacDougall et al., 1982; Golden and Vaccaro, 1984).

Training for Aerobic Power

Aerobic power can be improved with training (Fox et al., 1973; Henriksson and Reitman, 1976; Pederson and Jorgenson, 1978; Poole and Gaesser, 1985). A system must be repeatedly exposed to stress in order to elicit a training adaptation, and it is believed that the stress necessary to tax the aerobic energy system is hypoxia, because adaptations to chronic exposure to high altitude are similar to those elicited from an endurance training program (MacDougall and Sale, 1981). Acclimatization to prolonged high altitude exposure includes the following increases: muscle capillary density (Cassin et al., 1966), muscle myoglobin (Reynafarje, 1962), and aerobic enzyme activity in muscle (Reynafarje, 1962), while endurance training also enhances capillary density (Andersen, 1975; Andersen and Henriksson, 1977; Klausen et al., 1981), muscle myoglobin (Pattengale and Holloszy, 1967), and aerobic enzyme activity (Gollnick et al., 1973; Henriksson and Reitman, 1977). If during endurance training the working muscles are forced to perform without an adequate oxygen supply, simulated high altitude exposure is causing adaptations to occur in the oxygen transport system. A high degree of hypoxia is experienced when workloads are at 100% VO_{2max} intensity, but intensities exceeding this level do not produce much more hypoxia (MacDougall and Sale, 1981). Therefore, working at 100% VO_{2max} should elicit the greatest training adaptations in aerobic power because work intensities greater than VO_{2max} intensity will hasten the onset of fatigue and decrease training duration. Wenger and Bell (1986) found that 90 - 100% VO_{2max} workloads are most effective for increasing VO_{2max}. Training intensity must be high to enhance the oxidative potential of fast twitch (FT) motor units because FT motor units are not recruited at intensities that are less than about 90% VO_{2max} (Gollnick et al., 1974). Research performed with rats has shown that fast twitch white (FTW) motor units are recruited at high intensity workloads and the adaptive response in FTW muscle fibers only occurs with high intensity training (Dudley et al., 1982; Harms and Hickson, 1983; Terjung, 1976), and Henriksson and Reitman (1976) found that changes in human FT succinate dehydrogenase (an aerobic enzyme) are significant only after a high intensity interval training program as opposed to a low intensity continuous program.

Duration is also an important component of a training program, as a training stimulus must be applied long enough to warrant adaptations. Wenger and Bell (1986) suggest that an optimal combination of training intensity and duration is to train at 90 - 100% VO_{2max} intensity for 35 - 45 min, but this work must be performed intermittently because continuous work at VO_{2max} intensity can only be maintained for about 9 min before fatigue forces the activity to cease (Astrand et al., 1960a). Horvath and Michael (1970) found that continuous work at VO_{2max} power output ($VO_{2max}PO$) produced a higher VO_2 than an incremental VO_{2max} test. Lavoie and Mercer (1987) showed that VO_{2max} was not reached during continuous effort at $VO_{2max}PO$ maintained for a mean of 3.8 min by trained female rowers on a cycle ergometer but working on a rowing ergometer which was more specific to their training might have produced different results. The subjects tested by Lavoie and Mercer (1987) pedalled at 60 revolutions per min at were stopped when cadence was 4 revolutions per 5 s for 3 consecutive 5 s readings. A mean of 4.6 min of continuous running at VO_{2max} intensity by female education majors on a treadmill was observed by Higgs (1973), but termination criteria was not reported. Continuous high intensity work is accompanied by a high degree of glycogen depletion and lactate accumulation and a major dependence upon carbohydrates for oxidative energy production (Pruett, 1970; Saltin and Karlsson, 1971).

Intermittent Exercise

More high intensity work may be performed by introducing rest periods between periods of work. Astrand et al.(1960a) found that 30 min of VO_{2max} intensity work can be completed in separate experiments using interval lengths of 30 s, 1, 2, and 3 min with a 1:1 work:rest ratio. They also discovered that with 30 s intervals, the cardiorespiratory system is not substantially taxed as VO_2 is only 64% of VO_{2max}, heart rate is 150 beats per min (bpm), and blood lactate is 2.2 $mmol \cdot l^{-1}$. Work by other researchers also shows that when high intensity activity is split into intervals of 30 s duration or less, the metabolic responses are not maximal (Christensen et al., 1960; Edwards et al., 1973; Essen, 1978; Essen et al., 1977; Saltin and Essen, 1971), as glycogen depletion and lactate accumulation are decreased (Essen, 1978; Essen et al., 1977; Saltin and Essen, 1971), and fat utilization is increased, (as indicated by a lower respiratory exchange ratio) (Christensen et al., 1960), suggesting that anaerobic glycolysis does not play a major role in energy production under these conditions. Essen (1978) found that the smaller glycogen depletion in intermittent intense exercise is not due to a different muscle fiber recruitment pattern as both ST and FT fibers show glycogen breakdown, indicating that work intensity is a key factor in FT fiber recruitment. It has been suggested that the maximal loads do not elicit a maximal aerobic response when performed over short intervals because muscle myoglobin acts as an oxygen store so that the oxygen supply to mitochrondria in working muscles is adequate (Astrand et al., 1960b; Cole, 1982) and there is enough intramuscular high energy phosphates (ATP and CP) to meet the energy demands of the muscle for approximately 20 s (Green, 1982). Both of these energy sources can be replenished during the rest periods, but in continuous exercise there is no replenishment of myoglobin oxygen or ATP-CP stores so anaerobic glycolysis is used to supply the metabolic needs of the working muscle. Saltin and colleagues (1976) suggested that regulatory mechanisms govern substrate utilization during intermittent exercise. With each work period in intense intermittent work, ATP-CP stores are consumed leading to stimulation of glycolysis and Krebs cycle activity. During rest periods ATP and CP are resynthesized, retarding glycolysis and Krebs cycle activity. Krebs cycle activity is still high in the early stages of the rest period so citrate levels are low but as Krebs cycle slows citrate will accumulate because acetyl-CoA is still produced from fatty acid oxidation. The excess citrate will diffuse from the mitochondria to the cytoplasm and inhibit phosphofructokinase and pyruvate dehydrogenase, thus inhibiting glycolysis.

Increasing work interval lengths necessitates the use of anaerobic glycolysis for energy production because oxygen stores of myoglobin and ATP-CP levels are depleted, taxing anaerobic and aerobic energy systems more, evident by increased blood lactates and higher VO_2 (Astrand et al., 1960a). One min loads at VO_{2max} intensity produced a heart rate of 167 bpm, VO_2 at 64% VO_{2max}, and blood lactate of 5.0 $mmol \cdot l^{-1}$; two min loads elicited heart rates of 178 bpm, VO_2 of 96% VO_{2max}, and blood lactate of 10.6 $mmol \cdot l^{-1}$; intervals of 3 min duration produce the most hypoxia as VO_{2max} is reached, heart rate was 188 bpm, and blood lactate reached 13.3 $mmol \cdot l^{-1}$, but still less than 16.7 $mmol \cdot l^{-1}$, which is the blood lactate after 9 min of continuous work (Astrand et al., 1960a). In all of these interval experiments 30 min of high intensity work can be completed. From these data, it can be suggested that intervals should be at least 2 min in length to provide close to maximal stress on the aerobic energy system, with peak hypoxia reached during 3 min loads. Astrand and Saltin (1961) found that trained subjects could reach VO_{2max} within 2 min during very heavy exercise while Mahler and associates (1984) demonstrated that elite rowers could attain VO_{2max} within 1 min and maintain that VO_2 for the duration of a 6 min all-out test.

Measuring Oxygen Consumption

When measuring VO_2 it should be known that problems can exist because of the lag between the actual turnover of oxygen in the working muscle and pulmonary oxygen uptake due to circulatory time and diffusion velocities. Therefore, the fastest methods of determining pulmonary oxygen uptake will always involve a delay of up to several s when compared to the actual oxygen utilization in the working muscle (Saltin et al., 1976).

Oxygen Consumption With Rowing Ergometers and a Single Scull

Chenier and Leger (1986) compared oxygen consumption during VO_{2max} tests on Concept II and Gjessing rowing ergometers and oxygen consumption during 3 4-min all out single scull trials on water. 7 male and 7 female regional and national rowers were tested. Pearson correlation results were as follows: 0.92 (Concept II vs Gjessing), 0.93 (Gjessing vs Scull) and 0.96 (Concept II vs Scull). It was determined that VO_2 peak attained on the rowing ergometers was specific and similar to the one achieved in sculling on the water.

Metabolism and/or Removal of Lactate and H^+

Blood lactate levels rise with increasing duration of work intervals as anaerobic glycolysis is supplying the energy for a significant number of motor units as they work at intensities approaching VO_{2max} (Nagle et al., 1970). A decrease in muscle pH is necessary to attain VO_{2max}, as the increased H^+ concentration enhances the unloading of oxygen at the working muscle due to the Bohr effect (Smith and Kampine, 1985). In order to continue performing high intensity work intervals, muscle must buffer an/or release H^+ into the blood. Muscle pH at fatigue can drop to 6.60 from a resting value of 7.08 (Sahlin, 1983), but the p should be 1.5 if the H^+ concentration is added to an unbuffered solution (Hultman and Sahlin, 1980). H^+ can be buffered in the muscle, with the major buffers being bicarbonate ions, phosphate ions, proteins, and creatine phosphate, or H^+ can be removed and buffered by the blood (Sahlin, 1978). Hermansen and Osnes (1972) observed that blood pH decreases from 7.42 at rest to 7.11 after 5 maximal work loads of 40-60 s with rest periods of 4 min in between. The main buffer systems of the blood are proteins (hemoglobin and plasma proteins), bicarbonate ions, and phosphate ions (Shepherd, 1984).

The increased intramuscular lactate and H^+ may be the stimulus for enhancing H^+ buffering and removal, as elite anaerobic athletes have a higher muscle buffering capacity than aerobic athletes (McKenzie et al., 1983). Sharp et al. (1983) found that endurance trained athletes do not differ from untrained individuals in blood buffering capacity and suggested that endurance athletes have trained their systems to delay lactic acid accumulation as long as possible rather than adapting with buffers. Bell and Wenger (1986) showed that a sprint training program at 150% of VO_{2max} power output will enhance intramuscular buffering capacity. Working at intensities approaching VO_{2max} will result in lactate accumulation (Nagle et al., 1970), so interval training at VO_{2max} intensities may enhance lactic acid tolerance and/or removal.

Removal of lactate and H^+ from muscle during recovery intervals is crucial because of the effects of accumulated H^+ (Belcastro and Bonen, 1975; Boileau et al., 1983; Dodd et al.,1984). Research indicates that an active recovery is more effective in the removal of lactate than passive recovery (Belcastro and Bonen, 1975; Boileau et al., 1983; Dodd et al.,1984; Gisolfi et al., 1966; Koutedakis and Sharp, 1985; McGrail et al., 1978; Weltham et al., 1979). Blood flow is higher to muscle during exercise, so exercising during recovery can enhance delivery of lactate to sites such as skeletal muscle, heart, and liver to be metabolized. Blood lactate removal rates are optimal at intensities between 30 - 40% VO_{2max} when cycling or running (Belcastro and Bonen, 1975; Boileau et al., 1983) and at 40% maximum rowing speed when rowing (Koutedakis and Sharp, 1985). These recovery data are based on blood lactates, which may not accurately indicate muscle lactate levels, since at a given blood lactate level, lactate turnover may be 2 to 4 times greater during exercise than during rest (Mazzeo et al., 1986). However, data from Saltin and Essen (1971) shows that concentrations of blood and muscle lactate may not be similar but the patterns of change in blood and muscle lactate are similar so blood lactates can be used to indicate what is happening within the muscle.

Phosphagen Repletion

An active recovery will impede ATP and CP repletion because the energy for ATP-CP replenishment is provided by the aerobic energy system (Piiper and Spiller, 1970) and this process occurs during rest since muscle contraction involves the splitting of ATP. ATP-CP stores can be 70% repaid in 30 s (Hultman et al., 1967), but Saltin and Essen (1971) found that ATP-CP replenishment during 20 s rest intervals is quantitatively insignificant, necessitating recovery to be at least 30 s in length in order to recover some ATP-CP stores. However, repletion of phosphagens during pauses between work intervals may be decreased because ATP-CP concentrations are reduced in relation to the metabolic activity in the cell (Karlsson et al., 1971) and metabolic rates are high even during recovery. Also, any decrease in pH causes a shift to the right in the reaction

Creatine Phosphate <----> Creatine + Phosphate

(Harris et al., 1976) so that repletion of CP is reduced if the work intervals cause a drop in intramuscular pH.

It would appear that recovery intervals should involve both active and passive periods so that lactate can be removed and ATP-CP levels are increased because without phosphagen repletion, the energy demand upon the anaerobic lactic system will increase which will lead to a greater H^+ accumulation and glycogen depletion, hastening the onset of fatigue.

Summary

In summary, maximal aerobic power is an important component of endurance performance and is most rapidly improved by working at the intensity that demands VO_{2max}. The duration of continuous work at this intensity will not produce optimal training adaptations in aerobic power, so intermittent work must be utilized. High intensity intervals can also result in lactate accumulation which may be the stimulus for enhanced lactate and H^+ buffering and/or removal. An active recovery phase will enhance the removal and/or metabolism of accumulated lactate in the working muscle while a passive recovery phase may allow for the repletion of intramuscular phosphagens. Varied duration of work intervals at VO_{2max} intensity will result in different metabolic responses, as different degrees of hypoxia and lactate accumulation are experienced. It is not known how varied work interval lengths and W:R ratios will affect the degree and total amount of stress that can be placed upon the aerobic system and the mechanisms that deal with increased intramuscular levels of lactate and H^+.

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