Cardiorespiratory and Lactate Responses to A 1-hour Submaximal Running at the Lactate Threshold

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Cardiorespiratory and blood lactate (La) responses to prolonged submaximal running at an intensity relative to lactate threshold (LT) were examined in 15 recreational runners, aged 19 to 32. In test 1 where treadmill speed was progressively incremented by 10-20m/min until exhaustion, oxygen uptake at the LT ($\dot{V}O_2$ @ LT: 2.34 ± 0.33 l/min or 41.6 ± 5.7 ml/kg/min) and $\dot{V}O_{2\max}$ (3.58 ± 0.34 l/min or 63.6 ± 5.5 ml/kg/min) were measured. In test 2, the subject was required to run on the treadmill for 1 hour at a fixed velocity (V_t) which corresponded to his V_t @LT. As expected, mean $\dot{V}O_2$ ranged during the 1-h submaximal running from 2.31 ± 0.41 l/min or $63.0 \pm 7.8\%$ $\dot{V}O_{2\max}$ at min 10-20 to 2.52 ± 0.35 l/min or $69.2 \pm 6.2\%$ $\dot{V}O_{2\max}$ at min 50-60, both of which were close to $\dot{V}O_2$ @LT ($65.2 \pm 4.4\%$ $\dot{V}O_{2\max}$). The slight decrease in blood La was found from min 20 to min 60, and this was accompanied by a parallel decline in respiratory exchange ratio. Shifts in the energy substrate toward a reliance on fat oxidation may occur during the course of 1-h running at V_t @LT. The small oxygen debt observed after the 1-h running may confirm the assumption that prolonged running at V_t @LT would be performed in an almost fully aerobic steady state. We conclude that prolonged running at V_t @LT may possibly maximize health-related benefits in the healthy adult.

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Moderately trained individuals are able to exercise for about 1 hour with an oxygen uptake ($\dot{V}O_2$) up to approximately 50% of their maximal aerobic power ($\dot{V}O_{2\max}$), maintaining the $\dot{V}O_2$ and many other circulatory and respiratory events such as heart rate (HR), cardiac output, ventilatory volume ($\dot{V}E$) at approximately the same level as attained about 5 min after the onset of exercise (Astrand and Rodahl, 1986). When the duration of the exercise is further prolonged with the same intensity, however, there may be a progressive increase in $\dot{V}O_2$ and HR, and the individual would become more or less fatigued. With the above in mind, the 1990 ACSM Position Stand suggests that continuous aerobic exercise of 3-5d/wk, 50-85% of $\dot{V}O_{2\max}$ or HRmax reserve (or 60-90% of HRmax) and 20-60min/d is

necessary for developing and maintaining fitness for the healthy adult.

Highly trained individuals appear to maintain a steady state for hours even at a much higher relative exercise intensity than the 50% of $\dot{V}O_{2\max}$, indicating a more efficient O_2 transport and substrate utilization in their working muscles (Astrand et al., 1963; Costill, 1970; Costill and Fox, 1969; Davies and Thompson, 1979; Hedman, 1957; Maron et al., 1963; Tanaka et al., 1988a). Davies and Thompson (1979) have reported an estimated % $\dot{V}O_{2\max}$ of over 80% for elite nationally ranked British marathon runners. Most studies (Costill and Fox, 1969; Maron et al., 1976; Tanaka et al., 1988a) have suggested that trained marathon runners utilize 70-80% of their $\dot{V}O_{2\max}$ while running their

best race.

Very interestingly, the mean value (i.e. 75% of $\dot{V}O_{2\max}$) is nearly identical to $\dot{V}O_2$ at anaerobic threshold (AT) or lactate threshold (LT) (Farrell et al., 1979; Tanaka and Matsuura, 1984; Tanaka et al., 1988a). AT or LT has been found to show equal or greater associations with endurance performance than other physiological variables, including $\dot{V}O_{2\max}$ (Farrell et al., 1979; Kumagai et al., 1982; Tanaka et al., 1981; Tanaka and Matsuura, 1984; Yoshida, 1986; Yoshida et al., 1987). It denotes an exercise intensity or $\dot{V}O_2$ where the energy metabolism is just at a breakpoint between aerobic ATP production and anaerobic ATP production through lactate (La) formation (Sahlin, 1986). The importance of the AT concept may be that exercise above this threshold brings about a progressive loss of glycogen within the working muscle which will lead to muscle fatigue (Sahlin, 1986).

Previous studies involving marathon runners seem to have been limited to elite or well-trained competitors. It seems worthwhile to investigate the cardiorespiratory responses of non-elite or less experienced runners competing in a marathon event, since participation in marathon races is no longer restricted to highly experienced runners. Furthermore, not only cardiorespiratory and blood La responses to prolonged exercise at the LT level, but also the O_2 debt with the running, have not been well understood.

In view of the preceding discussion, the purposes of this study were (1) to determine the cardiorespiratory and blood La responses to a prolonged submaximal running at intensities relative to individual LT and the O_2 debt that may occur with the running, and (2) to discuss the significance of running (moderate intensity and longer duration) for health-related benefits. In the present study, the term LT is operationally defined as the treadmill running velocity (V_t), or $\dot{V}O_2$ corresponding to the point at which blood lactate concentration exhibits a systematic increase above a resting base-line value,

and hereafter is expressed as $V_t@LT$ and $\dot{V}O_{2@LT}$, respectively.

METHODS

1. Subjects. Fifteen male, recreational runners, aged 19-32, all of whom were in good health, volunteered to be subjects in this study. All runners were running on a regular basis (3-5d/wk) and some were training for endurance events such as 5km, 10km, and 20km runs. The training distance per week ranged from approximately 20km to 80km (mean=48km). All subjects were informed about the possible risks and discomfort involved with the participation in the study and gave informed consent to be studied. The physical characteristics of the subjects were as follows: age, 21.6 ± 3.5 yr (mean $\pm$ SD); stature, 170.1 ± 4.8 cm; weight, 56.3 ± 3.0 kg; and percent body fat estimated from skinfold thickness measurements, $10.8 \pm 1.1\%$.

2. Experimental protocol. Subjects performed two treadmill exercise tests, which were conducted at nearly the same time of day. The tests were separated by an interval of 4 to 6 days, while training programs remained virtually constant. These tests were made in November 1984, December 1985, and November 1987, in the Exercise Physiology and Sports Medicine Laboratories at Osaka City University.

In the first exercise test a progressive incremental protocol was used for the determination of the individuals' LT and $\dot{V}O_{2\max}$. Each of the subjects performed the test in which a series of six to seven different exercise bouts of 3-min duration each was administered. The use of 3-min duration has been reported previously (Kindermann et al., 1979; Kumagai et al., 1982; Tanaka and Matsuura, 1984). The initial treadmill velocity ranged from 140 to 210m/min according to subjects' running abilities, and this was progressively increased by 10-20m/min every 3.5 min until near maximal work. The exercise was interrupted for 30s for blood sampling after a completion of each 3-min exercise bout.

Ventilatory and gas exchange data utilized in analysis were those measured during the last 1 min of each exercise bout. Thereafter, the velocity was increased by 10-20m/min every minute until exhaustion (Tanaka and Matsuura, 1984).

In the second exercise test, each subject ran on a treadmill continuously for 1 hour at a fixed velocity which corresponded to his $\dot{V}_t@LT$. All subjects were able to complete the 1-h running test. Recovery gas and ventilation for determination of O_2 debt were measured for 15 minutes after the 1-h running in the sitting position. O_2 debt was defined as the amount of O_2 consumed ($\dot{V}O_2$) during recovery, above that which would have ordinarily been consumed at rest in the same time.

Mixed expired gas concentrations, $\dot{V}E$, and associated variables were measured every 30 s both in tests 1 and 2 with Mijnhardt Oxycon System (Tanaka et al., 1986a). These variables were calculated on line by a microcomputer involved in the system. Electrocardiograms were recorded continuously for measurement of heart rates (HR). Blood samples obtained 10-15 s after the subject completed each exercise bout were collected from the antecubital vein through an indwelling needle. All samples were analyzed for plasma lactate (La) concentration by enzymatic assay (lactate dehydrogenase) using NADH production. All assays were performed in a Hitachi spectrophotometric analyzer (Type 220).

A repeated-measures ANOVA design, with time as the repeated factor, was utilized to analyze the data. When an overall time effect was observed, the Newman-Keuls Significant Difference test was employed to locate significant pairwise differences. Statistical significance was established at the 0.05 level.

RESULTS

$\dot{V}O_2@LT$ and $\dot{V}O_{2max}$ of the subjects averaged 41.6 ± 5.6 ml/kg/min (range 32.9-50.4) and 63.6 ± 5.5 ml/kg/min (range 53.5-71.2), respectively. Other characteristics of the subjects measured in the 1st

Fig. 1 Mean changes in oxygen uptake during a 1-h treadmill run at the intensity relative to lactate threshold and oxygen debt after the run.

Fig. 2 Mean changes in ventilation and respiratory exchange ratio during a 1-h treadmill run at the intensity relative to lactate threshold.

exercise test were as follows: $HR@LT$, 151.1 ± 8.8 b/min; HR_{max} , 192.7 ± 5.4 b/min; $\dot{V}E@LT$, 64.2 ± 8.6 l/min; $\dot{V}E_{max}$, 132.4 ± 16.8 l/min; and maximal breathing frequency, 63.5 ± 5.4 .

Figs. 1, 2, and 3 illustrate that, during the 1-h submaximal running at individual $\dot{V}_t@LT$ (198.7 ± 27.7 m/min), such variables as $\dot{V}O_2$, $\dot{V}E$, and HR gradually but significantly increased with time. The average change in $\dot{V}E$ and HR from the 10th to the 60th min of exercise was only 2.5 l/min (or 4.4%) and 6.1 b/min (or 4.0%), respectively. The mean $\dot{V}O_2$ of 2.31 ± 0.41 l/min at min 10-20, 2.45 ± 0.32 l/min at min 30-40, and 2.52 ± 0.35 l/min at min 50-60 corresponded to $63.0 \pm 7.8\%$, $67.5 \pm 5.4\%$, and $69.2 \pm 6.2\%$ of $\dot{V}O_{2max}$ respectively, the first two of which did not differ significantly from $\% \dot{V}O_{2max}@LT$ ($65.2 \pm 4.4\%$). The average change in $\dot{V}E$ and HR

Fig. 3 Mean changes in blood lactate concentration and heart rate during a 1-h treadmill run at the intensity relative to lactate threshold.

from the 10th to the 60th min of exercise was 2.5 l/min (or 4.4%) and 6.1 b/min (or 4.0%), respectively. The highest mean La concentration of 18.8 ± 5.0 mg/dl was observed at min 20 of exercise (Fig. 3), and slightly decreased thereafter. The mean La of 15.2 ± 4.4 mg/dl significantly differed from the other mean La values. The slight decrease in La from the 20th min to the 60th min was accompanied by a parallel reduction in RER (Fig. 2). RER averaged 0.873 ± 0.039 at min 10-20, 0.844 ± 0.039 at min 30-40, and 0.824 ± 0.036 at min 50-60, all of which showed significant differences.

$\dot{V}O_2$ during recovery was approximately 0.77 ± 0.23 l/min (min 60-65), 0.43 ± 0.11 l/min (min 65-70), and 0.37 ± 0.11 l/min (min 70-75). Since mean $\dot{V}O_2$ at rest was 0.30 ± 0.04 l/min, the net O_2 debt (7.33 liters— 0.3 l/min $\times$ 15 min = 2.83 liters) during the 15 min recovery period was calculated to be only 2.83 liters or 0.19 l/min on the average.

DISCUSSION

Highly trained distance runners are usually characterized by a high level of $\dot{V}O_{2\max}$ and/or LT (Costill et al., 1973; Davies and Thompson, 1979; Pollock, 1977; Kuroda, 1973). $\dot{V}O_{2\max}$ and/or $\dot{V}O_2$ @LT of the runners used in the present study were substantially lower than those of previously studied average Japanese distance runners (Kumagai et al., 1982; Tanaka and Matsuura, 1984). Thus, the subjects in the present study were, as expected, consid-

ered less conditioned runners from both the aerobic power and distance running performance standpoints.

The 1-h running at V_t @LT elicited La concentrations in excess of only one and a half times the resting level. The slight but temporary rise of La above the resting level is considered to be a result from the transient increase of glycolytic turnover following an acute augmentation of muscular activity (Cerretelli et al., 1980). The relatively low level of blood La well agrees with our previous findings (Tanaka et al., 1988a). Relatively constant La levels observed during the 1-h running (Fig. 3) indicate that the rate of La production almost equaled its removal. Since a removal of La and pyruvate by oxidation and through gluconeogenesis is involved in the aerobic fraction of the whole body energy metabolism, the net contribution of anaerobic glycolysis for the energy release system can be considered insignificant when steady state levels in blood La are observed (Riberio et al., 1986). It should be remembered that gluconeogenesis is a primary source of glucose production, although the production of glucose via gluconeogenesis is not without cost to the body since the production of 1 mol of glucose from pyruvate requires the use of 6 mol of ATP.

Submaximal exercise RER values (usually between 0.7 and 1.0) indicate a mixed contribution of fat and carbohydrate to energy metabolism. It is important to note that the contribution of each substrate to total energy production is best estimated during steady state conditions where the respiratory exchange over the lungs accurately reflects tissue metabolism. Apparently steady state conditions for each 10 min observed in this study enable us to calculate changes in the contribution of each substrate during the 1-h running. However, the significant change in RER (i.e., -0.053 or -6.1%) from the min 10-20 to min 50-60 of exercise may indicate that the change in substrate utilization occurs during the submaximal exercise at individual

$V_t@LT$ (Fig. 2).

With the assumption that the nonprotein R (i.e., RER) reflects the combustion of only carbohydrate and fat, estimates of the metabolic mixture from the RER values imply that 58% of the energy demands was supplied by the oxidation of fat during the last 10 min of exercise, which is substantially higher than 42% calculated for minutes 10 to 20. The time between the onset of exercise and the existence of a significant rise in plasma free fatty acids has been known to be somewhere between 20 and 30 min. Thus, the slight but gradual rise of $\dot{V}O_2$ which was evident during the 1-h running at $V_t@LT$ (Fig. 1) may be accounted for by the increased utilization of free fatty acids in the muscle metabolism.

While glycogen can be used both anaerobically and aerobically, anaerobic use of glycogen results in an accumulation of La that lowers intramuscular pH due to a higher hydrogen ion concentration, a response that may interfere with a number of cellular processes, including continued energy production (Sahlin, 1978). Overall data obtained in this study suggest that (1) 1-h running at $V_t@LT$ can be performed under steady state conditions in aerobic energy metabolism, and that (2) some fluctuations in cardiorespiratory and blood La responses are due to a shift in a primary energy source predominantly from carbohydrates to fats.

Previous studies (Davies and Thompson, 1986; McLellan and Cass, 1989; Tanaka et al., 1986b; Tanaka et al., 1988a) have reported a gradual, but small rise in $\dot{V}O_2$ and $\dot{V}E$ during constant-load exercise similar to the protocol used in the present study. It is very likely that steady state cardiorespiratory responses do occur with some fluctuations during a 1-h run simulated at the LT pace, so that individuals can continue to run at the velocity relative to the LT for at least an hour. In addition, it has been found previously (McLellan and Cass, 1989) as was observed in the present study that a similar metabolic and cardiorespiratory response can be attained regardless of the level of $\dot{V}O_2@LT$. This

may be the major reason why the LT or AT has been recommended as a better reference standard to base submaximal exercise intensities.

As calculated previously, net O_2 debt (i.e., 2.83 liters) was found to be very small (Fig. 1). Assuming an RER of 0.96, it can be further calculated that only extra 14.15kcal ($RER=0.96=4.998$, or 5kcal per liter O_2 consumed; hence, $5kcal/liter \times 2.83liters = 14.15kcal$ or $0.94kcal/min$) was expended during the 15 min recovery period. In general, post-exercise heavy breathing and high $\dot{V}O_2$ are needed to remove CO_2 that has accumulated in the body tissues, and to pay the debt left from the use of ATP-PCr (phosphocreatine) and anaerobic glycolysis. The small O_2 debt observed in the present study substantiates the assumption that the 1-h running at $V_t@LT$ would be performed in an almost fully aerobic steady state.

One simple inquiry may be raised that endurance performance would be decreased even with the continuation of such relatively low intensity of exercise as LT. However, a previous study has shown increases not only of $\dot{V}O_2@LT$ and $\dot{V}O_{2max}$ but also of endurance running performances after the addition of a 60-to 90-min LT level running to regular intensive training (Tanaka et al., 1986c). Additionally, from two studies that have examined the effects of exercise intensity on selected measurements of skeletal muscle aerobic metabolism (Dohm et al., 1977; Harms and Hickson, 1983), it is suggested that the ability to perform prolonged endurance exercise would be maintained or even be enhanced with the LT level training. Dohm et al. (1977) have found that training at the lowest intensity elicits a significant increase in muscle oxidative capacity and that this adaptation is not further enhanced by increasing the training intensity. Moreover, the training adaptation in muscle succinate dehydrogenase has been shown to be influenced, to a greater extent, by the length of daily exercise than by the intensity of exercise. In previous studies (Dohm et al., 1977; Harms and Hickson, 1983), the activities of citrate synthase and succinate dehy-

drogenase, mitochondrial markers of the citric acid cycle, were found to be increased in the red (or slow-twitch) and mixed muscle types to nearly the same extent, whether the rats were running at exercise intensities requiring between ~50% and 90% $\dot{V}O_2\text{max}$ or more (90-100% $\dot{V}O_2\text{max}$). In human-kind, trained runners have usually been reported to possess more slow-twitch fibers, more mitochondria (which use fuels and O_2 to produce large amounts of ATP), and higher oxidative enzyme activities than untrained individuals.

A recent study with master athletes (Pollock et al., 1987) has shown that if training (although for high-level competition) is maintained, aerobic capacity does not change over a 10-yr follow-up period. Effects of jogging training on $\dot{V}O_2\text{max}$ and related attributes are evident in young and middle-aged men (Tanaka et al., 1988b; Wilmore et al., 1970; Naughton and Nagle, 1965). It is of high interest that ACSM (1990) has made an important distinction between the quantity and quality of exercise needed to attain health-related benefits and what is recommended for fitness benefits. In order to attain potential health-related benefits, exercise ought to be performed frequently and for a longer duration, but at relatively low to moderate intensities (ACSM, 1990). Significance of a prolonged running relative to the LT as an optimal training intensity should be studied in more detail.

In conclusion, the running velocity at LT would reflect the highest exercise intensity that the individual can sustain for an extended period of time without accumulating limiting amounts of La and hydrogen ions. Although the relative contribution that fat can make to the exercise metabolism depends upon the intensity and duration of the exercise and the individual's fitness level, shifts in the energy substrate toward a reliance on fat oxidation is very likely to occur even during the course of 1-h running at $V_t@LT$. Mitochondrial adaptations to regular endurance training may be maintained with the training intensity corresponding to LT, if

the amounts of frequency and duration are sufficient. The training-induced shifts in the exercise metabolism will help conserve glycogen. It must be borne in mind that the relative contribution of fat to the exercise metabolism becomes less when the intensity of exercise increases. Consequently, it is postulated that prolonged running at $V_t@LT$ may possibly improve exercise performance and maximize health-related benefits in the healthy adult, since aerobic metabolism is the predominant energy source during running. We suggest that individuals who wish to become positively addicted to exercise should jog or run at paces varying from 20 m/min below to 10 m/min above their $V_t@LT$.

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