VARIATIONS IN THE VENTILATORY AND LACTATE THRESHOLDS WITH PROLONGED AEROBIC EXERCISE

by

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ABSTRACT

The purpose of this study was to examine the changes in the ventilatory (VT) and lactate (LT) thresholds and $\dot{V}O_2max$ following prolonged aerobic exercise. Six well-trained distance runners (T:age=25.2 yrs, Ht=170.0 cm, Wt=65.0 kg, $\dot{V}O_2max$=59.6 $ml \cdot kg^{-1} \cdot min^{-1}$) and six untrained (UT:age=25.3 yrs, Ht=180.3 cm, Wt=79.2 kg, $\dot{V}O_2max$=46.8 $ml \cdot kg^{-1} \cdot min^{-1}$) males were studied on two occasions seven days apart. The initial evaluation involved a continuous horizontal treadmill test with a starting velocity of 2.22 $m \cdot s^{-1}$, which was increased by 0.22 $m \cdot s^{-1}$ each minute until fatigue. Expired gases were continuously sampled and analyzed by a Beckman Metabolic Measurement Cart. Measurements were processed by a data acquisition system (HP 3052A), which determined respiratory gas exchange variables every 15 seconds. Blood lactate measurements were taken via an indwelling catheter during the last 10 sec of each minute of work. VT and LT were determined by visual inspection of the excess CO_2 elimination and lactate curves, respectively. Seven days later the subjects repeated the treadmill test preceded by a 60 minute treadmill run at a heart rate corresponding to their LT. The physiological measurements recorded during the first session were repeated. There were significant ($p<0.10$) reductions in $\dot{V}O_2max$, LT, VT, and total treadmill time on the $\dot{V}O_2max$ test (TTT) in the T group (59.6 to 56.9 $ml \cdot kg^{-1} \cdot min^{-1}$, 9.6 to 9.3 mph, 8.9 to 8.2 mph, and 925.0 to 882.5 sec, respectively). $\dot{V}O_2max$, LT, VT, and TTT were

reduced in the UT group (46.8 to 45.0 ml$\cdot$kg$^{-1}\cdot$min^{-1}, 7.7 to 7.6 mph, 8.0 to 7.2 mph, and 730.0 to 652.5 sec, respectively), however, only VT and TTT were reduced significantly ($p<0.10$). Although the groups were significantly different ($p<0.05$) in the initial physiological measures due to training status, there was no change in the rate of decline in $\dot{V}O_2max$, LT, VT, or TTT when the UT group was compared to T. As LT and VT are affected by prolonged aerobic exercise it is questionable whether these thresholds can be used with confidence to predict endurance performance in events up to 60 min duration for well-trained and recreational athletes.

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I. INTRODUCTION

The energy requirements of brief, high-intensity (anaerobic) and prolonged, low-intensity (aerobic) exercise are well understood (Gollnick and Hermansen 1973, Armstrong 1976, Holloszly 1975). Controversy exists, however, in explaining the phenomenon of transition from aerobic to anaerobic metabolism during prolonged intense physical activity. This phenomenon was first investigated by Wasserman et al. (1964, 1973); they observed increases in both blood lactate and respiratory exchange variables above resting levels during incremental exercise to fatigue. They defined the level of work or oxygen consumption just below that at which metabolic acidosis and the associated changes in gas exchange occur as the "anaerobic threshold".

Investigators have either invasively determined the anaerobic threshold with serial blood lactates (McLellan et al. 1981, Simon et al. 1982, Yoshida et al. 1981) or non-invasively with such variables as $\dot{V}_E$, $\dot{V}CO_2$, R, FEO_2 and $FECO_2$ (Wasserman et al. 1973, Simon et al. 1982, Rupp 1981), $\dot{V}_E/\dot{V}CO_2$, $\dot{V}_E/\dot{V}O_2$ (McLellan et al. 1981, Davis et al. 1983, Caiozzo et al. 1982), O_2P (Sankar et al. 1978), and excess CO_2 (Volkov et al. 1975, Rhodes and Mckenzie 1984), during incremental exercise to fatigue. The anaerobic threshold was defined as the nonlinear increase in the above designated variables plotted over time during progressive increases in workload.

However, Kinderman et al. (1979) and Skinner and McLellan (1980) have recorded two "breakaway" points; the first, corresponding to 2 mM/l lactate and to the first significant nonlinear increase of $\dot{V}_E$ and R was termed aerobic threshold. The second, corresponding to the steep part of exponential increase in lactate concentration of 4 mM/l lactate was termed anaerobic threshold. The correlation between the gas exchange measurement and the venous blood lactate measurement of the anaerobic threshold was found to be highly significant, r=0.95 (Davis et al., 1976). These two measurements were found to be very reproducible (Sucec et al., 1982).

The association between the "breakaway" points in ventilatory and blood lactate variables was believed to be due to the release of H^+ which increases CO_2 delivery to the lungs and, subsequently, stimulating the abrupt increase in ventilation (Wasserman et al. 1973, Whipp and Davis 1979). However, several researchers have demonstrated that these abrupt changes in both ventilation and blood lactate during incremental exercise are not causal but rather coincidental (Hagberg et al. 1982, Farrell et al. 1983, Morrison et al. 1983). Recently, investigators realizing the oversimplification of the physiological events represented by the anaerobic threshold termed the threshold determined by gas exchange measurements as the ventilatory threshold (Hagberg et al. 1982, Reybrouck et al. 1982, 1983), while that determined by lactate measurements as the lactate threshold (Ivy et al. 1980, 1981, Gilman and Lemon 1982, DePasquale et al. 1983).

Research has shown that success in distance running is influenced by such factors as $\dot{V}O_2max$, running economy, muscle fiber composition, substrate availability, onset of plasma lactate, and anaerobic threshold (Costill et al. 1971, 1976, Bergstrom et al. 1967, Daniels 1974, Rusko et al. 1978, Wyndham et al. 1969, Farrell et al. 1979). The importance and application of the latter in distance running is considerable; the athlete who knows his anaerobic threshold is able to choose a running pace at which he exercises aerobically without delving into anaerobic metabolism and, consequently, avoiding fatigue and the termination of exercise due to lactate accumulation (Rhodes and McKenzie, 1984). Other pertinent applications of the anaerobic threshold include: 1) exercise prescription (Dwyer and Bybee, 1983), 2) characterizing endurance athletes (Rusko et al., 1980), and 3) predicting endurance performance (Sjodin and Jacobs 1981, Tanaka et al. 1983, Rhodes and McKenzie 1984).

While running at anaerobic threshold speed an equilibrium exists between the amount of oxygen transported to and that needed by the tissues; theoretically, the exercise can last indefinitely. However, factors such as elevation of temperature, electrolyte and fluid unbalance, depletion of glycogen stores, and the shift of muscle fibers recruited from slow twitch (ST) to fast twitch (FT) cause the athlete to experience fatigue. One assumption in using the anaerobic threshold to predict endurance performance was that this variable does not change throughout the event. However, it is questionable whether the anaerobic threshold stays unchanged in the course of prolonged aerobic exercise so that it can be used with accuracy for time prediction. Indeed, Wiswell et al. (1980) reported a 10.7% decrease of the anaerobic threshold and 8.4% decrease in $\dot{V}O_2max$ following 2 hours of exhaustive running in marathon runners (average $\dot{V}O_2max$=57.3 ml/kg/min). The significantly lower R that was found postexercise in this study indicated a change in the type of fuel substrate utilized and the lowering of the anaerobic threshold was attributed to the reduction of muscle glycogen.

The above study investigated the fate of the anaerobic threshold after a very prolonged aerobic exercise which caused depletion of muscle glycogen storage. The literature reveals a lack of information about the state of the anaerobic threshold in less prolonged aerobic exercise where the individuals are not glycogen depleted. Thus the purpose of this study was to determine the effect of one hour of aerobic exercise on the ventilatory and lactate inflection points and $\dot{V}O_2max$ of untrained subjects and trained runners.

II. METHODS

Subjects. Six well-trained distance runners and six untrained males volunteered for the study. The procedures and tests were explained and informed consent was obtained. The selection of subjects was such that the runners had been trained and competed in road races from 10km up to the marathon for more than 4 years, while the untrained were not involved in any regular activities. They were instructed to consume a mixed diet for 3 days prior to the testing day and, in addition, the runners modified their training. This procedure has shown to result in similar pretest muscle glycogen concentrations (Miller et al., 1983). They were also asked to refrain from eating or drinking 2 hours before their scheduled testing time and from training on their testing day.

Procedure. Data collection took place on two sessions approximately 7 days apart. This time period was chosen to avoid fluctuations in both body weight and physical conditioning of the subjects. The evaluation of the physiological characteristics of the subjects involved a continuous horizontal treadmill test with a starting velocity of 2.22 $m \cdot s^{-1}$. Following a 5-minute warm-up, the velocity was increased by 0.22 $m \cdot s^{-1}$ each minute until volitional fatigue. Expired gases were continuously sampled and analyzed by a Beckman Metabolic Cart. Measurements were processed by a data acquisition system (Hewlett Packard 3052 A), which determined respiratory gas exchange variables every 15 seconds. Maximal oxygen consumption was determined by averaging the four highest consecutive 15-second values. Heart rate was continuously monitored by direct lead ECG (Avionics Electrocardiograph 4000).

Blood lactate measurements were taken from each subject by placing, under sterile technique, a 20 g catheter (32 mm) in the cephalic vein. This approach allowed a rapid and easy sampling of venous blood without interfering with the running technique of the subjects. The blood samples were taken during the last 10 seconds of each minute of work. The blood samples were centrifuged and the serum was frozen. The serum was later analyzed for lactate via an automated electrochemical technique (Kontron 640; Racine et al. 1975, Guillot et al. 1976).

Blood lactate values were plotted versus treadmill speed. The lactate threshold was determined by visual inspection of the lactate curve; the first "breakaway" point was the indicator of the lactate threshold (fig. 1) and was established independently by two researchers. Similarly, by examining the excess CO_2 elimination curves for each subject the ventilatory threshold was determined (Volkov et al. 1975, Rhodes and McKenzie 1984) (fig.2). The reliability of these methods have been reported elsewhere (Sucec et al. 1982, Goodman 1982).

During the second session the subjects ran for 60 minutes on the treadmill at a heart rate corresponding to their lactate threshold. This heart rate was attained within 10 minutes of work. It was monitored every 5 minutes and when it exceeded the lactate threshold value, the treadmill speed was reduced, accordingly. The subjects were allowed to drink water. Room temperature was maintained at 23°C. Following the 60-minute run the treadmill was stopped for 2-10 minutes to apply the gas collection apparatus and to allow any elevation in blood lactate to return to normal. The subjects then repeated the initial test to exhaustion. The physiological parameters measured during the first session were re-evaluated.

Statistical Analysis.

The statistical significance of the data was evaluated using three two-way MANOVA designs. The chosen level of significance was $p \leq 0.05$. Multiple comparisons using Scheffé's method were further applied to detect significant differences between pre and post values. The 10 percent level of significance was used for these comparisons (Scheffé, 1959).

III. RESULTS

Physical characteristics of the subjects are presented in Table 1.

TABLE 1. Physical Characteristics of Subjects (Means + SD)

Measures	Trained (n=6)	Untrained (n=6)
Age (year)	25.2±2.0	25.3±3.1
Height (cm)	170.0±5.4	180.5±10.1
Weight (kg)	65.0±3.9	79.2±10.0*
$\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	59.6±2.7	46.8±3.2*

* Significant differences between groups at $p<0.05$

The statistical differences in $\dot{V}O_2max$ between groups reflected their training status. In addition, the trained runners weighed significantly less than the untrained subjects.

The physiological data is summarized in Table 2. $\dot{V}O_2max$ averaged 59.6±2.7 and 46.8±3.2 $ml \cdot kg^{-1} \cdot min^{-1}$ for the trained runners and untrained individuals, respectively. These values were reduced to 56.9±2.8 and 45.0±2.6 $ml \cdot kg^{-1} \cdot min^{-1}$, respectively, following the one-hour treadmill run. However, only the trained runners' reduction was significant ($p<0.10$).

The lactate threshold was found to occur at 9.6±0.8 and 7.7±0.5 mph for the trained and untrained subjects, respectively. The 60-min run caused reductions in both of these thresholds to 9.3±0.7 mph (trained) and 7.6±0.3 mph (untrained), but only the trained subjects' value was significantly ($p<0.10$) different (fig.3). The prolonged aerobic exercise did not change significantly the percentage of O_2 consumption corresponding to the lactate threshold; Trained : 81.5±9.3 versus 82.7±8.9 (%$\dot{V}O_2$max) and Untrained: 80.2±6.5 versus 82.2±4.8 (%$\dot{V}O_2$max).

The ventilatory threshold was recorded at 8.9±0.8 mph (trained) and 8.0±0.6 mph (untrained). The 60-min run significantly ($p<0.10$) shifted these values to 8.2±0.6 mph (trained) and 7.2±0.5 mph (untrained)(fig. 3). As in the case of the lactate threshold, the percentage of O_2 consumption corresponding to the ventilatory threshold did not change significantly in both groups; Trained: 76.1±8.6 versus 73.4±8.7 (%$\dot{V}O_2$max) and Untrained: 81.5±7.6 versus 78.5±6.5 (%$\dot{V}O_2$max). Furthermore, it was observed that although the lactate threshold (%$\dot{V}O_2$max) tended to increase following the 60-min run, the ventilatory threshold (%$\dot{V}O_2$max) moved in the opposite direction.

The total treadmill time (TTT) on the $\dot{V}O_2$max test was significantly ($p<0.10$) reduced in both trained (925.0±61.9 versus 882.5±77.3 sec) and untrained (730.0±52.5 versus 652.5±75.7 sec) subjects.

No significant changes were observed in the heart rates at the time the lactate threshold occurred; Trained: 166.5±8.3 versus 167.3±9.0 (b/min) and Untrained: 167.3±8.3 versus 167.0±11.1 (b/min).

The respiratory quotient corresponding to the lactate threshold was significantly ($p<0.10$) reduced in both trained (0.99±0.06 versus 0.95±0.03) and untrained (1.04±0.03 versus

0.96±0.04) subjects.

The ventilatory and lactate thresholds (expressed in $\%\dot{V}O_2max$) correlated very low; r_T=0.42 and r_{UT}=0.54.

Finally, no significant interactions were obtained in any of the variables measured. Thus we conclude that training status seemed to have no effect on the changes observed. However, by visually examining the data we speculated that we might obtain unequal changes in some of the variables. Indeed, by using Scheffé tests, in two of the variables (lactate threshold, $\dot{V}O_2max$) the groups did not show equal changes between pre-post, although the overall interaction was non-significant.

TABLE 2. Physiological Data of Subjects (Means±SD)

Measures	Trained (n=6) Pre	Trained (n=6) Post	Untrained (n=6) Pre	Untrained (n=6) Post
LT (mph)	9.6±0.8	9.3±0.7*	7.7±0.5	7.6±0.3
LT (% $\dot{V}O_2max$)	81.5±9.3	82.7±8.9	80.2±6.5	82.2±4.8
VT (mph)	8.9±0.8	8.2±0.6*	8.0±0.6	7.2±0.5*
VT (% $\dot{V}O_2max$)	76.1±8.6	73.4±8.7	81.5±7.6	78.5±6.5
$\dot{V}O_2max$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	59.6±2.7	56.9±2.8*	46.8±3.2	45.0±2.6
TTT (sec)	925.0±61.9	882.5±77.3*	730.0±52.5	652.5±75.7*
HR_{LT} (b/min)	166.5±8.3	167.3±9.0	167.3±8.3	167.0±11.1
R_{LT}	0.99±0.06	0.95±0.03*	1.04±0.03	0.96±0.04*

LT : Lactate threshold
VT : Ventilatory threshold
VO_2max : Maximum O_2 consumption
TTT : Total treadmill time on the $\dot{V}O_2max$ test
HR_{LT} : Heart rate at the lactate threshold
R_{LT} : Respiratory quotient at the lactate threshold

* Significant differences between pre-post at $p<0.10$

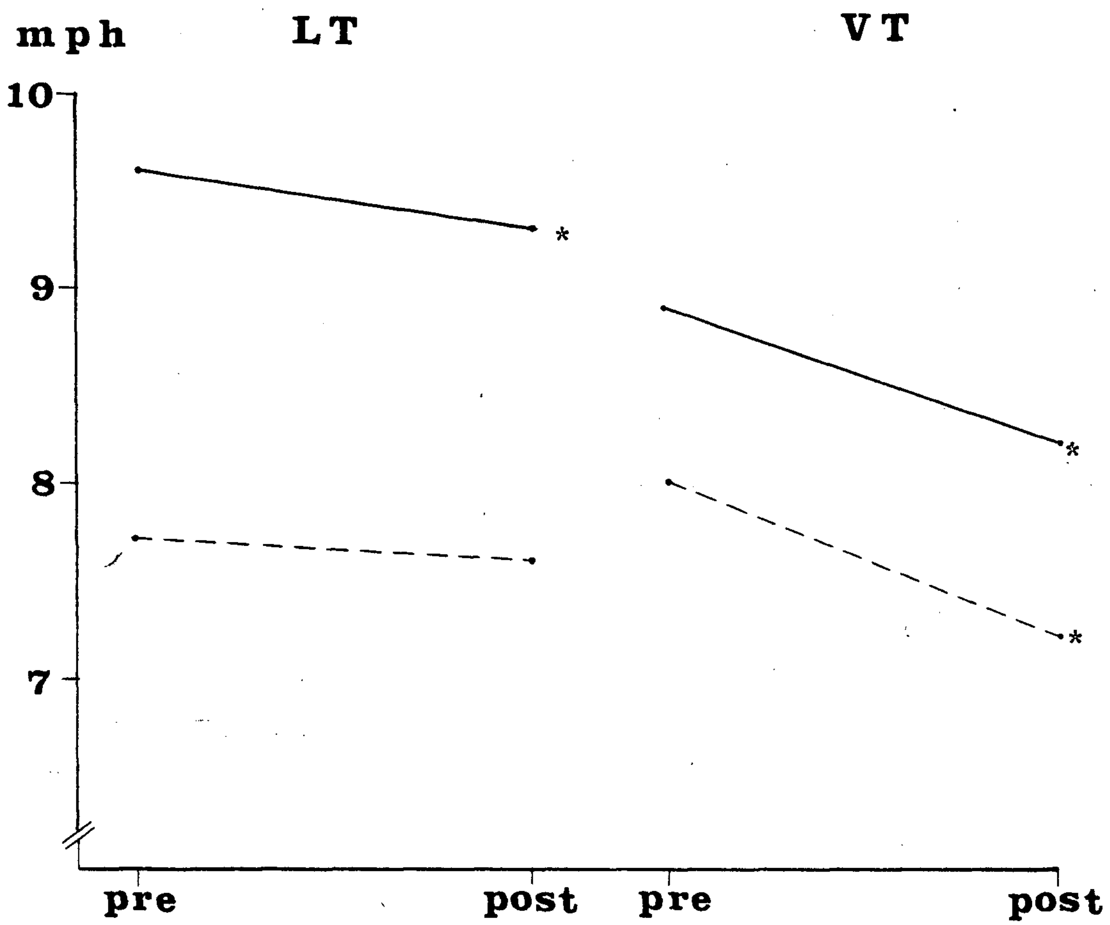

FIGURE 3. Lactate (LT) and ventilatory (VT) threshold values before and after 60 min of exercise.Trained (——) versus untrained (---). The asterisk indicates significant differences between prepost at $p<0.05$.

IV. DISCUSSION

The subjects examined in this study constitute two heterogeneous groups; well-trained endurance athletes and untrained individuals. Differences in $\dot{V}O_2max$, lactate and ventilatory threshold are attributed to the training status. Previous evidence (Dunwoody and Rhodes 1981, Rhodes and McKenzie 1984, Volkov et al. 1975, MacDougall 1977) supports our finding that trained individuals have higher $\dot{V}O_2max$, lactate and ventilatory thresholds than untrained individuals. No significant differences were found, however, on the thresholds between the two groups when they were expressed as a percentage of $\dot{V}O_2max$. This finding is in agreement with Parkhouse et al. (1982). As it was expected, the well-trained subjects lasted a much longer time on the $\dot{V}O_2max$ test than the untrained subjects. Finally, the heart rates corresponding to the lactate threshold were not significantly different between the groups. Parkhouse et al. (1982) reported similar values for heart rates corresponding to the ventilatory threshold in three groups with different fitness levels.

Ivy et al. (1981), Kowalchuk and Hughson (1981), and Hughes et al. (1982) have shown that substrate availability affects the lactate and ventilatory threshold. Thus it was of high importance to consider a special training and diet modification prior to the testing. We feel confident that the procedure we followed resulted in similar pretest muscle glycogen concentrations (Miller et al., 1983). In addition, the intensity and duration of our exercise protocol were such that it excluded a significant muscle glycogen depletion which would cause fatigue; in exhaustive runs of 72.5 min at 80% of $\dot{V}O_2max$ (Costill et al., 1971-b), 69.4 min at 80% $\dot{V}O_2max$ (Costill et al., 1971-c), and 83 min at 86% of $\dot{V}O_2max$ (Sherman et al., 1981) muscle glycogen depletion has not been implicated as the cause of the fatigue. Consequently, the results obtained in this study are not attributed to the depletion of muscle glycogen stores. Keeping the laboratory at constant temperature avoided environmental induced variations in the metabolic response to exercise which has been shown to affect the lactate threshold (Gilman and Lemon, 1982).

Following the 60-min run the trained subjects showed significant reductions in $\dot{V}O_2max$, lactate and ventilatory threshold, and total treadmill time on the $\dot{V}O_2max$ test; 4.5%, 3.1%, 7.9%, and 4.6%, respectively. Wiswell et al. (1980), reported an 8.4% and 10.7% reductions in $\dot{V}O_2max$ and ventilatory threshold, respectively, following 2 hours of exhaustive running in marathon runners with a similar fitness level ($\dot{V}O_2max$=57.3 $ml \cdot kg^{-1} \cdot min^{-1}$) as our trained group. The high intensity and the long duration of the exercise in that study and, particularly, the significantly lower R that was found post-exercise indicated a change in the type of fuel substrate utilized. Consequently, the lowering of the ventilatory threshold was attributed to the reduction of muscle glycogen.

$\dot{V}O_2max$, lactate and ventilatory threshold, and total treadmill time on the $\dot{V}O_2max$ test were also decreased in the untrained subjects by 3.8%, 1.3%, 10.0%, and 10.6%, respectively. However, only the last two variables were significantly different. Due to lack of pertinent information in the literature we cannot compare these findings with other studies.

In both groups, the lactate and ventilatory thresholds expressed in $\%\dot{V}O_2max$, as well as, the heart rate corresponding to the lactate threshold showed no significant changes following the 60-min run.

For the reasons we proposed above we do not believe that those changes obtained following the 60-min run are attributed to the muscle glycogen depletion. Our speculation is further supported by the post-R values we obtained; if the subjects were glycogen depleted their R at the lactate threshold would have expected to be close to 0.70, contrary to 0.95(T) and 0.96(UT) that were found post-exercise. The only explanation that we can offer for those reductions in the thresholds, is the combined effects of the following factors: 1) elevation of body temperature which, possibly influenced minute ventilation (Sutton and Jones, 1979); 2) electrolyte and fluid unbalance as brought about with prolonged exercise (Costill et al. 1970, Wyndham and Strydom 1968); 3) the shift of muscle fibers recruited from slow twitch (ST) to fast twitch (FT) (Brooks and Fahey, 1984); 4) neuromuscular fatigue caused by a failure in neural transmission

(McArdle et al. 1981); and 5) a reduction in efficiency of running.

As was shown by the interactions, the reductions observed in all of the variables measured seem to be unaffected by the training status.

The use of excess CO_2 and lactate measurements for the determination of ventilatory and lactate thresholds, respectively, was shown to be valid as well as reliable methods (Volkov et al. 1975, Rhodes and McKenzie 1984, Sucec et al. 1982, Ivy et al. 1981, Kumagai et al. 1982). Studies have revealed that the invasive and non-invasive methods of determining the threshold of anaerobic metabolism correlate highly between them (Ivy et al. 1981, Kumagai et al. 1982, Yoshida et al. 1981, Caiozzo et al. 1982, Davis et al. 1976). These papers suggest that both thresholds almost coincide. Other authors (Hughes et al. 1982, Denis et al. 1982), however, reported lower relationships, while Simon et al. (1983-a) and Gutin et al. (1980) reported that the ventilatory threshold occurred before the lactate threshold. In the present study, we observed very low correlations between the two thresholds (expressed in $\%\dot{V}O_2max$); r_T=0.42 and r_{UT}=0.54. Furthermore, the associated changes in gas exchange occurred before a marked increase in plasma lactate in three of six trained subjects, while the opposite was observed in three of six untrained subjects. This was an unanticipated finding because the majority of studies in the literature reveal a coincidence of the two "breakaway" points. Based on our finding that the ventilatory threshold may occur before the lactate threshold, we question the concept that increases in blood lactate lead to the ventilatory changes as it was hypothesized by Wasserman et al. (1973), Whipp and Davis (1979). Furthermore, looking at the effect the 60-min run had on these thresholds, we observed that the decrease in the ventilatory threshold was greater than the decrease in the lactate threshold (expressed in mph) in both groups. This finding suggests, once more, that blood lactate accumulation is not responsible for the increase in ventilation. This conclusion is also supported by the observation that the lactate threshold (%$\dot{V}O_2$max) tended to increase following the 60-min run, while the ventilatory threshold (%$\dot{V}O_2$max) moved in the opposite direction.

Investigators (Rhodes and McKenzie 1984, Sjodin and Jacobs 1981, Farrell et al. 1979) have correlated the anaerobic threshold (using either the invasive or non-invasive method) very highly with marathon running performance. In those studies it was theorized that marathoners are able to run throughout the race at that critical point before anaerobic metabolism starts; it was assumed that the critical point stays unaltered until the end of the race and, consequently, it is possible to predict endurance performance with high accuracy, taken into account that all other factors which affect perfomance have to be optimal. In addition, LaFontaine et al. (1981), Farrel et al. (1979), and Kumagai et al. (1982)

have also correlated the anaerobic threshold very highly with performace at various shorter races from 2 up to 10 miles. However, based on the findings of the present study, we question the validity of using the ventilatory and lactate thresholds in predicting endurance performance in events up to 60 min duration for well-trained athletes. We also conclude the same for recreational athletes, although we were unable to show significant reductions in the lactate threshold and $\dot{V}O_2max$ of our untrained subjects; this would appear to be due to the small sample size. Other factors, such as $\dot{V}O_2max$, running economy, muscle fiber composition, and substrate availability may also be of importance in predicting endurance performance in events up to 60 min duration.

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APPENDIX A - REVIEW OF LITERATURE

Introduction

Although the concept of the anaerobic threshold originated twenty years ago (Wasserman et al., 1964), it remains a contemporary issue with practical application to sports and clinical exercise physiology.

Different terminology is now used to characterize the changes in blood lactate concentration and ventilatory gas exchange that occur with incremental exercise intensities. The initial non-linear increase in $\dot{V}_E$ or excess CO_2, relative to oxygen consumption, is termed the ventilatory threshold; the "breakaway" point for blood lactate versus exercise intensity has been defined as the lactate inflection point.

Basic scientists do not agree on the physiological events surrounding these thresholds. A high correlation between the alterations in gas exchange and a continuous rise in lactate values has been reported (Davis et al. 1976, Yoshida et al. 1981). Hagberg et al. (1982), Heigenhauser et al. (1983), and Hughes et al. (1982) have demonstrated an uncoupling of the ventilatory threshold and lactate inflection point. Thus although the mechanisms controlling these controversial events have not been elucidated equivocally they would appear to be related to acid-base balance (Wasserman et al. 1973, 1981). This has a direct practical application to the exercising individuals in terms of performance and muscle fatigue.

This paper represents a current review of the information and mechanisms of the anaerobic threshold and its application to sport science.

Measurement and Determination of the Anaerobic Threshold

Wasserman et al. (1973) determined the noninvasive indicators of the onset of anaerobic metabolism. Eighty-five normal subjects between 17 and 91 years of age were given incremental exercise tests on the bicycle ergometer with increments of 15W every minute while changes in gas exchange were examined. The anaerobic threshold could be identified by the point of : 1) nonlinear increase in $\dot{V}_E$ 2) nonlinear increase in $\dot{V}CO_2$ 3) an increase in end-tidal O_2 without a corresponding decrease in end-tidal CO_2, and 4) an increase in R.

Volkov et al. (1975) investigated measurements of excess CO_2 plotted versus incremental running speeds on a horizontal treadmill of four highly experienced middle-distance runners. Excess CO_2 was measured by sampling the expired air throughout the tests where excess CO_2 was : $ExcCO_2$ (ml/kg/min)= $\dot{V}CO_2 - R_{rest} \times \dot{V}O_2$. By plotting the values of $ExcCO_2$ in semilogarithmic scale against corresponding running speeds it was possible to determine the running speed corresponding to threshold of anaerobic metabolism (V_{TAM}), characterized by metabolic acidosis and increase in arterial blood lactate. They observed that at low speeds not exceeding V_{TAM}, $ExcCO_2$ changed only slightly. However, when running speed exceeded V_{TAM}, $ExcCO_2$

exhibited a rapid exponential increase. The running speed corresponding to the "breakaway" point gave the value of V_{TAM}, for which a systematic increase of anaerobic metabolism began. Additionally, they noticed that subjects with different levels of training exhibited considerable differences in the speed at which $ExcCO_2$ began to show a rapid exponential increase; the best trained athlete met the "breakaway" point at a significantly higher speed than did the least trained athlete.

Sankar et al. (1978) examined determination of anaerobic threshold by oxygen pulse. Thirty-four male firefighters, aged 19-31 were used for the study. They chose those subjects with $\dot{V}O_2max$ of < 3.75 l/min because they observed no plateau of oxygen pulse in similar subjects with very high $\dot{V}O_2max$. The subjects underwent incremental treadmill exercise while blood lactates and other cardiorespiratory variables were measured at the fourth minute of steady-state work continuing to approximately 80% of $\dot{V}O_2max$. The oxygen pulse increased linearly to approximately 70% of $\dot{V}O_2max$ or at lactic acid of approximately 30 mg/dl and plateaux at approximately 18 ml/beat after that. Between 60-70% of $\dot{V}O_2max$, $\dot{V}_E$, $\dot{V}CO_2$, R, HR, $PETO_2$, and lactate increased out of proportion to $\dot{V}O_2$ indicating the onset of metabolic acidosis. The investigators concluded that curvilinear plateauing of oxygen pulse could be the index of the metabolic acidosis, and the leveling of oxygen pulse is a measure of approaching $\dot{V}O_2max$.

According to Wasserman et al. (1964, 1973, 1978) the anaerobic threshold coincides with the first increase in lactate level, to approximately 2 mmol/l. However, Kinderman et al. (1979) showed that work load intensities above the anaerobic threshold defined by Wasserman et al. (1964, 1973, 1978), can be maintained with slightly elevated lactate levels for prolonged periods of time. Seven cross-country skiers were used in that study. After their maximal working capacity (heart rate, $\dot{V}O_2$, performance, lactate) was determined by running on the treadmill, treadmill speed, oxygen intake and heart rates at lactate levels of 4 mmol/l were determined by interpolation. The subjects then underwent two additional exercises, each with a duration of 30 min. The heart rate determined for 4 mmol/l lactate (174 b/min) was kept constant for the duration of the first exercise while the treadmill speed determined for the same lactate concentration remained unchanged during the second exercise. In order for the heart rate determined for 4 mmol/l lactate to be kept constant for 30 min duration, the treadmill speed had to be reduced continuously. The arterial lactate concentration displayed an approximately twofold rise when compared to 4 mmol/l up to 10 min and after that was continuously reduced as a result of the reduction of the treadmill speed. When the exercise lasting 30 min was performed with a constant running speed as determined for 4 mmol/l lactate, the heart rate rose and the arterial lactate concentration was nearly 4 mmol/l during the whole exercise. Finally, the authors suggested new concepts of thresholds, as follows:

I. Aerobic threshold : approximately 2 mmol/l lactate - first significant elevation of lactate level, nonlinear increase of $\dot{V}_E$, RQ.

II. Aerobic - anaerobic transition : approximately 2 to 4 mmol/l lactate.

III. Anaerobic threshold : approximately 4 mmol/l lactate-steep part of exponential increase in lactate concentration.

McLellan et al. (1981) do not agree with the above designated lactate levels of 2 and 4 mmol/l for the aerobic and anaerobic threshold, respectively. They designed a study in which they investigated the effect of work load duration on indirect and direct determinations of the aerobic and anaerobic thresholds. Six subjects underwent cycle ergometer tests while the work load was increase 15W each 1 or 2 min and 30W each 3 or 4 min. The first and second "breakaway" points in the plot of $\dot{V}_E$ versus $\dot{V}O_2$ were used as an indirect method for the determination of the aerobic and anaerobic thresholds, while the work load at an initial rise in lactate and the onset of the rapid rise in lactate was used as a direct method. The findings showed that relative aerobic and anaerobic threshold values were significantly higher for the 4 versus 1 min test (60.13 vs. 52.03% $\dot{V}O_2$max, and 85.09 vs. 77.52% $\dot{V}O_2$max, for aerobic and anaerobic threshold, respectively). Lactic acid at aerobic threshold was significantly higher for the 3 versus 1 min test but there was no difference in lactate levels at anaerobic threshold. In addition, $\dot{V}O_2$ associated with these lactate values was found to be different from those at aerobic and anaerobic threshold determined indirectly. Based on these findings the investigators concluded that although lactate levels of 2 and 4 mmol/l are usually found at aerobic and anaerobic threshold, respectively, they are arbitrary and do not always apply. Relative aerobic and anaerobic threshold values may vary significantly depending on the test protocol.

Davis et al. (1983) examined whether the gas exchange anaerobic threshold occurs at a fixed blood lactate concentration of 2 or 4 mM. Twelve males and two females (mean age=22.3 years) underwent incremental cycle ergometer tests while gas exchange and lactate measurements were taken. The anaerobic threshold was chosen using four criteria : 1) systematic increase in $\dot{V}_E/\dot{V}O_2$, without a concomitant increase in $\dot{V}_E/\dot{V}CO_2$, 2) systematic increase in blood lactate, 3) 2 mM lactate, and 4) 4mM lactate concentrations. Subsequently they compared the $\dot{V}O_2$ values for each criterion among all subjects. Their findings showed that the mean value of $\dot{V}O_2$ for the $\dot{V}_E/\dot{V}O_2$ criterion was 1.819 l/min, for the second criterion was 1.863 l/min, for the third 2.099 l/min, and for the fourth 2.847 l/min. The last two values differed significantly from the $\dot{V}_E/\dot{V}O_2$ anaerobic threshold result, as well as between them.

In addition, the maximal percent differences from the gas exchange anaerobic threshold were 17, 41, and 87 compared to the second, third, and fourth criterion, respectively. These observations led the investigators to conclude that the anaerobic threshold discerned from gas exchange or the lactate break point does not correspond with a fixed, absolute lactate concentration of 2 or 4 mM.

Simon et al. (1982) designed an experiment to investigate whether the invasive anaerobic threshold (AT_i) and noninvasive anaerobic threshold (ATn) occur together in both trained and untrained sedentary men. The AT_i was determined from a marked increase in plasma lactate and the ATn from a nonlinear increase in $\dot{V}_E$ during incremental leg cycling tests. The findings showed that the trained subjects' AT_i (68.8% $\dot{V}O_2max$) and ATn (65.8% $\dot{V}O_2max$) did not differ significantly. Additional observations showed that the trained subjects' mean peak lactate concentration (10.5 mM) did not differ significantly from the untrained subjects' mean peak lactate concentration (11.5 mM). However, the mean time of appearance of the peak lactate concentration during passive recovery occurred significantly earlier for the trained (1.8 min) compared to the untrained (4.3 min). This observation led the investigators to suggest that there may be a slower lactate translocation from muscle to blood in the untrained compared to trained individuals.

Rupp (1981) investigated whether 4 different methods for the determination of the anaerobic threshold are similar. Twenty men and women served as subjects for the study and they underwent a maximal incremental bicycle ergometer exercise. The methods tested were : Method 1(M_1 - nonlinear increase in $\dot{V}_E$ and $\dot{V}CO_2$) method 2(M_2 - increase in FEO_2 without a decrease in $FECO_2$), method 3 (M_3 - second nonlinear increase in $\dot{V}_E$), and method 4(M_4 - a decrease in $FECO_2$ as work intensity increased). Their findings showed the following : 1) M_3 and M_4 (32 and 31 $\dot{V}O_2$ ml/kg) were significantly different from M_1 and M_2 (20.7 and 19.7 $\dot{V}O_2$ ml/kg). 2) No significant difference between males and females (26.4 and 25.2 $\dot{V}O_2$ ml/kg). 3) The heart rate at which M_1 and M_2 occurred (130.5 and 126.7 b/min) was significantly different from heart rate of M_3 and M_4 (164.7 and 159.2 b/min). 4) No significant difference between heart rate of M_1 and M_2 or between M_3 and M_4. 5) The heart rate of females (151.3 b/min) was significantly different than males (139.2 b/min) across all methods. 6) M_1 and M_2 (53.6 and 51.9% $\dot{V}O_2max$) were significantly different than M_3 and M_4 (84 and 81.3% $\dot{V}O_2max$). 7) No significant difference in % $\dot{V}O_2max$ between M_1 and M_2 or between M_3 and M_4. 8) Females (71.2 % $\dot{V}O_2max$ were significantly different than males (64.2% $\dot{V}O_2max$) across all methods. Based on these observations the author's conclusions were: 1) M_1 and M_2 measure the same anaerobic threshold, 2) M_3 and M_4 measure the same anaerobic threshold, 3) a distinction exists between M_1, M_2 and M_3, M_4 ($\dot{V}O_2$ ml/kg, heart rate, and % $\dot{V}O_2max$), 4) anaerobic threshold heart rates for women are higher than those of men, and 5) anaerobic threshold occurs at a higher % $\dot{V}O_2max$ in females than males.

Sucec (1981) designed an experiment to examine the validity and reliability of an incremental horizontal protocol for the concurrent determination of $\dot{V}O_2max$ and anaerobic threshold in males and females. Twelve male and twelve female distance runners were used for the study. The means of $\dot{V}O_2max$ for the horizontal treadmill protocol were found to be equal to the paired mean $\dot{V}O_2max$ scores from an inclined treadmill test for both sexes. The determination of anaerobic threshold from the horizontal treadmill protocol was found to be valid and reliable for both the males (r=0.86) and females (r=0.93). The males' $\dot{V}O_2$ at anaerobic threshold was 3.28 l/min or 48.0 ml/kg/min while the females' $\dot{V}O_2$ at anaerobic threshold was significantly lower 2.33 l/min or 40.6 ml/kg/min. However, when the anaerobic threshold was expressed as a percentage of their $\dot{V}O_2max$, no significant difference was found between the males' and females', 72.3% and 73.2%, respectively. The author concluded that horizontal treadmill protocol will produce valid and reliable $\dot{V}O_2max$ and anaerobic threshold values similar to values made during inclined treadmill protocol for distance runners of both sexes. In addition, males have a higher anaerobic threshold when expressed in l/min or ml/kg/min, than females, but when anaerobic threshold is expressed as a % of $\dot{V}O_2max$ it is independent of sex.

Caiozzo et al. (1982) examining 16 subjects 20 to 31 years of age showed that the most sensitive and reliable ventilatory index for detection of the anaerobic threshold among indices such as $\dot{V}_E$, $\dot{V}CO_2$, R, and $\dot{V}_E/\dot{V}O_2$, was the $\dot{V}_E/\dot{V}O_2$. $\dot{V}_E/\dot{V}O_2$ had the highest correlation among all the indices tested with the blood lactate anaerobic threshold (r=0.93). The $\dot{V}_E/\dot{V}O_2$ index also showed the highest test-retest correlation for the detection of the anaerobic threshold (r=0.93). These correlations are in close fit with findings from Davis et al. (1976, 1979) and Sucec et al. (1982), while Hughes et al. (1982) and Denis et al. (1982) reported a correlation of only 0.71 and 0.77, respectively, between ventilatory and lactate thresholds.

Gladden et al. (1983) designed a study to examine the agreement between gas exchange and lactate anaerobic threshold determinations among independent investigators. Sixteen subjects underwent incremental cycle ergometer tests while gas exchange and lactate measurements were taken, and the values were plotted versus time. Subsequently, these plots were sent to 9 independent investigators who were asked to determine the anaerobic threshold. Agreement among the independently determined anaerobic threshold values (ventilatory versus lactate) was very poor with correlation coefficients ranging from 0.16 to 0.82, with a median value of 0.46. For the ventilatory threshold, the r ranged from 0.37 to

0.96 with a median of 0.66, while for the lactate threshold, the r ranged from 0.59 to 0.97 with a median of 0.72. Based on these results the authors suggested that independent evaluations of gas exchange and lactate anaerobic threshold have less agreement than previously reported. In addition, agreement among independent investigators for a given anaerobic threshold method is less than that previously reported for investigators within a given laboratory.

Determination of anaerobic threshold by a Douglas bag method was found to be as valid as with arterial blood lactate anaerobic threshold measurements (Yoshida et al., 1981). By examining 10 male college-aged subjects they observed that $\dot{V}O_2\%$, $\dot{V}O_2max$, $\dot{V}_E$, heart rate, and R at anaerobic threshold did not differ significantly when measured either with gas exchange or lactate measurements. Furthermore, they recorded a correlation coefficient of r=0.86 between lactate threshold and gas exchange threshold when expressed in $\dot{V}O_2$ values (l/min).

Conconi et al. (1982) designed a noninvasive field test to determine the anaerobic threshold. They examined 210 runners who run continuously on the track from an initial velocity of 12-14 km/h up to submaximal velocities varying according to the runners' capability while heart rates were recorded and plotted versus running speeds. The velocity at which the linearity of running speed-heart rate relationship was lost was called deflection velocity (V_d). It was shown that the V_d correlated very highly (r=0.99) with the anaerobic threshold determined by blood lactate measurements, while the reproducibility of the V_d determination was also found to be highly significant (r=0.99). Furthermore, they recorded very high correlations between V_d and competitive running speeds, an r=0.93 in 5000M, r=0.95 in the marathon, and r=0.99 in 1-hr races. These findings highly demonstrate the feasibility of measuring the anaerobic threshold by using noninvasive running speed-heart rate relationships, an approach which can be carried out in the field.

Moritani et al. (1980) showed that surface electromyography is a valid noninvasive method for the determination of anaerobic threshold. Eighteen males (25.3 years) and eighteen females (20.9 years) underwent incremental cycle exercise while surface electrodes were applied on their quadriceps muscle. The anaerobic threshold was determined by the nonlinear increase in the electromyogram, i.e., the point at which three consecutive electromyogram values deviated above one standard error of estimate from the linear regression equation. This method was tested for its validity by correlating the $\dot{V}O_2$ values at the anaerobic threshold as derived by the electromyogram-work plots with those derived from gas exchange measurements. The findings showed highly significant correlations between the two methods for males (r=0.96), females (r=0.89) and the pooled data (r=0.97). Further studies by Moritani et al. (1982) showed that analysis of myolectric signals may provide a noninvasive measure of lactate threshold.

Orr et al. (1980) examined whether the subjective evaluation (SE) of anaerobic threshold based on the $\dot{V}_E/\dot{V}O_2$ criteria and using a 15 sec sampling period correlate with a computerized algorithm technique (CE) using multiple linear regressions. A 2(CE-2) and 3(CE-3) regression model fitted to the data determined on the basis of the smallest pooled residual sum of squares were used for the comparison. Ten subjects were used for the study whose anaerobic threshold was determined by incremental work tests. The findings showed that anaerobic threshold in % $\dot{V}O_2max$ was higher for the CE-2 (72.6) determination than for the SE (63.6) and the CE-3 (58.9) determinations. SE and CE-2 correlated significantly (r=0.82) as well as SE and CE-3 (r=0.65). However, no significant correlation was found between CE-2 and CE-3 (r=0.51). The researchers concluded that the method used to determine the point of "breakaway" can significantly affect the value used for anaerobic threshold.

Anaerobic Threshold and Various Modes of Exercise

Davis et al. (1976) investigated the comparability of the anaerobic threshold among three modes of exercise (arm cranking, leg cycling, and treadmill walk-running) with duplicate determinations obtained from 30 male subjects. The anaerobic threshold for arm cranking, leg cycling, and treadmill walking-running occurred at 46.5, 63.8, and 58.6% of $\dot{V}O_2max$, respectively. No significant difference was found between the anaerobic threshold mean values for leg cycling and treadmill walking-running while the mean anaerobic threshold for arm cranking was significantly lower than leg cycling or treadmill walking-running.

Anaerobic threshold during one- versus two-legged cycling was examined by Stamford et al. (1978). They found that anaerobic threshold approximated 48% of $\dot{V}O_2max$ for both one- and two-legged cycling. According to the authors, this finding indicated that the size of the total exercising muscle mass does not influence anaerobic threshold when expressed on a relative basis, but, rather, the mode of exercise is probably the primary influencing factor as it is shown by the findings of the previous study by Davis et al. (1976).

Payne and Lemon (1982) compared anaerobic threshold during treadmill running and tethered swimming. Six male competitive swimmers were used for the study and lactate and gas exchange measurements were taken. The results showed that: 1) Treadmill running was significantly greater than tethered swimming for anaerobic threshold: % of treadmill $\dot{V}O_2max$ (73.0 versus 50.4), 2) a non-significant difference was found for 5 min post exercise lactate values (11.87 versus 11.31 mmol/l) and anaerobic threshold: % mode specific $\dot{V}O_2max$ (73.0 versus 65.9), and 3) treadmill lactate threshold and anaerobic threshold (75.4 versus 71.7) were non-significant.

Based on these findings the authors suggested that specific arm training results in an anaerobic threshold (% mode specific $\dot{V}O_2max$) during tethered swimming that it is not different from treadmill running.

Hagerman and Mickelson (1980) examined anaerobic threshold among competitive oarsmen by using a rowing ergometer and a motor-driven treadmill. Thirty-three candidates for the U.S. National Men's Rowing Team served as subjects whose anaerobic thresholds were determined by gas exchange measurements on incremental exercises in the rowing ergometer and in the treadmill. The findings indicated that the anaerobic threshold for the rowing exercise occurred at 82% of $\dot{V}O_2max$ (at an average power output of 1748 $kg\text{-}m \cdot min^{-1}$), while the anaerobic threshold for the treadmill exercise occurred at 72% of $\dot{V}O_2max$ (at an average power output of 780 $kg\text{-}m \cdot min^{-1}$). However, $\dot{V}O_2max$ values did not differ significantly for the two modes of exercise. The investigators attributed the 10% difference in anaerobic threshold between the two exercises to the specificity of training and to adaptability and they suggested the use of task specificity testing for reliable evaluation of an athlete's physiological capacity.

Wiswell et at. (1979) compared anaerobic threshold on bicyle ergometer and treadmill. Thirty males, 18 to 25 years of age were used as subjects. Using gas exchange measurements they determined the anaerobic threshold for bicycling and treadmill running which occurred at 69.4% and 74.5% of

$\dot{V}O_2max$, respectively. These values were equivalent of 2.58 and 2.90 l/min, respectively, when expressed in absolute terms. Their statistical analysis showed a significant difference between anaerobic threshold on bicycle and treadmill. In addition, they observed a significant relationship between anaerobic threshold ($\dot{V}O_2$ in l/min) and $\dot{V}O_2max$ (r_{bike}=0.79, $r_{treadmill}$=0.76). However, when anaerobic threshold was expressed as % $\dot{V}O_2max$, relationships for anaerobic threshold and $\dot{V}O_2max$ were found to be non-significant (r_{bike}=0.4, $r_{treadmill}$=0.10). Based on these findings the authors concluded that anaerobic threshold may be exercise modality dependent.

Ball et al. (1981) investigated the change in the pattern of ventilation (V_T, f) during progressive work above and below anaerobic threshold and the influence of different muscle groups (arm versus leg) in affecting the response. Seven male and six female college-aged subjects underwent progressive leg and arm ergometer tests until fatigue, while gas exchange measurements were taken. The findings showed that for both arm and leg ergometry, the nonlinear increase in $\dot{V}_E$ above anaerobic threshold was coincident with a nonlinear increase in f and a plateauing of V_T for leg exercise, the slope of $\dot{V}_E$ and f versus time increased from 2.75 and 0.75 below the anaerobic threshold to 10.0 and 4.14 above the anaerobic threshold, respectively, while for arm exercise, these slope changes for $\dot{V}_E$ and f were 2.60 and 1.16 below the anaerobic threshold and 10.3 and 4.88 above the anaerobic threshold. Furthermore, it was found that V_T plateaued at a significantly lower volume during arm exercise although no significant differences were noted in maximum f. The authors concluded that the lower anaerobic threshold during arm exercise compared to leg exercise and the plateau of V_T at anaerobic threshold during both forms of exercise, suggests a relationship between hypocapnia and the V_T plateau.

The specificity of the anaerobic threshold was examined by Withers et al. (1981) in 10 endurance-trained cyclists and 10 endurance-trained runners. When anaerobic threshold was expressed in relative terms (%$\dot{V}O_2$max) they observed no significant differences between the cyclists (66.3%) and runners (61.2%) on the bicycle ergometer or the runners (77.3%) and cyclists (74.3%) on the treadmill. However, when anaerobic threshold was expressed in absolute terms the cyclists demonstrated significantly greater anaerobic thresholds than the runners (3.0 versus 2.56 l/min) on the bicycle ergometer, while the runners demonstrated significantly higher anaerobic thresholds than the cyclists (52.7 versus 46.8 ml/kg/min) on the treadmill. The investigators attributed the tendency for the better anaerobic thresholds to be recorded by the group tested on the activity for which it trained to the specific local muscular adaptations to cycling and running.

The Relationship Between the Onset of Metabolic Acidosis and Hyperventilation

Studies have shown that ventilation and blood lactic acid display similar abrupt increases during an incremental exercise test to fatigue. Researchers have speculated that these similarities in occurence at the "breakaway" point between ventilation and blood lactate may be due to the release of H^+ which increases CO_2 delivery to the lungs and, subsequently, stimulate ventilation (Wasserman et al. 1973, Whipp and Davis 1979).

Hagberg et al. (1982) designed a study where they could test the aforementioned speculation. They examined four McArdle's disease patients who, due to the lack of myophosphorylase, are incapable of muscle glycogenolysis. Their ventilatory threshold occurred at 81% of $\dot{V}O_2max$. They observed that blood lactic acid did not rise above resting values and venous pH did not decrease but rather increased. These observations suggested that hyperventilation during exercise is not causally related with the metabolic acidosis.

Farrel et al. (1983) examined 8 males who underwent cycle ergometer tests on two separate occasions; the control and the experimental treatment. In the control treatment the subjects pedaled for 4 min at 0 work-load and thereafter, at a work-load which was increasing 135 kpm every min until fatigue, while lactate measurements were taken prior to the test and at the end of each work-load. Ventilatory measurements were also monitored at each work-load. In the experimental treatment, the subjects performed the same test as in the control treatment, after they first performed two 3-min work bouts at 1300-2000 kp/min on the cycle ergometer in order to prematurely raise blood lactate levels and lower blood pH. They observed that the onset of hyperventilation occurred at the same $\dot{V}O_2$ in both treatments (control=2.32, experimental= 2.15 l/min) although at this point, blood lactate was significantly elevated (control=1.99, experimental=10.30 mM) and blood pH significantly depressed (control=7.352, experimental=7.267) during the experimental treatment. These observations led the investigators to conclude that the rise in blood lactate and decline in blood pH with the onset of hyperventilation are coincidental rather than causal.

Morrison et al. (1983) investigated the effect of alkaline infusion on the anaerobic threshold. Six males (mean $\dot{V}O_2max$=4.01 l/min) underwent incremental cycle ergometer tests until fatigue. Blood pH at maximum power output was 7.24, and plasma bicarbonate 18.1 mmol/l. In a repeat test on another occasion, 4.2% $NaHCO_3$ was infused intravenously at a rate which kept blood pH and bicarbonate at resting levels. Consequently, blood pH (7.36) and bicarbonate (27.0 mmol) were significantly higher under neutral conditions that those under acidemic conditions, while $\dot{V}O_2max$ did not differ significantly in the two conditions. Ventilatory "breakaway" was also found to be not significantly different for the neutral (79.1% $\dot{V}O_2max$) and acidemic (76.8% $\dot{V}O_2max$) condition. Ventilation at 100% $\dot{V}O_2max$ was also similar for acidemic (150 l/min) and neutral (154 l/min) condition, as well as peak blood lactate for acidemic (10.4 mmol/l) and neutral (10.9 mmol/l). However, peak CO_2 output was significantly different for acidemic (4.58 l/min) and neutral (5.10 l/min) condition. These findings led the investigators to conclude that the ventilatory "breakaway" is unaffected when acidosis is corrected with $NaHCO_3$, and they suggested that non-chemical stimuli contribute toward the increase in ventilation at the anaerobic threshold.

The general conclusion of the aforementioned studies, that the increase in lactate concentration is not responsible for the increase in ventilation during an incremental exercise, is also confirmed with studies by Davis and Gass (1981), Ivy et al. (1981), and Gutin et al. (1980). Of special interest is the finding of Gutin et al. (1980) and Simon et al. (1983-a) that the ventilatory "breakpoint" occurred before the lactate "breakpoint."

Training and Anaerobic Threshold

Costill et al. (1973) and Daniels (1974) have reported that individuals with similar $\dot{V}O_2max$ values perform quite differently in an endurance competition. In addition, Astrand and Rodahl (1977) and Wilmore (1977) point out that athletes may continue to improve their performance although their $\dot{V}O_2max$ reaches a plateau. These observations indicate that other factors than $\dot{V}O_2max$ may also affect endurance performance. Davis et al. (1979) designed an experiment where they investigated one such factor, the anaerobic threshold. Nine middle-aged men performed cycle endurance training 5 days per week each for 45 min per exercise session for 9 weeks. For the first 4 weeks of training the subjects exercised at a target heart rate designed to correspond to a $\dot{V}O_2max$ 50% of the way between the anaerobic threshold and $\dot{V}O_2max$. For the last 5 weeks of training this value was increased to 70%. After training, the anaerobic threshold increased significantly by 44%, expressed as absolute $\dot{V}O_2$, and by 15%, expressed relative to $\dot{V}O_2max$.

Ready and Quinney (1982) examined alterations in anaerobic threshold as the result of endurance training and detraining in 21 males, 25 years of age. The training consisted of cycling on the ergometer at 80% of $\dot{V}O_2max$ for 30 min four times per week for 9 weeks. Training resulted in 70.4% and 19.4% increases in anaerobic threshold expressed as absolute (l/min) and relative (%$\dot{V}O_2max$) terms, respectively. However, the change in relative anaerobic threshold was not statistically significant. Following 9 weeks of detraining 37.1% of the increase in absolute anaerobic threshold was remained. Although the decrease in anaerobic threshold was substantial 6 weeks after training, the final value remained significantly elevated above the pre-test measurement. The authors concluded that

9 weeks of training is sufficient time to cause significant changes in anaerobic threshold and the loss of anaerobic threshold due to detraining appears to be similar to changes in $\dot{V}O_2max$.

The effect of endurance training at an intensity corresponding to 4 mmol/l arterial blood lactate concentration was examined by Yoshida et al. (1982). Seven male college students underwent cycle ergometer training for 15 min on 3 days per week for 8 weeks, at an intensity corresponding to 4 mmol/l arterial blood lactate determined during an incremental exercise test. This training resulted in significant increase in absolute anaerobic threshold (37%), in the onset of respiratory compensation of metabolic acidosis (17%), and $\dot{V}O_2max$ (14%). Furthermore, they observed significant decreases in submaximal $\dot{V}O_2$ (4%), $\dot{V}_E$ (15%), heart rate (10%), R (5%), and lactate (23%). Based on these findings the investigators suggested that the endurance training intensity corresponding to 4 mmol/l arterial lactate, as suggested by Kinderman et al. (1979), would be one of the most effective methods for endurance training.

Denis et al. (1982) investigated the effect of 40 weeks of endurance training on the anaerobic threshold in five subjects, 35 years of age. The subjects underwent bicycle ergometer exercise lasted 60 min per day 3 days a week at an intensity corresponding to 80-85% of $\dot{V}O_2max$. This training resulted in increases in the ventilatory threshold (10%), lactate threshold (11%), anaerobic threshold at 4 mmol/l lactate (18%), maximal work load (22%), and net efficiency (14%). However, no significant increase was observed in $\dot{V}O_2max$. Furthermore, it was shown that although the increase in maximal work load was significant from the 10th week of training, the increase in anaerobic thresholds appeared at the 20th week.

Sjodin et al. (1982) examined muscle enzyme activity changes occurring with an added training of 20 min running at a velocity where V_{OBLA} occurred (4 mmol/l lactate) once a week for 14 weeks to the regular program of eight well-trained middle and long distance male runners. They observed a significant increase in V_{OBLA} (from 4.69 to 4.89 m x s^{-1}), significant decrease in phosphofructocinase (from 7.65 to 5.35 moles x g^{-1} x min^{-1} x 10^{-6}), while the activities of lactate dehydrogenase and citrate synthase were unchanged. However, a significant decrease in PFK/CS activity ratio from 1.42 to 0.90 moles x g^{-1} x min^{-1} x 10^{-4} was observed. The $\dot{V}O_2max$ of the runners did not increase significantly over the 14 weeks. These observations led the investigators to conclude that the training intensity corresponding to V_{OBLA} will increase V_{OBLA} and will result in local metabolic adaptations in the active skeletal muscles of well-trained runners without a significant change in $\dot{V}O_2max$.

Alterations in muscle metabolites and blood lactate in work above and below the anaerobic threshold were investigated by Green et al. (1980). Five active college students served as subjects for the study and they exercised at constant work-load on different occasions at $\dot{V}O_2$ values corresponding to 50, 70, 107 and 117% of $\dot{V}O_2$ at anaerobic threshold. When the subjects exercised below the $\dot{V}O_2$ anaerobic threshold, no change was found in anaerobic threshold, creatine, lactate, glucose-6-P or citrate while a 20% reduction in creatine phosphate was observed. At 107% $\dot{V}O_2$ anaerobic threshold, creatine phosphate was reduced (12.2 to 9.6 $mmol \cdot kg^{-1}$ wet wt) and lactate was increased (3.1 to 7.7 $mmol \cdot kg^{-1}$). At 117% $\dot{V}O_2$ anaerobic threshold, creatine phosphate was decreased even further (to 5.2 $mmol \cdot kg^{-1}$), lactate increased (to 16.7 $mmol \cdot kg^{-1}$), as well as glucose-6-P (0.37 to 0.83 $mmol \cdot kg^{-1}$), and creatine (13.8 to 18.6 $mmol \cdot kg^{-1}$). Blood lactate increases were only observed in work above the $\dot{V}O_2$ anaerobic threshold, and the blood concentrations were consistently below the muscle concentrations. The latter became more exaggerated the higher the $\dot{V}O_2$ anaerobic threshold.

Henritze et al. (1982) investigated the effects of training above and below the onset of blood lactate accumulation on cardiovascular and body composition parameters in college women. The subjects who trained 5 days per week for 12 weeks were divided in two groups, above-OBLA and below-OBLA. After the training period it was observed that only the above-OBLA group showed a significant increase in $\dot{V}O_2max$ (6%) and $\dot{V}O_2$-OBLA (48-50%). It was further observed that while both the above-OBLA and below-OBLA groups showed significant increases in $\dot{V}O_2$-OBLA/$\dot{V}O_2max$ pre-post training the below-OBLA group demonstrated only a 16% increase while the above-OBLA group increased by 42%. Body composition parameters remained unchanged. The investigators concluded that OBLA may be a critical training intensity for eliciting changes in $\dot{V}O_2max$ and $\dot{V}O_2$-OBLA, and that large improvements in $\dot{V}O_2max$ may not be required for large improvements in $\dot{V}O_2$-OBLA.

Robinson and Sucec (1980) examined the relationship of training intensity and anaerobic threshold to endurance performance as measured by a 15 min run. Twenty-one normally active males, 22.3 years of age were divided into distance, interval and control groups. The training program lasted 12 weeks and each group was training as follows: 1) Distance (D) - running continuously for 30 min for a mean frequency of 2.8 times per week (ca. 85% $\dot{V}O_2max$) and a mean speed of 217 m/min. 2) Interval (I) - running intervals of 100m, 200m, 300m at a time work to rest ratio of 1:3 for 30 min for a mean frequency of 2.9 times per week (ca. 125% $\dot{V}O_2max$) and a mean speed of 323 m/min. 3) Control (C) - continued the same activity pattern during the training period. The findings showed that: 1) the mean $\dot{V}O_2max$ scores increased 8.9% (3.73 to 4.06 l/min) for D group and only 3.1% (3.80 to 3.9o l/min) and 3.2% (3.30 to 3.41 l/min) for I and C groups, respectively. 2) The anaerobic threshold changes resulted in mean increases of 15.6% (2.35 to 2.72 l/min) for $\dot{V}O_2$ at anaerobic threshold for D group, 11.3% (2.55 to 2.84 l/min) for I group and 6.5% (2.08 to 2.81 l/min) for C group. 3) increases in anaerobic threshold when expressed in relative terms (% $\dot{V}O_2$max) were 6.2% for D group (63.1 to 67.0 %), 8.1% for I group (67.8 to 73.3%), and 3.0% for C group (63.3 to 65.2%). 4) endurance performance increased 19.3% for D group (2.95 to 3.5 km), 12.8% for I group (3.07 to 3.47 km), and 1.3% for C group (2.97 to 3.0 km). The correlation coefficients for the change in $\dot{V}O_2$max and anaerobic threshold ($\dot{V}O_2$ and % $\dot{V}O_2$max) with changes in endurance performance were 0.14, -0.61, and -0.35, respectively. Based on these observations the authors concluded that both moderate (ca. 85% $\dot{V}O_2$max) and intensive (ca. 125% $\dot{V}O_2$max) training increases anaerobic threshold and endurance performance, ant that anaerobic threshold changes are closely related to endurance performance changes than $\dot{V}O_2$ changes.

Metabolic and performance responses to anaerobic threshold and high intensity training were studied by Rivera et al. (1980). Twenty-four female swimmers, 12-19 years of age were subjected to six weeks of interval training while they were divided in two groups as follows: Group I - high intensity training (84.11% of subjects' best performance time). Group II - training at the anaerobic threshold (an intensity which elicited an accumulation of 4 mmol/l lactate). Maximal aerobic capacity, maximal alactacid capacity, and maximal lactacid capacity were determined from a tethered swimming test, while 100 and 400 meters timed swim were also performed from each subject.

The findings showed that both groups had significant increases in maximal aerobic capacity, maximal alactacid capacity, and maximal lactacid capacity. However, the Group I demonstrated significantly greater gains over the Group II: maximal aerobic capacity 11.42 versus 3.08 cal/kg•min, maximal alactacid capacity 13.10 versus 2.62 cal/kg, and maximal lactacid capacity 11.42 versus 8.73 cal/kg. With regards to performance, both groups improved, with the Group II improving at a faster rate than Group I in 100 m (2.07 versus 1.63 sec) and 400 m (8.18 versus 4.63 sec). The authors' conclusion from this study was that Group I training had a more profound effect on the metabolic responses, but Group II was more effective on the performance tests.

Gibbons et al. (1981) examined the effect of various training intensities on anaerobic threshold, anaerobic power and $\dot{V}O_2max$ in 29 young (mean age = 19.8 years) lowfit (mean $\dot{V}O_2max$ = 35 ml/kg/min) females. The subjects were divided in three groups, Group I (anaerobic threshold heart rate), Group II (anaerobic threshold heart rate plus 40% of anaerobic threshold heart rate), and Group III (anaerobic threshold heart rate minus 40% of anaerobic threshold heart rate). They trained for 8 weeks on treadmills at individual training heart rates ($\pm$ 5 b/min). After the training period the three groups increased significantly in anaerobic threshold, anaerobic power and $\dot{V}O_2max$ from pre- to post-test. No significant difference was found between groups. The authors concluded that anaerobic threshold, anaerobic power, and $\dot{V}O_2max$ are all trainable within the intensity levels which were investigated and they recommended that low-fit females should train at a level 40% below their anaerobic threshold.

The effect of intensity and quantity of exercise on the aerobic (2 mmol/l lactate) and anaerobic (4 mmol/l lactate) thresholds were investigated by LaFontaine et al. (1982). Forty moderately fit (anaerobic thresholds of 55% to 70% of $\dot{V}O_2max$) males were used for the study. The subjects trained at either low (anaerobic threshold minus 20 b/min), medium (aerobic threshold), or high intensity (anaerobic threshold) and either low (15 miles per week) or high (30 miles per week) quantity for ten weeks. Training occurred five days per week and intensity was monitored daily. After the training period the investigators found: 1) the low intensity groups did not increase their aerobic or anaerobic thresholds, 2) the groups training at medium and high intensity increased their aerobic thresholds significantly more than the groups training at low intensity, and 3) the groups training at medium intensity-high quantity and at high intensity-low quantity increased their anaerobic threshold significantly more than the other groups. $\dot{V}O_2max$ did not change in the subjects tested. According to the authors these findings indicated in intensity threshold for increases in the aerobic threshold.

Howard et al. (1982) examined mitochondrial volume changes in different muscle fiber types due to training at the anaerobic threshold. Five untrained subjects underwent 6 weeks of bicycle ergometer training 5 times a week for 30 min at an intensity of 60-82% of their individual $\dot{V}O_2max$, eliciting a blood lactate concentration of 4 mmol/l. This training resulted in significant increases in maximal power (12%), $\dot{V}O_2max$ (13%), power at a blood lactate concentration of 4 mmol/l (18%), volume density of mitochondria in vastus lateralis muscle (40%), and the number of capillaries per number of muscle fiber (21%). Type IIB fibers demonstrated the largest increases in mitochondrial volume (from 2.47% to 4.07%), followed by the Type IIA fibers (from 4.47% to 6.60%) and the Type I fibers (from 6.21% to 7.13%). These observations led the investigators to conclude that untrained subjects exercising at anaerobic threshold show a significant increase in aerobic capacity and an even greater increase in muscle mitochondrial volume, especially in Type II fibers.

Anaerobic Threshold Alterations Following Prolonged Aerobic Exercise

Wiswell et al. (1980) examined whether lowering the muscle glycogen affects the anaerobic threshold. Six marathon runners (mean $\dot{V}O_2max$ =57.26 ml/kg/min) were subjected to a $\dot{V}O_2max$ test on a bicycle ergometer. After the test the subjects rested for 20 min and then they ran for 2 hours in maximal effort (covering 14-17 miles). When the run was completed they rested for another 20 min and repeated the $\dot{V}O_2max$ test. Anaerobic threshold was obtained by using gas exchange measurements ($\dot{V}_E$, $\dot{V}_E/\dot{V}O_2$ and FEO_2) and blood lactates were taken at 4 min after exercise. The findings showed an 8.4% reduction in $\dot{V}O_2max$ (from 4.5 to 4.12 l/min) accompanied with a reduction in anaerobic threshold of 10.7% when expressed in absolute terms (from 3.65 to 3.26 l/min) or 10.4% when expressed in relative terms (from 81.3% to 72.0%). A decrease of 45% was also observed in post-exercise maximum lactate. Furthermore, respiratory exchange ratio was significantly reduced at any given $\dot{V}O_2max$ during the second test. The investigators speculated that this might be the result of a change in type of fuel substrate utilized after the run. A non-significant relationship between the decrease in post-exercise lactate and the decrease in anaerobic threshold was found. The investigators concluded that the increase in anaerobic threshold that occurs with endurance training may be brought about at least in part by increasing muscle glycogen levels.

Sucec et al. (1980) investigated the effect of ultramarathon performance on maximal aerobic power and anaerobic threshold. Five ultramarathon runners, five ultramarathon walkers and 5 control runners served as subjects whose $\dot{V}O_2max$ and anaerobic threshold were tested prior to (9-4 days) and following (2-6 days) a 100-mile track race. For the five days following the race joint and muscle soreness was recorded using Henry's 9 point Pain Scale. The ultramarathon runners covered a mean distance of 108.7 km (16.77 hours), while the ultramarathon walkers covered a mean distance of 100.9 km (16.38 hours). Following the race the runners' $\dot{V}O_2max$ was decreased by 5.4% (from 4.24 to 4.01 l/min), while the walkers' $\dot{V}O_2max$ did not decrease significantly (from 3.23 to 3.17 l/min). The anaerobic threshold was decreased for both runners and walkers, 7.3% (from 2.86 to 2.63 l/min) and 8.0% (from 1.92 to 1.78 l/min), respectively. It was also observed a generalized, moderately intensive joint and muscle soreness throughout the lower and mid-regions of the body which persisted for 2 to more than 5 days following the race. The investigators concluded that mechanisms underlying post exercise soreness are related to the decrements seen in the post $\dot{V}O_2max$ and anaerobic threshold values.

Perceived Exertion Relative to Anaerobic Threshold

Simon et al. (1983-b) examined perceived exertion relative to anaerobic threshold in six highly trained and six sedentary untrained men. Borg Scale ratings of perceived exertion, lactate, and gas exchange measurements were taken throughout an incremental cycle ergometer test. $\dot{V}O_2max$ and anaerobic threshold for the trained group averaged 63.8 ml/kg/min and

60.6% $\dot{V}O_2max$, while those of the untrained group averaged 35.5 ml/kg/min and 45.1% $\dot{V}O_2max$, respectively. The trained subjects' perceived exertion at the anaerobic threshold (13.5) was significantly greater than that of the untrained subjects' (10.5). However, the mean perceived exertion corresponding to a lactate concentration of 4 mmol/l in the trained (16.2) and untrained (15.4) were similar which occurred at 85% and 80.1% $\dot{V}O_2max$, respectively. It was also observed that the correlation between perceived exertion and % $\dot{V}O_2max$ for both groups combined was 0.94, while for perceived exertion and % anaerobic threshold was significantly lower and correlated at 0.87. The investigators concluded that 1) trained subjects rate the effort of work at the anaerobic threshold to be greater than untrained subjects but both groups rate it similarly at a lactate concentration of 4 mmol/l, and 2) perceived exertion is more highly related to % $\dot{V}O_2max$ than % anaerobic threshold.

Dressendorfer et al. (1981) examining 110 non-athletic men, 30 to 61 years of age reported a rating of perceived exertion of 14 $\pm$ 2 ("somewhat hard" to "hard") at the time the anaerobic threshold occurred.

Anaerobic Threshold Relationships With Various Metabolic Parameters

Green et al. (1979) investigated whether the variability in anaerobic threshold which exists between individuals may be explained by muscle fiber type and composition. Examining 10 active college males (mean $\dot{V}O_2max$=53.9 ml/kg/min) they found that their muscle fiber type distributions were 46.3, 44.3 and 8.9% for type I, IIA, and IIB, respectively, while their anaerobic threshold occurred at 75% $\dot{V}O_2max$. Correlation coefficients between the fiber type distributions and anaerobic threshold were found to be non-significant and ranged between -0.11 and 0.30. No significant difference was also found when fiber type was expressed as a percent of cross sectional area (r=-0.44 to 0.37) or when SDH activity was used. The investigators concluded that the muscle characteristics studied do not influence the onset of anaerobiosis as represented by the anaerobic threshold.

Rusko et al. (1980) examined anaerobic threshold, skeletal muscle enzymes and fiber composition in 15 young (mean age=17.6 years) female cross-country skiers. Their anaerobic threshold averaged 40.9 ml/kg/min or 86% of $\dot{V}O_2max$. It was observed that $\dot{V}O_2max$ correlated significantly (r=0.60) with anaerobic threshold, expressed in ml/kg/min (absolute) and non-significantly when expressed in % $\dot{V}O_2max$ (relative). The % ST fibers showed no significant correlation with relative anaerobic threshold.

SDH correlated significantly with relative anaerobic threshold (r=0.63) and citrate synthase with anaerobic threshold expressed in ml/kg/min (r=0.58). The age of the subjects correlated positively with relative anaerobic threshold (r=0.54). According to the authors these results support the hypothesis that anaerobic threshold is related to oxidative capacity of muscle.

The relationship between anaerobic threshold and oxygen transport was investigated in 32 biathlets 18.7 years of age (Rusko and Pahkila, 1980). The subjects had a $\dot{V}O_2max$ and anaerobic threshold of 62 ml/kg/min and 49 ml/kg/min (78% $\dot{V}O_2max$), respectively. It was observed that heart volume ($\bar{x}$ = 383 ml/m^2) and hematocht ($\bar{x}$ = 46.9%) correlated significantly with $\dot{V}O_2max$ and anaerobic threshold. The investigators concluded that determinants of oxygen transport may have influence on the onset of metabolic acidosis.

Komi et al. (1981) examining 9 subjects reported a significant relationship between %ST muscle fibers and V_{OBLA} (r=0.78), and between average mechanical power output at V_{OBLA} and V_{OBLA} (r=0.90), while the mechanical work was not related significantly to V_{OBLA}.

Ivy et al. (1980) studying 13 male subjects found significant relationships between the capacity of muscle homogenates to oxidize pyruvate and absolute (r=0.94) or relative (r=0.83) lactate thresholds; between %ST muscle fibers and absolute (r=0.74) and relative (r=0.70) lactate thresholds; and between $\dot{V}O_2max$ and absolute lactate threshold (r=0.91).

Sjodin et al. (1981) examined 19 male marathoners and reported a relationship between V_{OBLA} and LDH and PFK/CS ratio of r=-0.46 and -0.68, respectively. %ST muscle fibers and capillary density correlations with V_{OBLA} were r=0.62 and r=0.58, respectively. Furthermore, it was shown that PFK/CS ratio together with capillary density accounted for 61% of the variance in V_{OBLA}.

Tesch et al. (1981) reported that 16 males showed a significant correlation between OBLA (%$\dot{V}O_2$max) and %ST area. However, no correlation was found between O_2 consumption at OBLA and %ST area. Furthermore, it was shown that %ST area plus capillary density accounted for 92% of the variance in OBLA (r=0.96). When $\dot{V}O_2$max was added as another variable the correlation was only slightly higher (r=0.98). The investigators suggested that both inherent and adaptative qualities of the exercising muscle are of significance for the onset of blood lactate accumulation.

Anaerobic Threshold as a Predictor of Distance Performance and its Relationship with Race Pace

Weiser et al. (1978) investigated the relationship of anaerobic threshold and race pace of 3.2 km in 7 men and 5 women joggers. The subjects underwent an incremental test where it was observed that eight of them showed two abrupt changes in the $\dot{V}_E/\dot{V}O_2$ ratio, the first occurred at 73% $\dot{V}O_2$max and the second at 87% $\dot{V}O_2$max. Four subjects showed only the first abrupt change at 78% $\dot{V}O_2max$. From a 3.2 km time trial, the running speed for each 400 m of the middle 2.4 km was averaged. The subjects who showed two anaerobic threshold changes ran at the second one, while those with one anaerobic threshold change ran at that speed. It was observed that running speed was significantly correlated with the treadmill speed at the critical anaerobic threshold (r=0.92) and with $\dot{V}O_2max$ (r=0.86), while the critical anaerobic threshold expressed as %$\dot{V}O_2max$ was not significantly correlated with $\dot{V}O_2max$ (r=0.19). Based on these observations the investigators suggested that a person's running speed for 3.2 km closely approximates that pace above which an exponential increase in hyperventilation occurs as pace is increased.

Thorland et al. (1980) studied relationships between cross country (5000m) running times and metabolic responses during treadmill running in ten female (18.8 to 28.2 years) collegiate cross-country competitors. They observed that the anaerobic threshold was the best predictor of cross-country run time and this relationship was described by the following equation: Best time (sec) = 2091.23 - (19.363 x anaerobic threshold). Anaerobic threshold values accounted for 71% of the variance (r=0.84) in the running performances, while $\dot{V}O_2max$ values either singularly (r=0.78) or in combination with anaerobic threshold (r=0.81) was not as accurate a predictor of running times.

The relationship between anaerobic threshold and $\dot{V}O_2$ at self-paced running was investigated by Dwyer et al. (1982) in 16 women. The velocity of individual 15 min self-paced running was determined on a track and these velocities were then used in 8 min treadmill runs to obtain $\dot{V}O_2$ at a self-paced running pace. These data were compared to $\dot{V}O_2max$ and anaerobic threshold obtained in incremental treadmill runs to fatigue. The $\dot{V}O_2max$ was 47.5 ml/kg/min and anaerobic threshold averaged 34.7 ml/kg/min or 73.2% $\dot{V}O_2max$. It was observed that in self-paced running and anaerobic threshold correlated highly (r=0.87). The investigators concluded that women run slightly above anaerobic threshold when they run at what they perceive to be a comfortable pace for aerobic training.

Green et al. (1981) examining 18 highly trained male adolescent and adult distance runners observed that one and two mile track times were inversely related to anaerobic threshold and $\dot{V}O_2max$. It was also suggested by the authors that anaerobic threshold may plateau with training and with age like $\dot{V}O_2max$.

Kumagai et al. (1982) examined relationships between anaerobic threshold and performances in 5km, 10km, and 10 mile races in 17 endurance runners (16-18 years of age). Anaerobic threshold averaged 51.0 ml/kg/min and $\dot{V}O_2max$ averaged 64.1 ml/kg/min. They observed that correlations between $\dot{V}O_2max$ and performances in 5km, 10km, and 10 mile races were not high (r=-0.64, r=-0.67, r=-0.57, respectively), while those between anaerobic threshold and performances were very high (r=-0.94, r=-0.83, r=-0.83, respectively). Anaerobic threshold accounted for 83.9%, 70.4%, and 69.7% of the variance in the 5 km, 10 km, and 10 mile performances, respectively.

Tanaka et al. (1983) compared the contribution of the anaerobic threshold and OBLA to endurance performance in eleven non-endurance trained active males, aged 22-28 years. They observed that anaerobic threshold (expressed in ml/kg/min) correlated higher with 1500-m min run performance (r=-0.81) than did $\dot{V}O_2max$ (r=-0.77) and OBLA (r=-0.60), as well as work rate at anaerobic threshold (r=-0.77) with performance versus work rate at OBLA (r=-0.70). Anaerobic threshold, work rate at anaerobic threshold, OBLA, and work rate at OBLA accounted 67, 60, 37 and 50% of the variance in endurance performance, respectively. When heart rate at anaerobic threshold was combined to anaerobic threshold as another predictor, the variance of these two variables to endurance performance increased to 84%.

Reybrouck et al. (1983) examined relationships between ventilatory threshold for short-term exercise (defined as the work rate or $\dot{V}O_2$ immediately below the work rate at which ventilation increased disproportionately relative to work rate or $\dot{V}O_2$) and ventilatory threshold for long-term exercise (defined as the work rate or $\dot{V}O_2$ immediately below the work rate at which ventilation continued to increase with time rather than attain a steady state) with endurance performance

(12-min run) in 8 males. They observed that 12-min run showed the highest correlation with the ventilatory threshold for long-term exercise (r=0.82) in comparison to the ventilatory threshold for short-term exercise (r=0.73). They concluded that the ventilatory threshold for long-term exercise is a more specific measure to predict endurance performance.

Sjodin and Jacobs (1981) examining 18 male marathoners reported a very high correlation (r=0.96) between V_{OBLA} and marathon running velocity. Furthermore, it was shown that V_{OBLA} accounted for 92% of the variance in marathon running velocity, while V_{OBLA} together with training volume prior to the marathon accounted for 96% of this variance. Farrel et al. (1979) showed that V_{OBLA} was most closely related ($r \geq 0.91$) to performance (3.2km, 9.7km, 15km, 19.3km, and marathon races) than did %ST muscle fibers ($r \geq 0.47$), $\dot{V}O_2max$ ($r \geq 0.83$), running economy ($r \geq 0.49$), and $\dot{V}O_2$ corresponding to the OBLA ($r \geq 0.91$). They also observed that the high relationship between V_{OBLA} and race pace is independent of the competitive level of the runner.

LaFontaine et al. (1981) studied the relationship between maximal steady state (defined as the oxygen uptake, heart rate and/or treadmill velocity at which plasma lactate concentration was 2.2 mmol/l of plasma) and various running events. They observed that running paces for the 402,3m, 3.22km, 8.05km, 16.09km, and 20km distancs correlated highly with the treadmill pace at maximal steady state (r=0.84 to 0.995).

Rhodes and McKenzie (1984) designed a study to examine the relationship between predicted marathon times (calculated from the running velocity at the threshold of anaerobic metabolism-V_{TAM}) and actual performance times, in a marathon. They examined eighteen male marathon runners whose V_{TAM} was determined by excess CO_2 elimination curves as described by Volkov et al. (1975). From the V_{TAM} values they estimated the predicted times for the marathon and correlated these with the actual times taken from a marathon race. They found a highly significant correlation (r=0.94) between the predicted and actual marathon times, and they suggested that, with other factors being optimal, V_{TAM} may be a good predictor for marathon performance.

Heart Rate Indices and Anaerobic Threshold

Dressendorfer et al. (1981) examining 110 nonathletic men, 30 to 61 years of age, observed that the heart rates at anaerobic threshold were significantly higher than 85% of actual maximum rate (152 b/min) or 85% of the age-predicted (220 minus age) maximum heart rate (151 b/min). However, heart rates at anaerobic threshold were not significantly different from 80% of maximum heart rate reserve (154 b/min) as calculated by the Karvonen equation. In 78 of the 110 subjects (71%), heart rate at anaerobic threshold was higher than 85% of maximum heart rate.

Patton et al. (1979) examined 5 runners and 6 non-runners and found that the runners' anaerobic threshold occurred at higher absolute and relative levels at $\dot{V}O_2max$. However, the heart rate at anaerobic threshold for both groups was not significantly different, runners=181 b/min, non-runners= 185 b/min. The investigators concluded that regardless of an individual's fitness level absolute heart rate measures provide a good indication of work level required for anaerobic threshold.

Dwyer and Bybee (1983) investigated the heart rate response and percent maximum heart rate of anaerobic threshold in 20 young females. The subjects' anaerobic threshold, $\dot{V}O_2max$ and maximum heart rate were determined during an incremental cycle exercise to fatigue, while the heart rate at anaerobic threshold was determined by regressing heart rate on $\dot{V}O_2$ using individual regression equations. The mean value for anaerobic threshold was 70.1% $\dot{V}O_2max$ with corresponding heart rate of 158.4 b/min (86.3% of maximum heart rate). They observed that all subjects were below anaerobic threshold at 70% of maximum heart rate. However, a zone of non-uniform work stress with respect to anaerobic threshold was observed between 75-90% of maximum heart rate (58-75% $\dot{V}O_2max$). Within this zone a highly variable number of subjects exercised above their anaerobic threshold at any specific percent at maximum heart rate. Furthermore, the low correlation of r=0.60 that was found between % of maximum heart rate of anaerobic threshold and $\%\dot{V}O_2max$ of anaerobic threshold did allow, according to the authors, the translation of anaerobic threshold to a percent maximum heart rate or absolute heart rate figure for training prescription. The investigators concluded that standard values for % maximum heart rate at anaerobic threshold, grouped by age or sex, should not be applied to individuals due to the wide range among homogeneous subjects in relative heart rate at the anaerobic threshold.

Parkhouse et al. (1982) examined thirty-three men, 17 to 28 years of age who were divided into 3 groups; untrained, trained, and highly trained. They observed that the heart rates at anaerobic threshold for the 3 groups were almost identical (163.9, 164.4, and 167.0 b/min), as well as the percentage of maximum heart rate at anaerobic threshold (82, 84, and 86). In addition, 67% of all subjects had a heart rate at anaerobic threshold above 80% of maximum heart rate. The investigators concluded that % of maximum heart rate may be used for exercise prescription, however, training at 80% of maximum heart rate may be too low a stimulus for maximal aerobic/anaerobic improvement.

Anaerobic Threshold Alterations with Changes in Substrate Availability

Ivy et al. (1981) investigated the lactate threshold of 9 active subjects during cycle ergometer exercises under control, high blood glucose, and high blood free fatty acid conditions. During the glucose trial blood lactate was greater than control at all work-loads. Corrected blood lactate values (blood lactate - pre-exercise value = change in blood lactate) were the same for control and glucose trials. It was observed that the lactate threshold was not different for the two treatments (control = 53.9% $\dot{V}O_2max$; glucose = 52.7% $\dot{V}O_2max$). However, free fatty acid condition caused a reduction in both blood lactate and change in blood lactate at all work-loads although $\dot{V}O_2$ was the same as control. The free fatty acid condition also caused a shift in the lactate threshold (59.8% $\dot{V}O_2max$). Based on these observations the investigators concluded that the lactate threshold can be altered by changing substrate availability.

Kowalchuk and Hughson (1981) showed that 5 days of dietary manipulation affects the anaerobic threshold determined by gas exchange measurements. Five female subjects were tested under high carbohydrate diet (H), low carbohydrate diet (L) and a normal mixed diet (M). The significantly lower R that was found for L than that for H and M, certified the changes in the relative proportion of carbohydrate and fat metabolized during exercise. The plasma lactate levels were lower during L and higher during H. However, $\dot{V}O_2max$ was significantly higher following H (2535 ml/min) than following L (2305 ml/min). Furthermore, the $\dot{V}_E/\dot{V}CO_2$ was higher in L throughout the exercise, while the oxygen uptake corresponding to the anaerobic threshold was higher in H (1595 ml/min) and lower in L (1310 ml/min). These observations led the investigators to conclude that dietary manipulation alters the ventilatory response to progressive exercise.

Hughes et al.(1982) studying 9 males observed that the anaerobic threshold was affected by the glycogen state of the subjects. When the subjects were under a glycogen-depleted state the ventilatory threshold was shifted to a lesser work rate, while the lactate threshold to a greater work rate relative to a normal glycogen state.

Summary

The anaerobic threshold is determined by 1) lactate measurements, 2) gas exchange measurements, 3) electromyography, and 4) field tests. These methods appear to correlate highly among them, however, the determination of anaerobic threshold is very subjective; independent investigators may obtain different anaerobic thresholds. The ventilatory measurements which determine the anaerobic threshold are $\dot{V}_E$, $\dot{V}CO_2$, $\dot{V}_E/\dot{V}O_2$, $\dot{V}_E/\dot{V}CO_2$, R, FEO_2, $FECO_2$, O_2P, and excess CO_2. $\dot{V}_E/\dot{V}O_2$, $\dot{V}_E$, and the excess CO_2 methods seem to be the most valid and reliable. Recently, investigators discern two "breakaway" points; the first corresponding to approximately 2 mmol/l lactate (aerobic threshold) and the second corresponding to approximately 4 mmol/l lactate (anaerobic threshold).

New terms of thresholds have also been introduced ; the threshold determined by gas exchange measurements is called ventilatory, while that determined by lactate measurements is called lactate threshold.

Anaerobic threshold is exercise modality dependent; athletes tend to show a higher anaerobic threshold when they are tested at the activity for which they train. This reflects the specificity of training and adaptation.

The belief that the increase in blood lactate concentration was responsible for the abrupt increase in ventilation during an incremental exercise does not hold true any longer. It was shown that these abrupt changes are not causal but rather only coincidental.

Part of the improvement in endurance performance is attributed to the increase of anaerobic threshold after specific training. There is disagreement among investigators concerning the magnitude of improvement of the anaerobic threshold, probably because of different training protocols used and different fitness levels of subjects. it seems, however, that a training intensity corresponding to approximately 4 mmol/l lactate is the most effective in eliciting the maximum improvement.

Anaerobic threshold decreases after prolonged aerobic exercise; it is also affected by substrate availability.

There is a relationship between $\dot{V}O_2max$, SDH, citrate synthase, heart volume, hematocrit, hemoglobin, and %ST fibers with anaerobic threshold.

Anaerobic threshold determines the pace which individuals can run aerobically for a long distance. Knowing the anaerobic threshold allows an approximation of performance in prolonged aerobic activities.

Heart rate can be a good indicator of the anaerobic threshold, regardless of sex, age, and fitness levels of individuals.

Anaerobic threshold is a controversial issue in the area of exercise physiology. Undoubtedly, there is a need for more information to be obtained in this area which will lead into clarification of the phenomenon of transition from aerobic to anaerobic metabolism.

APPENDIX B - MARGINALS

FACTOR	LEVEL	VARIATE	COUNT	MEAN	STD DEV
STATUS	TRAINED	LT	12	9.5	0.8
		LT(%$\dot{V}O_2$max)	12	82.1	8.8
		VT	12	8.5	0.8
		VT(%$\dot{V}O_2$max)	12	74.8	8.4
		VO_2max	12	58.3	3.0
		TTT	12	903.7	70.4
		HR_{LT}	12	166.9	8.3
		R_{LT}	12	0.97	0.05
	UNTRAINED	LT	12	7.6	0.4
		LT(%$\dot{V}O_2$max)	12	81.3	5.6
		VT	12	7.6	0.7
		VT(%$\dot{V}O_2$max)	12	80.0	7.0
		VO_2max	12	45.9	2.9
		TTT	12	691.2	74.2
		HR_{LT}	12	167.2	9.4
		R_{LT}	12	1.00	0.06
PREPOST	PRE	LT	12	8.6	1.2
		LT(%$\dot{V}O_2$max)	12	80.9	7.7
		VT	12	8.5	0.9
		VT(%$\dot{V}O_2$max)	12	78.8	8.3
		VO_2max	12	53.2	7.3
		TTT	12	827.5	115.6
		HR_{LT}	12	166.9	7.9
		R_{LT}	12	1.02	0.06
	POST	LT	12	8.5	1.1
		LT(%$\dot{V}O_2$max)	12	82.5	6.9
		VT	12	7.7	0.8
		VT(%$\dot{V}O_2$max)	12	76.0	7.8
		VO_2max	12	51.0	6.7
		TTT	12	767.5	140.5
		HR_{LT}	12	167.2	9.7
		R_{LT}	12	0.96	0.04

APPENDIX C-INDIVIDUAL SUBJECTS PHYSIOLOGICAL DATA

	LT (mph)	.LT (%VO_2max)	VT (mph)	.VT (%VO_2max)	$\dot{V}O_2$max (ml.kg^{-1}.min^{-1})	TTT (sec)	HR_{LT} (b/min)	R_{LT}
TRAINED-PRE VALUES								
1	10.0	79.91	7.5	61.76	61.73	990	175	1.03
2	10.0	87.01	10.0	87.01	59.54	900	166	0.94
3	10.0	78.51	9.0	74.71	57.85	915	176	1.05
4	8.0	67.11	8.5	73.03	56.62	840	156	1.05
5	9.5	81.50	9.5	81.50	58.00	900	158	0.98
6	10.0	95.23	9.0	78.87	63.89	1005	168	0.89
TRAINED-POST VALUES								
1	9.5	78.64	7.5	63.97	57.40	945	169	0.98
2	10.0	83.20	8.0	68.18	60.66	945	167	0.99
3	9.5	81.96	9.0	77.00	58.22	855	179	0.99
4	8.0	70.19	7.5	67.80	53.94	795	158	0.95
5	9.0	84.26	8.0	75.38	53.19	795	156	0.93
6	10.0	97.76	9.0	88.21	58.00	960	175	0.90
UNTRAINED-PRE VALUES								
7	7.5	83.13	8.5	87.09	41.30	690	176	1.07
8	7.5	72.05	7.0	67.09	46.73	720	155	1.01
9	8.0	75.06	8.5	80.78	49.00	825	169	1.06
10	7.0	76.99	8.5	87.49	46.20	735	175	1.00
11	8.5	88.61	8.0	80.90	50.84	735	169	1.10
12	7.5	85.59	7.5	85.59	46.69	675	160	1.05
UNTRAINED-POST VALUES								
7	7.5	83.95	7.5	83.95	41.88	630	170	0.99
8	7.5	77.09	7.0	72.18	47.05	690	163	0.93
9	8.0	78.98	7.0	68.52	45.80	780	164	0.99
10	7.0	80.84	7.0	80.84	46.40	630	186	0.92
11	8.0	81.85	8.0	81.85	47.34	630	152	0.94
12	7.5	90.82	6.5	83.86	41.51	555	167	1.03

APPENDIX D - BLOOD LACTATE VALUES

(mph):	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0
TRAINED-PRE VALUES															
1					2.1	2.1	2.6	2.3	2.9	3.9	4.9	4.9	8.1	7.6	
2					1.0	1.0	1.3	1.4	1.4	2.2	2.1	2.2	5.2		
3					1.1	2.3	2.1	2.8	3.3	4.1	5.2	4.9	7.2		
4	3.3	3.3	2.9	2.9	3.0	3.6	3.2	3.8	5.2	6.7					
5			1.7	1.4	1.2	1.1	1.6	1.5	3.3	2.6	3.2	6.7	8.5		
6					2.7	2.1	2.1	2.8	2.7	3.6	6.3	7.1	9.4	14.8	21.6
TRAINED-POST VALUES															
1					1.3	1.2	1.5	2.0	2.8	4.3	4.4	5.4	6.9	10.0	
2					1.1	1.1	0.9	1.1	1.3	1.8	2.3	3.0	3.8		
3					1.6	1.2	2.0	2.2	2.7	4.0	4.8	6.6			
4	1.2	1.1	2.1	1.4	1.4	1.7	2.1	2.7	5.8	4.6	5.7				
5			1.5	0.9	1.4	1.1	1.4	2.2	2.9	3.5	4.6				
6					1.2	1.2	1.4	2.0	2.2	4.0	4.8	7.1	9.3	15.6	
UNTRAINED-PRE VALUES															
7	2.9	2.9	3.7	4.1	5.1	5.0	6.1	6.3	7.9						
8	3.6	2.7	3.3	3.1	4.9	6.7	8.2	13.8							
9		1.3	1.1	1.9	2.0	3.5	4.7	6.0	8.9	10.6					
10	1.9	2.1	2.3	3.0	3.1	3.7	5.0	6.2	6.4	8.5					
11	4.5	4.1	5.4	4.7	6.4	6.1	7.9	10.0	10.2	13.1					
12	4.0	3.9	4.6	6.0	4.8	7.3	10.0								
UNTRAINED-POST VALUES															
7	1.4	1.7	1.7	2.0	2.5	3.9	4.5								
8	1.3	2.0	1.6	2.2	3.0	4.0	6.1	8.8	11.4						
9	0.9	0.9	0.9	1.4	1.4	2.1	3.1	4.2	6.4	9.5					
10	1.7	1.7	2.1	2.8	4.2	4.7	6.6	8.7	11.3						
11	1.4	1.5	1.8	2.2	2.5	4.1	4.1	4.9	5.7						
12	6.3	5.8	6.2	6.9	8.5	10.5	11.1								

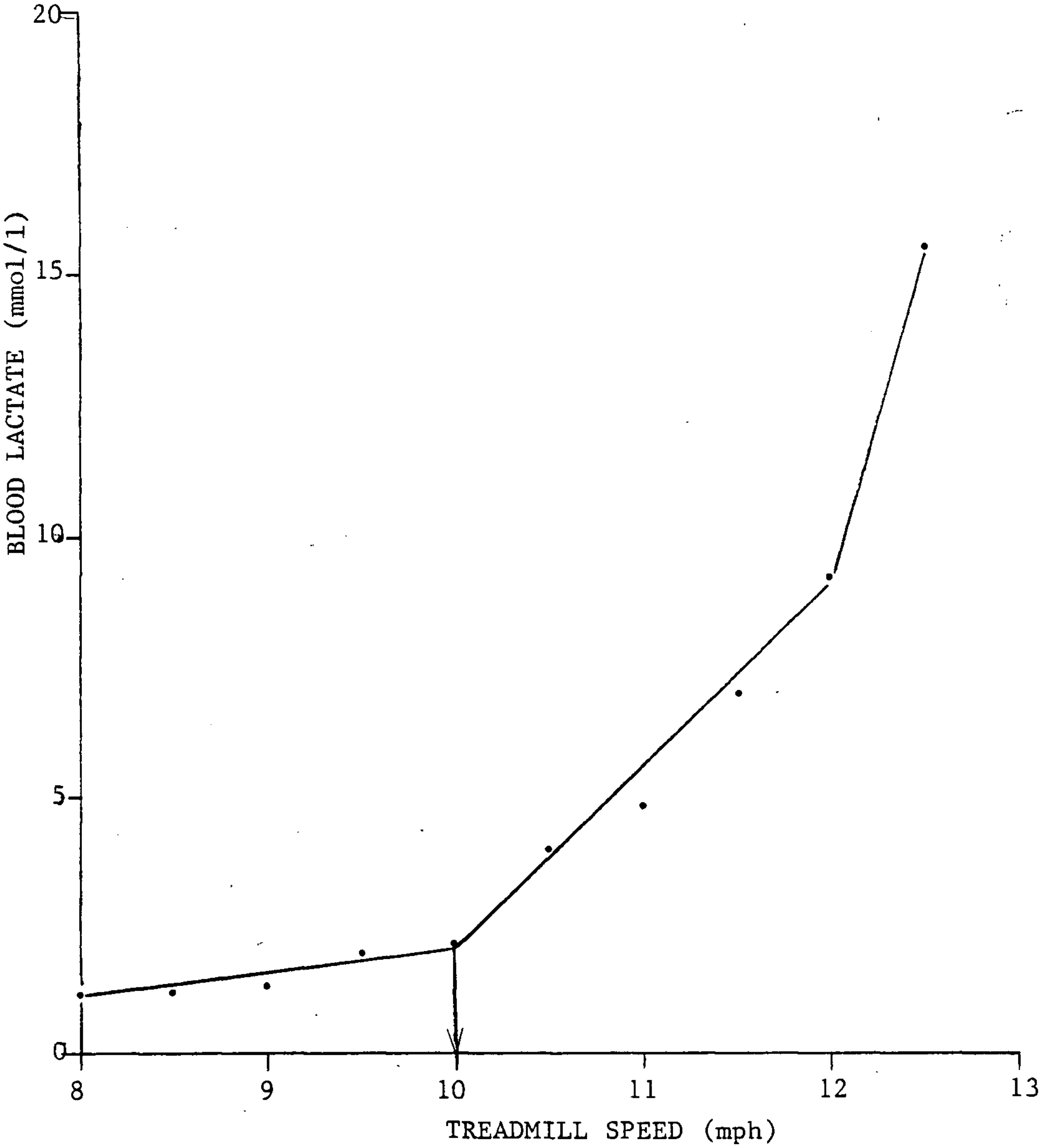

FIGURE 1. Lactate curve for one subject shows a velocity of 10.0 mph at the lactate threshold.

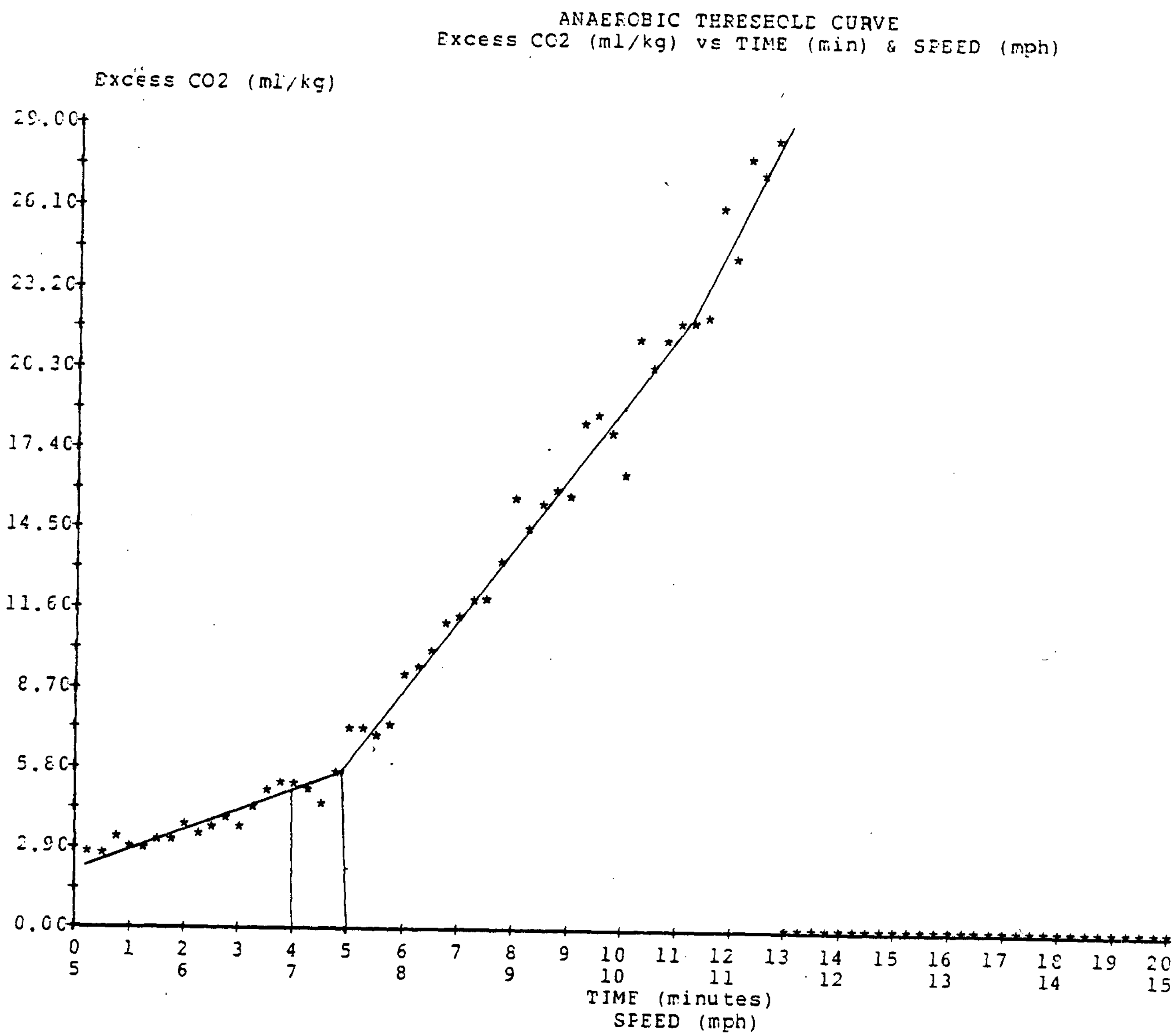

FIGURE 2. Excess CO_2 curve for one subject shows a velocity of 7.0 mph at the ventilatory threshold.