A CORRELATIONAL ANALYSIS OF MAXIMAL OXYGEN UPTAKE AND ANAEROBIC THRESHOLD AS COMPARED WITH MIDDLE AND LONG DISTANCE PERFORMANCES

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Abstract

Various studies have reported on $\dot{V}O_2\text{max}$ differences in men, with or without respect to distance run performances, and demonstrated that $\dot{V}O_2\text{max}$ was the most important factor in endurance work capacity. This study was undertaken to reveal whether $\dot{V}O_2\text{max}$ would still be the best determinant of endurance work capacity (or distance run performances), comparing it with AT parameters using the technique of correlational analyses. Twenty-seven distance runners, 16-26 years of age including an Olympic runner, underwent a multistage-incremental treadmill test for the assessment of submaximal and maximal work capacity. ATs were subjectively evaluated and determined as the point of breakaway of gas exchange criterion parameters according to Davis et al.'s method, and also referring to Wasserman et al.'s method.

The mean $\dot{V}O_2\text{max}$ was 4.518 l/min (70.1 ml/kg $\cdot$ BW/min, 78.1 ml/kg $\cdot$ LBM/min), whilst the mean AT appeared to be 3.444 l/min (52.8 ml/kg/min, 75.6% of $\dot{V}O_2\text{max}$). These results are in good agreement with previous results reported by others. Interestingly, all distance performances (i.e., 1-mile, 2-mile, and 3-mile) correlated highest with AT(ml/kg/min), secondly with exhaustion time, and thirdly with either $\dot{V}O_2\text{max}$ or another AT parameter. AT(ml/kg/min) alone accounted for approximately 51%, 73%, and 80% of the variance in the 1-mile, 2-mile, and 3-mile performances, respectively.

Since absolute $\dot{V}O_2\text{max}$ is known to be a function of body size (e.g., body weight), an attempt was made to evaluate the relationships between the metabolic parameters and the distance performances through partial correlations holding the influence of body weight or LBM statistically constant. As a result, the correlation of $\dot{V}O_2\text{max}$ (l/min) with the 3-mile performance increased considerably to $r_p = -0.781$; however, the degree of the relationship was not greater than the zero-order correlation ($r = -0.896$) obtained between AT (ml/kg/min) and the performance. Furthermore, when entered into a forward selection multiple regression with the 3-mile performance as the dependent variable, AT (l/min) accounted for only an additional 0.8% of the variance. $\dot{V}O_2\text{max}$ (l/min), true % O_2 , % body fat body weight, $\dot{V}O_2\text{max}$ (ml/kg/min), and vital capacity also accounted for only an additional 0.1%, 0.4%, 0.5%, 0.8%, 1.8%, and 1.8% of the variance, respectively. These data indicate that, considering the sample studied and limitations within this study, AT (ml/kg/min) could be the most significant determinant of the 3-mile run performance and, though to a lesser extent, the 2-mile and 1-mile run performances.

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INTRODUCTION

Until quite recently considerable significance or importance has most commonly been at-

tached to maximal oxygen uptake ($\dot{V}O_2\text{max}$) as the single best determinant or predictor of total body endurance⁽¹⁾⁽⁴⁾⁽⁷⁾⁽¹⁸⁾⁽²³⁾⁽³⁴⁾. However, a significantly high relationship of endur-

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ance performance with running economy (or efficiency), which is defined as the oxygen uptake (or % $\dot{V}O_2\text{max}$) for a given standardized submaximal treadmill velocity²⁰⁾ or for a given amount of work load³⁹⁾, has been identified by some researchers³⁾⁴⁾⁵⁾³⁹⁾. This may in turn mean that $\dot{V}O_2\text{max}$ would not always be a critical determinant of distance performance excellence. Furthermore, anaerobic threshold (AT), lactate threshold or a roughly synonymous variable (i.e., onset of plasma lactate accumulation) with AT seems to have been assumed to be of equal or even greater prominence than $\dot{V}O_2\text{max}$ according to several studies mostly done in the last decade⁹⁾¹⁹⁾²⁸⁾²⁹⁾⁴¹⁾⁴³⁾. More attempt with regard to these relationships, however, must be done.

The purposes of the present study were (1) to investigate to what extent AT and connected parameters are related to middle-long distance performances, comparing these with the degree of relationships obtained between maximal cardiorespiratory parameters and the performances, and (2) to find the single best predictor or the best combination of predictors for the explanation of the performances.

A major limitation for the study lies in the fact that an invasive assessment of metabolic acidosis as evidenced by blood lactate sampling was not performed during a process of AT determination. An assumption was then established by adopting Davis et al.'s suggestion⁶⁾ that the onset of metabolic acidosis subsequent to lactate accumulation could be determined by a non-invasive gas exchange AT measurement. Davis et al. have, in fact, found a significantly high correlation ($r=0.95$) between venous blood lactate AT measurements and non-invasive gas exchange AT measurements. Many other researchers¹³⁾¹⁹⁾²⁴⁾²⁹⁾³⁸⁾⁴¹⁾ have also followed this line of experimentation.

METHOD

1) Subjects and their Performances

The subjects employed for this study were 27 highly motivated, well trained male volunteers, aged 16 to 26 years, classified as endurance runners. One of the subjects, Rod Dixon (R.D.), an Olympic runner from New Zealand, whose record in the 5000M run was

13'17"3 (July 5, 1976), was included in this study. His other records in the same year included 7'43"6 in the 3000M run and 3'36"1 in the 1500M run, both of which are still better than today's Japan records. The one-mile, 2-mile, and 3-mile run performances for all other subjects (Americans) were measured several times within 6 months before the maximal treadmill testing.

2) Experimental Techniques

The underwater, or hydrostatic weighing method was used to determine the percentage of adiposity (fat) and fat free mass (lean body mass). Prior to the hydrostatic weighing, each subject was measured for anthropometric attributes. Vital capacity recordings were based upon the average of three to five trials. An average value was then multiplied by a correction factor of 0.24 to attain the residual lung volume, as recommended by Wilmore⁴⁴⁾. Then, each subject was weighed under water in the fiberglass densitometric apparatus of Rich²⁷⁾, with corrections for the residual volume in the lungs and gas in the intestinal tract. An almost complete forced expiration was made before the submersion and any additional expiration while under water, until the subject could no longer expire. Submerged weight for body density was determined by averaging the three highest readings from seven measured values.

So as to obtain $\dot{V}O_2\text{max}$, the subjects were required to run continuously throughout the work bouts until volitional exhaustion, and were verbally encouraged to minimize discouragement and to avoid premature cessation of work.

Minute-by-minute pulmonary ventilation was monitored through a Parkinson C.D. IV gasometer with a high velocity flow during all phases of walking and running. A Collins triple "J" high velocity one way breathing valve with a rubber mouthpiece and standard nose clip was used for air direction control. Expired air temperature was recorded from a thermometer located in the intake hose of the gasometer. Expired gas samples of approximately 50cc each were taken into oiled glass syringes from a 2.56 l air mixing chamber, designed by Dill⁹⁾, every two minutes up to the 6th minute and then each minute thereafter. These gas samples were analyzed

for oxygen and carbon dioxide fractions, with the Instrumentation-Laboratory Ultra pH and Blood Gas Analyzing System, Model 113-51. The gas analyzer was calibrated before the test with the micro-Scholander method. Heart rate (HR) was monitored during the last fifteen seconds of each minute with a Sanborn 500 Electro-Cardiograph manufactured by Hewlett-Packard. The primary Bi-polar electrode placement was at a V_5 position.

3) Testing Protocol

The subjects performed the test on a Quinton motor driven treadmill with a remote modular control panel. Work loads for achieving the maximal level of work stress were primarily based on a gradual increase of both the speed and the inclination of the treadmill, as recommended by Taylor et al.⁴⁰⁾, Astrand¹⁾ and Stamford³⁵⁾ with several modifications.

A six-minute work bout with an initial speed of 3mph and a grade of 3% for the walk phase was performed, and then at the 7th and the 17th minute the speed was increased to 5mph and 7mph for the 2nd and 3rd run phases respectively, until exhaustion without resting periods between loads. The grade during the 2nd phase was gradually increased by 0.5% every minute, while during the 3rd phase the grade was increased 1.0% every two minutes up to the 28th min and thereafter maintained at 20%. No one could reach the work of the 29th min, except R.D. who continuously did work for 31 minutes.

4) Calculation of Body Density and Anaerobic Threshold

Calculation of body density and percent body fat were based upon the equation given by Brozek et al.²⁾.

For the determination of AT (i.e., the point of breakaway) gas exchange criterion parameters such as $\dot{V}E$, $\dot{V}CO_2$, FEO_2 , $FECO_2$, and R were used according to the method of Davis et al.⁶⁾. In addition to this, ventilatory equivalents for O_2 ($\dot{V}E/\dot{V}O_2$) and for CO_2 ($\dot{V}E/\dot{V}CO_2$) were used as supplementary criteria to discern the subjects' ATs. These criteria, based on the gas exchange parameters, are summarized as follows: a) the point of departure from a linear relationship in both $\dot{V}E$ and $\dot{V}CO_2$ which can be assumed in some stage of submaximal exercise duration, b) abrupt increases in FEO_2 , c) abrupt increases

in R , and d) a systematic increase in $\dot{V}E/\dot{V}O_2$ without any increase in $\dot{V}E/\dot{V}CO_2$. It should be mentioned that the point of breakaway was in general based on subjective evaluation using a visual inspection of the plotted function.

RESULTS AND DISCUSSION

The feasibility of determining the onset of anaerobiosis, i.e., AT, with a non-invasive procedure, has thoroughly been described by Wasserman and his co-workers, who defined the AT as "the level of work or O_2 consumption just below that at which metabolic acidosis and the associated changes in gas exchange occur." (42 : 236) According to their theoretical considerations and the method proposed by Davis et al., the present study was undertaken to compare AT with $\dot{V}O_{2max}$ in relation to distance performances.

Fundamental statistics for the anthropometric, body composition, maximal cardiorespiratory, and distance performance tests are given in Table 1. Mean values of height, weight, and percent body fat for the present subjects were approximately 178cm, 64kg, and 8.6%, respectively. $\dot{V}O_{2max}$ obtained during the uphill treadmill running averaged 4.518 l/min (70.1 ml/kg/min, 78.1 ml/kg·LBM/min), while AT averaged 3.444 l/min (52.8ml/kg/min). The mean $\dot{V}O_{2max}$ expressed as milliliters of oxygen per kilogram of body weight is very similar to previously reported data from our present laboratory³⁶⁾³⁷⁾³⁸⁾, as well as the results of other studies using distance runners²¹⁾²²⁾³⁹⁾⁴⁵⁾⁴⁶⁾. % AT ranged widely (i.e., 91.5 to 60.5%) and averaged 75.6%, which is relatively great as compared with that of normal individuals²⁹⁾³³⁾, and roughly equal to trained endurance athletes¹³⁾³⁰⁾. Note that % AT of R.D. was the highest and his AT (68.7 ml/kg/min) was also extremely high, enough so to contribute to his great success in distance events (Figure 1).

The variables which correlated significantly with at least one of the three distance performance variables and the coefficients of their correlations are shown in Table 2.

Among the correlation coefficients, particularly high ones (i.e., $r > 0.7$) are indicated by an asterisk. Very interestingly, all the

Table 1. Fundamental Statistics for the Variables

	$\bar{X}$	S D	C V	MAX—MIN
$\dot{V}O_2$ max l/min	4.518	0.560	12.4	5.684—3.379
$\dot{V}O_2$ max ml/kg/min	70.1	5.9	8.4	87.0—57.3
$\dot{V}O_2$ max ml/kg·LBM/min	78.1	6.6	8.5	94.1—64.0
$\dot{V}E$ max BTPS	162.3	16.2	10.0	195.0—135.5
O ₂ Pulse	23.9	3.3	14.0	33.4—16.9
True % O ₂	3.461	0.288	8.3	4.033—3.077
R	1.070	0.047	4.4	1.209—0.975
HRmax	195.0	9.7	5.0	219—178
% AT	75.6	7.9	10.5	91.5—60.5
AT l/min	3.444	0.663	19.3	4.911—2.384
AT ml/kg/min	52.8	7.9	15.0	68.8—40.8
Height	178.1	6.7	3.8	191.3—169.4
Weight	64.0	6.8	10.6	77.3—52.7
VC (BTPS)	5.241	0.670	12.8	6.289—3.569
LBM	58.5	6.1	10.4	70.1—48.5
% Fat	8.55	2.37	27.7	14.53—4.62
Age	20.7	3.0	14.6	26.2—16.5
Exhaustion Time	24'55"8	2'25"2	9.6	31'—21'
1-mile	4'19"2	16"3	6.3	4'56"0—3'50"1*
2-mile	9'35"8	30"3	5.3	10'26"7—8'21"1*
3-mile	14'50"8	55"4	6.2	16'11"1—12'50"2**

* computed by multiplying 1.08 to 1500M and 3000M performances of Rod Dixon so as to estimate his 1-mile and 2-mile performances

** computed by multiplying 0.966 to 5000M performance of Rod Dixon to estimate his 3-mile performance

Table 2. Zero-order Correlation Coefficients##

	Exhaustion Time	1-mile	2-mile	3-mile
$\dot{V}O_2$ max l/min	.508	-.607	-.624	-.473
$\dot{V}O_2$ max ml/kg/min	.724*	-.615	-.686	-.702*
$\dot{V}O_2$ max ml/kg·LBM/min	.571	-.626	-.651	-.572
$\dot{V}E$ max BTPS		-.422		
O ₂ Pulse		-.480	-.549	-.492
True % O ₂				-.454
HRmax				
% AT		-.540	-.678	-.712*
AT l/min	.523	-.637	-.654	-.552
AT ml/kg/min	.708*	-.716*	-.855*	-.896*
Height				
Weight				
VC (BTPS)			-.439	
LBM				
% Fat				.398
Exhaustion Time	1.000	-.664	-.744*	-.717*

: all correlations listed above are significant at the 0.05 level

Figure 1. Anaerobic threshold determination by the gas exchange method; solid vertical lines denote AT for Rod Dixon.

distance performance variables correlated highest with AT (ml/kg/min) and secondly with exhaustion time. In other words, correlations of $\dot{V}O_2\text{max}$ (l/min) or both relative $\dot{V}O_2\text{max}$ with the performances were all less than those of AT (ml/kg/min) or exhaustion time, although the degree of those relations did not differ significantly from one another. In a recent study of ours³⁶⁾ which did not include

Figure 2. A close relationship of AT (ml/kg) with the 3-mile performance.

AT, it was found that exhaustion time was the single best predictor of middle-long distance performances. With an implication that exhaustion time per se is not a direct indicator of physical resource as is $\dot{V}O_2\text{max}$, it is of vital importance that AT, as one of its direct indicators, was proved to correlate highly with the performances.

As mentioned above, the magnitudes of correlations of AT (ml/kg/min) with the performances tended to be greater when compared to those of exhaustion time. The squared coefficient of correlation of AT (ml/kg/min) with the 3-mile run performance is evaluated at more than 0.80. It can be inferred, therefore, that AT (ml/kg/min) could account for more than 80% of the individual differences in the 3-mile run performance, and exhaustion time only 50% of them. We may add that $\dot{V}O_2\text{max}$ (ml/kg/min) can account for 49%.

% AT correlated with performances as high as $\dot{V}O_2\text{max}$ (ml/kg/min). Other variables

Table 3. Partial Correlation Coefficients

	Ex. Time	1-mile	2-mile	3-mile	##
AT (l/min)	.610	-.635	-.678	-.664	Weight
	.573*	-.625	-.648	-.604	LBM
$\dot{V}O_2\text{max}$ (l/min)	.797	-.726	-.804	-.781	Weight
	.778	-.713	-.788	-.762	LBM

: a variable held constant

Figure 3. Comparison of simple and partial correlations of AT and $\dot{V}O_2\text{max}$ with the performances.

which correlated with at least one of the performances were O_2 Pulse, $\dot{V}E_{\text{max}}$, true % O_2 , vital capacity, and % body fat, with these correlations mostly being less than 0.5.

When body weight or LBM was held statistically constant by the partial correlation technique because $\dot{V}O_2\text{max}$ (l/min) is known to be a function of body size, the relations of the performances to $\dot{V}O_2\text{max}$ (l/min) increased to $r_p=0.726\sim0.804$ and $r_p=0.713\sim0.788$, respectively. The relations of the performances to AT (l/min), on the other hand, using the same technique, decreased to $r_p=0.610\sim0.678$ and $r_p=0.573\sim0.648$, respectively (Table 3). Thus, in contrast to the relations obtained by the zero-order correlation technique, the partial correlations between the performances and $\dot{V}O_2\text{max}$ (l/min) were all larger than 0.7, and those between the performances and AT (l/min) were all reduced to less than 0.7. These findings are graphically shown in Figure 3. It is of great importance, nevertheless, that zero-order correlations of the 2-mile and 3-mile performances with AT (ml/kg/min) are still greater than the partial correlations of them with $\dot{V}O_2\text{max}$ (l/min).

Table 4 shows the multiple correlations of the performances with the various metabolic and anthropometric measures. The use of either AT (l/min), % body fat, true % O_2 , or vital capacity as the independent variable neither appreciably changed the zero-order correlations between the performances and AT (ml/kg/min), nor the correlations between the performances and $\dot{V}O_2\text{max}$ (ml/kg/min). A multiple correlation of $r_m=0.906$ which was obtained by compositing AT (ml/kg/min) and $\dot{V}O_2\text{max}$ (ml/kg/min) when the dependent vari-

Table 4. Multiple Correlation Coefficients

Ex. Time	AT(ml/kg) + AT(l/min)	.709
	AT(ml/kg) + %Fat	.725
	AT(ml/kg) + % O_2	.710
	AT(ml/kg) + VC	.714
1-mile	AT(ml/kg) + AT(l/min)	.743
	AT(ml/kg) + %Fat	.739
	AT(ml/kg) + % O_2	.722
	AT(ml/kg) + VC	.728
2-mile	AT(ml/kg) + AT(l/min)	.859
	AT(ml/kg) + %Fat	.857
	AT(ml/kg) + % O_2	.855
	AT(ml/kg) + VC	.868
3-mile	AT(ml/kg) + AT(l/min)	.901
	AT(ml/kg) + %Fat	.899
	AT(ml/kg) + % O_2	.898
	AT(ml/kg) + VC	.907
Ex. Time	$\dot{V}O_2\text{max}$ (ml/kg) + AT(l/min)	.747
	$\dot{V}O_2\text{max}$ (ml/kg) + %Fat	.779
	$\dot{V}O_2\text{max}$ (ml/kg) + % O_2	.753
	$\dot{V}O_2\text{max}$ (ml/kg) + VC	.762
1-mile	$\dot{V}O_2\text{max}$ (ml/kg) + AT(l/min)	.685
	$\dot{V}O_2\text{max}$ (ml/kg) + %Fat	.618
	$\dot{V}O_2\text{max}$ (ml/kg) + % O_2	.621
	$\dot{V}O_2\text{max}$ (ml/kg) + VC	.659
2-mile	$\dot{V}O_2\text{max}$ (ml/kg) + AT(l/min)	.737
	$\dot{V}O_2\text{max}$ (ml/kg) + %Fat	.617
	$\dot{V}O_2\text{max}$ (ml/kg) + % O_2	.686
	$\dot{V}O_2\text{max}$ (ml/kg) + VC	.745
3-mile	$\dot{V}O_2\text{max}$ (ml/kg) + AT(l/min)	.706
	$\dot{V}O_2\text{max}$ (ml/kg) + %Fat	.785
	$\dot{V}O_2\text{max}$ (ml/kg) + % O_2	.711
	$\dot{V}O_2\text{max}$ (ml/kg) + VC	.703

able was the 3-mile performance, for instance, shows that the composite score of AT and $\dot{V}O_2\text{max}$ can explain 82% of the individual variance in the 3-mile run performance. This is very close to the amount of variance, 80 %, which is accounted for by a correlation of $r = -0.896$ obtained by AT (ml/kg/min) and the 3-mile run performance. Adding the body weight or LBM scores to AT (ml/kg/min) or $\dot{V}O_2\text{max}$ (ml/kg/min) also failed to raise prediction accuracy of the performances. Thus, it might be interpreted that the prediction of individual distance run times with the combination of the well known single predictor (e.g., $\dot{V}O_2\text{max}$ or AT to a lesser extent) and either a metabolic or anthropometric variable by the multiple correlation technique is not always appreciably more efficient than with only such a predictor as AT (ml/kg/min), as shown in the considerably high zero-order correlation. This may, however, be applicable to only when exhaustion time is not included in the independent variable group and when a few independent variables are used.

Similar to the present findings, Thorland et al., using 10 female runners, reported a high correlation between 5000M run performance and AT (ml/kg/min), which did account for 71% of the variance in the performance. They described AT to be a very significant factor in accounting for the 5000M run performance, and developed an equation for predicting the best time of the performance — $Y = 2091.23 - 19.363AT$. Other studies⁽²⁸⁾⁽²⁹⁾ have also indicated that AT was as much or more closely related to endurance performance than $\dot{V}O_2\text{max}$.

Davis et al.⁽⁷⁾ have shown that after nine weeks of training in middle-aged normal sedentary men, the amount of work performed without an accumulation of lactate is significantly increased due to the training-induced shift in the AT to the right. Consequently, slower rates of muscle glycogen depletion, and therefore, smaller lactate formation observed during submaximal work in the trained as compared with the untrained state⁽³⁾⁽⁷⁾⁽¹⁵⁾⁽¹⁶⁾⁽³²⁾ may be explained on the basis of the delayed onset of anaerobic glycolysis brought about by the shift in the AT. It seems reasonable to believe that good athletes with higher AT would be at a definite advantage in postpon-

ing the build-up of lactic acid, which has been shown to interfere with the excitation-contraction (E-C) coupling with consequent deficit in the developed force due to the effect of lowered intramuscular pH on the Ca^{++} binding to troponin⁽¹⁰⁾⁽¹¹⁾⁽²⁵⁾⁽²⁶⁾.

In may, therefore, be concluded that AT (ml/kg) and/or related variables (as evidenced by relatively high correlations of % AT or AT l/min with the performances) to some extent, could be one of the best predictors of distance run performances which must rely greatly on the effective functioning of the circulatory and respiratory system. An emphasis is particularly placed on the fact that improving AT may result in improving long distance performances to the same or larger extent than improving $\dot{V}O_2\text{max}$. More research for determining the relationships between AT parameters and distance run performances should be attempted using not only distance runners but other types of athletes or sedentary individuals, probably comparing different testing protocol on the treadmill or bicycle ergometer to better indicate AT.

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