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# The maximum lactate clearance : a new concept to approach the endurance level of an athlete

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(1 figure)

The purpose of this study is to present a mathematical model based on physiological observations which describes the evolution of the blood lactate concentration ($[LA^-]$) versus the oxygen uptake ($\dot{V}O_2$) during a continuous graded exercise test. This model is based on several assumptions : 1) $[LA^-]$ reflects the balance between the rates of appearance and disappearance of the lactate in the blood compartment; 2) $\dot{V}O_2$ measured at the end of each step, is a linear function of the power output and thus of the time; 3) the appearance rate of lactate into the blood is an exponential function of $\dot{V}O_2$; 4) the rate of disappearance is a saturable process which can be modelized by Michaelis-Menten kinetics; 5) the volume of distribution of lactate in the blood compartment is a constant during exercise.

The parameters used in this model correspond to the integration of several biochemical and physiological phenomenons. The originality of this approach is to express the rate of lactate appearance and disappearance *versus* $\dot{V}O_2$ rather than time. Whatever the general pattern of the data, the fitted curve gives always very good results. Especially, the theoritical curve fits the decrease in $[LA^-]$ usually observed during the first steps of such an exercise. From the computed parameters the evolution of lactate clearance during a continuous graded exercise test may be modelized. A strong relationship exists between the level of endurance training and the maximum lactate clearance (Clmax) reached during the exercise test. The $\dot{V}O_2$ for Clmax is an indicator of the shift of the relatioship $[LA^-]$-$\dot{V}O_2$. Then, we propose to use the maximum lactate clearance which is individually determined, to characterize the endurance level of an athlete.

*Key Words* : lactate clearance; oxygen uptake; endurance level; athlete.

## Introduction

Recently, several authors have demonstrated the strong relationship between the *anaerobic threshold* and the endurance performance of a subject (FARELL *et al.*, 1979; KUMAGAI *et al.*, 1982; TANAKA *et al.*, 1983). The test classically used is a continuous graded interval exercise. At the beginning of such an exercise, the subject outputs a relatively low power which is then increased by a few Watts every 3 minutes. The *anaerobic threshold* is defined as the level of oxygen consumption for which the blood lactate concentration begins to increase above its rest value, during the bicycle ergometer test (YOSHIDA, 1984).

On the other hand, similar concepts have also been developed, using constant values (2 and 4 $mmol.l^{-1}$) of the blood lactate concentration to determine the OBLA (Onset of Blood Lactate Accumulation) (JACOBS, 1981), the area of aerobic-anaerobic transition (KINDERMANN *et al.*, 1979) or the anaerobic threshold (RUSKO *et al.*, 1980).

In 1985, BEAVER *et al.* proposed a simple mathematical model to estimate the lactate threshold. This model requires the transformation to logarithmic coordinates of each value of oxygen consumption and of blood lactate concentration to determine a threshold visually apparent.

Basing on the conclusions of HUGHSON *et al.* (1987) which describe the $[LA^-]$ as a continuous function of the $\dot{V}O_2$, CAMPBELL *et al.* (1989) propose an empirical function to simulate the $[LA^-]$ evolution during exercise of progressively rising intensity. The LSI (Lactate Slope Index) is arbitrarily defined as the point at which $d[LA^-]/(d\dot{V}O_2) = 1$.

The purpose of this study is to propose a mathematical model describing the evolution of $[LA^-]$ versus $\dot{V}O_2$ during a progressively graded test. By opposition with other models recently presented in the literature, the equations described in this paper are not arbitrary but they are based on different physiological phenomenons which are demonstrated.

## The model

The blood lactate concentration represents the balance between the rate of appearance (Ra) and the rate of disappearance (Rd) of lactate in the blood compartment. If the same intensity of exercise remains for a long time (± 20 min), the subject reachs a steady state of the lactate concentrations. In such conditions, MAZZEO *et al.* (1986) observed a linear relationship between the turnover rate of lactate and the intensity of metabolism ($\dot{V}O_2$). Using a mathematical model which does not require labelled molecules, FRANCAUX *et al.* (1988) also observed that the production of lactate evolves linearly versus the intensity of exercise.

Nevertheless, in the protocols regularly used for the physiological evaluation of sportsmen, the short duration of the exercise stages (2-5 min) allows to reach a steady state of $\dot{V}O_2$, but not of [LA$^-$]. In this case, it exists a delayed liberation of lactate in the blood. In these conditions, STANLEY *et al.* (1985) described the rate of appearance of lactate in the blood as an exponential function of the $\dot{V}O_2$. This phenomenon may be described :

$$Ra = P.e^{\alpha.\dot{V}O_2} \quad (1)$$

where P is the ordinate origin, $\alpha$ is the slope.

FRANCAUX *et al.* (1988) demonstrated that the lactate clearance increases from rest to moderate exercise and then, decreases when the exercise intensity goes beyond a given level. It seems that the elimination of lactate from the blood is a saturable phenomenon which may be modelised by a MICHAELIS-MENTEN equation.

$$Rd = \frac{V_{max}.\dot{V}O_2}{K_M + \dot{V}O_2} \quad (2)$$

where $V_{max}$ is the maximal rate of lactate elimination, $K_M$ is a constant corresponding to the necessary $\dot{V}O_2$ to reach the half of $V_{max}$.

The difference between the rates of appearance and disappearance of lactate in the blood corresponds to :

$$Ra - Rd = P.e^{\alpha.\dot{V}O_2} - \frac{V_{max}.\dot{V}O_2}{K_M + \dot{V}O_2} \quad (3)$$

Ra and Rd are respectively equal to the amount of lactate appearing and disappearing by unit of time :

$$Ra = \frac{dQ_a}{dt} \quad (4)$$

$$Rd = \frac{dQ_d}{dt} \quad (5)$$

where $Q_a$ is the amount of appearing lactate, $Q_d$ is the amount of disappearing lactate.

During a continuous graded interval exercise, it exists a linear relationship between the time (t) and the oxygen uptake measured at the end of each step ($\dot{V}O_2$). Therefore considering this relationship and the equations (3), (4) and (5), one may write :

$$\frac{dQ}{dVO_2} = P.e^{\alpha.\dot{V}O_2} - \frac{V_{max}.\dot{V}O_2}{K_M + \dot{V}O_2} \quad (6)$$

where Q is the lactate amount in the blood.

If one assumes that the apparent clearance (Cl) may be defined as the volume of liquid completely purged by unit of $\dot{V}O_2$, its value may be calculated by the ratio between the rate of elimination and the concentration :

$$Cl = \frac{\frac{V_{max}.\dot{V}O_2}{K_M + \dot{V}O_2}}{[LA^-]} \quad (7)$$

Integrating equation 6 and considering the volume of distribution as a constant, one obtains :

$$[LA^-] = \frac{P}{\alpha} e^{\alpha.\dot{V}O_2}.V_{max}\left(<K_M + \dot{V}O_2> - <K_M \ln <K_M + \dot{V}O_2>>\right) \quad (8)$$

This equation describes the evolution of the blood lactate concentration versus the $\dot{V}O_2$, during a progressively increased exercise.

## Subjects

TABLE I. — *Biometrical data.*

| Subjects | Age (years) | Weight (kg) | Height (cm) | $\dot{V}O_2$ max ($l.min^{-1}$) |
|---|---|---|---|---|
| 1 | 18 | 78.8 | 179.2 | 5.19 |
| 2 | 17 | 79.7 | 188.8 | 4.94 |
| 3 | 29 | 78.8 | 184.2 | 4.45 |
| 4 | 26 | 86.7 | 190.1 | 5.00 |
| 5 | 18 | 81.9 | 188.4 | 5.45 |
| 6 | 19 | 77.6 | 177.4 | 5.62 |

Six healthy male volunteers took part in the study (Table I). All subjects were well trained. They were first informed about the experimental protocol, and then consent was obtained.

## Material and Methods

All subjects performed a continuous graded 3 min interval exercise test on a *Jaeger* electrically braked bicycle ergometer. The exercise started at a power output of 70 W (60-80 rpm) which was increased by 40 W every 3 min until voluntary cessation. At rest and at the end of each intensity level, 25 $\mu$l of capillary blood were taken from the ear lobe to measure the lactate concentration using a *YSI* lactate analyser. The

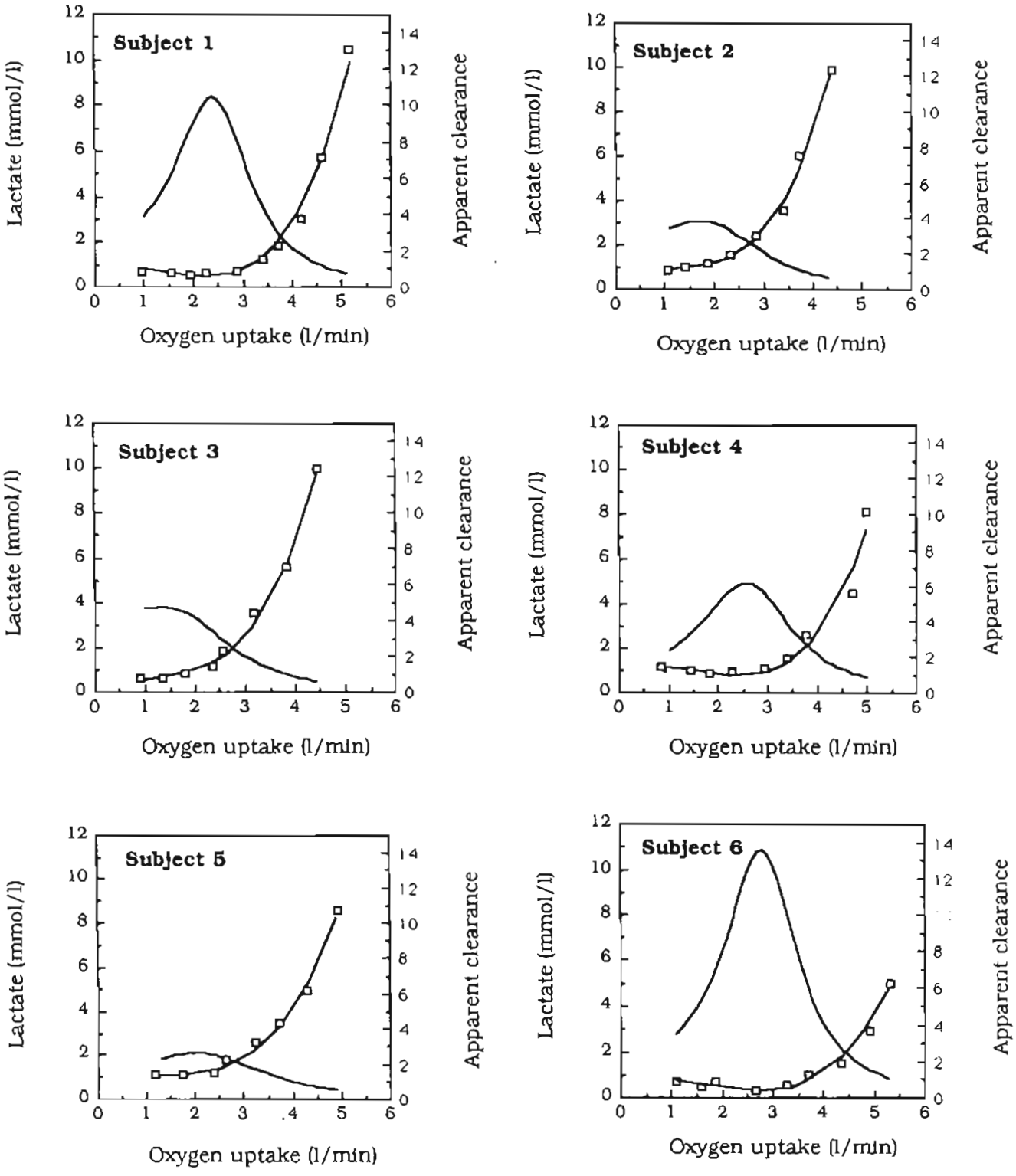


FIG. 1. — *Blood lactate concentration and apparent lactate clearance versus oxygen uptake during a continuous graded 3 min interval exercise test.* The fitted function corresponds to equation 8.

oxygen uptake ($\dot{V}O_2$) was measured at the end of each step using an Ergo-oxyscreen *Jaeger* spirometer.

The fit of the theoritical curve has been computed using *MINSQ* following the Simplex non-linear regression method (Derivative-Free Methods) described by NEDLER and MEAD (1965).

**Results**

Figure 1 presents 6 fitted curves from experimental data. Although the general pattern can dramatically vary between subjects, the obtained fit yields always very good results. Especially, it follows the decrease

of [$LA^-$] observed in subjects 1, 4, 6 at the beginning of the exercise, and that has never been considered by the previous empirical models.

The estimated parameters are presented in Table II. It has previously been demonstrated that the lactate clearance increases from rest to moderate intensity exercise and then, decreases during high intensity exercise (FRANCAUX *et al.*, 1988). Knowing the parameters values of equation 8, it is possible, using equation 7, to describe the evolution of the clearance versus $\dot{V}O_2$ and thus to compute the maximum value of Cl (Clmax). The $\dot{V}O_2$ corresponding to Clmax is kept to characterize the shift of the relationship [$LA^-$]-$\dot{V}O_2$ on the abscissa axis. $\dot{V}O_2$ for Clmax provides the $\dot{V}O_2$ just before the blood lactate accumulation. The values of $\dot{V}O_2$ for Clmax are presented in Table II.

TABLE II. — *Kinetic parameters of lactate measured on 6 trained subjects during a continuous graded 3 min interval exercise test.*

| Subjects | P | α | $K_M$ | $V_{max}$ | $VO_2$ for Clmax |
|---|---|---|---|---|---|
| 1 | 2.07 | 0.39 | 2.09 | 9.72 | 2.40 |
| 2 | 2.16 | 0.44 | 2.13 | 9.63 | 1.70 |
| 3 | 2.07 | 0.43 | 1.99 | 8.43 | 1.40 |
| 4 | 1.78 | 0.39 | 2.22 | 8.96 | 2.60 |
| 5 | 1.58 | 0.38 | 2.01 | 6.33 | 2.00 |
| 6 | 1.75 | 0.32 | 1.74 | 6.86 | 2.70 |
| X | 1.90 | 0.39 | 2.03 | 8.32 | 2.15 |
| SD | 0.23 | 0.04 | 0.16 | 1.43 | 0.54 |
| CV (%) | 12 | 11 | 8 | 17 | 25 |

P : $mmol.min.l_{O_2}^{-1}.l_{Vd}^{-1}$; α : $min.l_{O_2}^{-1}$; $V_{max}$ : $mmol.min.l_{O_2}^{-1}.l_{Vd}^{-1}$; $K_M$ : $l_{O_2}.min^{-1}$; Clmax : $min.l_{O_2}^{-1}$; $\dot{V}O_2$ for Clmax : $l.min^{-1}$

## Discussion

The anaerobic threshold is defined as the level of oxygen uptake for which a metabolic acidosis occurs. It may be determined by the $\dot{V}O_2$ for which the blood lactate concentration increases above its rest value, during a progressively graded exercise (YOSHIDA *et al.*, 1984). The term anaerobic has been chosen to indicate an insufficient supply of oxygen to the muscle to provide the energetic needs only from the aerobic metabolism (WASSERMAN *et al.*, 1985).

Nevertheless, a muscular anoxia has never been demonstrated during the exercise. Several studies using labelled molecules, indicate that the lactate turnover is considerable even during a moderate exercise (for review : see BROOKS, 1985). One must conclude that the term anaerobic threshold is used improperly in the context of the exercise physiology. The increase of the blood lactate concentration does not correspond to an intra-mitochondrial anaerobiosis.

Consequently, without consideration for the concept of anaerobic threshold and on basis of these conclusions, a mathematical model has been developed to simulate the evolution of the blood lactate concentration versus the metabolism intensity, during a progressively graded exercise. Although other models have recently been proposed in the literature (BEAVER *et al.*, 1985; CAMPBELL *et al.*, 1989), the mathematical development presented in this paper, is the first non-arbitrary model.

The first assumption of the model is based on the linear relationship, at the steady state, between the lactate amount produced in the muscle and the intensity of the metabolism. Really, in the skeletal muscle, the lactate concentration increases rapidly at the beginning of the exercise (GREEN *et al.*, 1983; JACOBS & KAISER, 1982) inducing a concentration gradient necessary for the lactate release in the blood. When the duration of each grade is extended, the concentration gradient between the muscle and the blood decreases (JORFELDT *et al.*, 1978; KNUTTGEN & SALTIN, 1972). Thus, when the exercise is extended for a time long enough, the blood concentration may be considered as representative (not equal) of the muscle concentration. Nevertheless, during a progressively graded exercise test, the short duration of each grade is insufficient to reach this steady state of concentrations. In such conditions, it exists a delay in the lactate appearance in the blood. For this reason, STANLEY *et al.* (1985) observed a rate of lactate appearance in the blood related following an exponential function versus the metabolism intensity. Thus, this function has been used to modelise the rate of lactate appearance in the blood.

During a standardized recovery, the rate of lactate elimination is directly proportional to the lactate amount present in the compartment. It may be characterized by a first order rate constant (FRANCAUX *et al.*, 1989). However, when a moderate exercise is continued following an intensive exercise, the lactate clearance is higher (FRANCAUX *et al.*, 1988). Inversely, if the recovery exercise exceeds a certain intensity, the lactate clearance decreases. As the rate of lactate elimination is equal to the product of the clearance multiplied by the concentration, a clearance decrease concomitant with a proportional increase of the concentration, indicated that the elimination rate reached a levelling off. The lactate elimination in function of the metabolism intensity is a saturable process which may be modelled by a MICHAELIS-MENTEN system.

As the blood lactate is a balance between the appearance and disappearance rates and considering the above discussion, the mathematical development easily yields the equation (8).

Nevertheless, the parameters used in this model, are apparent parameters because they do not correspond directly to a physiological reality. Actually, the units used to quantify the parameters values do not correspond to their definition. The origin of this contradiction is the rates of appearance and disappearance expressed, not in function of time, but in function of $\dot{V}O_2$ that evolves itself linearly versus the time. The values of Ra and Rd which can be calculated, do not correspond to the real physiological values. But, they are directly related to the physiological value, a constant excepted.

Moreover, the volume of distribution is also considered as a constant of the model.

The same discussion can be applied to the clearance that, in this case, is not really the volume of liquid completly purged by unit of time. Despite the change of the system of reference, the evolution of the apparent clearance is related to the evolution of the real clearance.

The fit of the theoretical function yields always very good results. Especially, it follows the decrease of [$LA^-$] regularly observed at the beginning of the exercise, and that has never been considered by the previous empirical models.

The lactate production *versus* $\dot{V}O_2$ does not seem to present the great inter-individual variation. The origin of the most important variation is found in the elimination processes. The interest of this approach is also to give the evolution of the apparent clearance of lactate from the blood which could be correlated with the endurance level of an athlete. Then the maximal apparent clearance is a new concept to approach the endurance of an athlete.

These observations confirm the results of DONOVAN and BROOKS (1983) which demonstrated, in rats, that the endurance training increases the lactate clearance and thus, decreases [$LA^-$].

The $\dot{V}O_2$ for Clmax is an indicator of the shift of the relationship [$LA^-$]-$\dot{V}O_2$. This indicator is not based on an arbitrary function (BEAVER *et al.*, 1985; CAMPBELL *et al.*, 1989) or on an identical lactate concentration for all subjects (HECQ *et al.*, 1985). The $\dot{V}O_2$ for Clmax is individually determined using equation 7. The $\dot{V}O_2$ for Clmax corresponds to the metabolism intensity just before the blood lactate accumulation.

## Conclusion

1. The proposed new model which is based on demonstrated physiological phenomenons, represents a non-arbitar model of [$LA^-$] *versus* $\dot{V}O_2$ during a continuous graded interval exercise test.

2. The apparent parameters from the model confirm that the low [$LA^-$] observed in endurance well trained subjects is related to a greater clearance. Then the maximal apparent clearance is a new concept to approach the endurance of an athlete.

3. The $\dot{V}O_2$ for Clmax is an indicator of the shift of the relationship [$LA^-$]-$\dot{V}O_2$. $\dot{V}O_2$ for Clmax is individually determined.

## references


BEAVER, W.L., WASSERMAN, K. & WHIPP, B. (1985) *J. Appl. Physiol.* 59, 1936-1940.

BROOKS, G.A. (1985) *Med. Sci. Sports Exerc.* 17, 22-31.

CAMPBELL, M.E., HUGHSON, R.L. & GREEN, H.J. (1989) *J. Appl. Physiol.* 66, 1104-1107.

DONOVAN, C.M. & BROOKS, G.A. (1983) *Am. J. Physiol.* 244, E83-E92.

FARRELL, P.A., WILMORE, J.H., COYLE, E.F., BILLING, J.E. & COSTILL, D.L. (1979) *Med. Sci. Sports.* 11, 338-344.

FRANCAUX, M., JACQMIN, P. & STURBOIS, X. (1988) *Can. J. Sport. Sci.* 13, 12.

FRANCAUX, M.A., JACQMIN, P.A. & STURBOIS, S.G. (1989) *Arch. Int. Physiol. Bioch.* 97, 235-245.

GREEN, H.J., HUGHSON, R.L., ORR, G.W. & RANNEY, D.A. (1983) *J. Appl. Physiol.* 54, 1032-1038.

HECK, H., MADER, A., HESS, G., MÜCKE, S., MÜLLER, R. & HOLLMANN, W. (1985) *Int. J. Sports Med.* 6, 117-130.

HUGHSON, R.L., WEISIGER, K.D. & SWANSON, G.D. (1987) *J. Appl. Physiol.* 62, 1975-1981.

JACOBS, I. (1981) *Acta Physiol. Scand. Suppl.* 495.

JACOBS, I. & KAISER, P. (1982) *Acta Physiol. Scand.* 114, 461-466.

JORFELDT, L., JUHLIN-DANNFELT, A. & KARLSSON, J. (1978) *J. Appl. Physiol.* 44, 350-352.

KINDERMANN, W., SIMON, G. & KEUL, L. (1979) *Eur. J. Appl. Physiol.* 42, 25-34.

KNUTTGEN, H.G. & SALTIN, B. (1972) *J. Appl. Physiol.* 32, 690-694.

KUMAGAI, S., TANAKA, K., MATSUURA, Y., MATSUZAKA, A., HIRAKOBA, K. & ASANO, K. (1982) *Eur. J. Appl. Physiol.* 49, 13-23.

MAZZEO, R.S., BROOKS, G.A., SCHOELLER, D.A. & BUDINGER, T.F. (1986) *J. Appl. Physiol.* 60, 232-241.

NEDLER, J.A. & MEAD, R. (1965) *Computer J.* 7, 308-313.

RUSKO, H., RAHKILA, P. & KARVINEN, E. (1980) *Acta Physiol. Scand.* 108, 263-268.

STANLEY, W.C., GERTZ, E.W., WINESKI, J.A., MORRIS, D.L., NEESE, R.A. & BROOKS, G.A. (1985) *Am. J. Physiol.* 249, E595-E602.

TANAKA, K., MATSUURA, Y., KUMAGAI, S., MATSUZAKA, A., HIRAKOBA, K. & ASANO, K. (1983) *Eur. J. Appl. Physiol.* 52, 51-56.

YOSHIDA, T. (1984) *Eur. J. Appl. Physiol.* 53, 196-199.

WASSERMAN, K., BEAVER, W.L., DAVIS, J.A., PU, J.-Z., HEISER, D. & WHIPP, B.J. (1985) *J. Appl. Physiol.* 59, 935-940.



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