Reçu le 24 octobre 1993

Time to exhaustion at $\dot{V}O_2$max and lactate steady state velocity in sub elite long-distance runners

BY

V. BILLAT [1], O. BERNARD [2], J. PINOTEAU [2], B. PETIT [3] and J.P. KORALSZTEIN [3]

[[1] *Laboratoire STAPS Université Paris XII, 61, Avenue du Général de Gaulle, F-94010 Créteil;* [2] *Laboratoire RESACT Sport, Université Joseph Fourier UFR APS, BP 53X 38041 Grenoble* and [3] *Centre de Medecine du Sport C.C.A.S., 2 Avenue Richerand F-75010 Paris, France*]

(5 figures)

The aim of the present study was to estimate the importance of lactate steady state velocity ($\dot{W}$CL) of the running velocity at maximal oxygen uptake (Va max) and its time to exhaustion (Tlim), in the performance of a half marathon stated by the velocity over 21.1 km sustained by the runners during 1 h 12 min ± 2 min 27 s. The population consisting of ten sub-elite male long distance runners (32 ± 4 years old) was homogeneous with regard to their velocities on 21 km (V21 = 17.5 ± 0.88 $km.h^{-1}$, coefficient of variation, CV = 5%) and their aerobic maximal speed (Va max) (21.6 ± 1.2 $km.h^{-1}$, CV 6%). The fractional utilization of $\dot{V}O_2$max on 21 km was calculated from their own running economy (oxygen consumed per kilo of body mass and kilometer run (194 ± 74 $ml.kg^{-1}.km^{-1}$). V21 represented 83 ± 5% $\dot{V}O_2$max ($\dot{V}O_2$max = 68.1 ± 4.1 $ml.kg^{-1}.min^{-1}$) and 81 ± 3.3% Va max. The velocity corresponding to lactate steady state and called "lactate steady state velocity" ($\dot{W}$CL) was measured according to a protocol proposed by CHASSAIN (1986). The subjects ran twenty minutes at a constant velocity representing 70-75% and 85-90% $\dot{V}O_2$max. Lactatemia was measured at the fifth (Lact 5) and the twentieth minute (Lact 20). Lactate slope was measured for two running velocities in order to determine the velocity ($\dot{W}$CL) corresponding to lactate steady state, i.e. the lactate slope is equal to zero. The main results showed that in the small and homogeneous sample of runners studied, $\dot{W}$CL ($km.h^{-1}$) was related to V21 ($km.h^{-1}$) ($r = 0.55$, $P < 0.07$); Va max ($km.h^{-1}$ was related to V21 ($km.h^{-1}$) ($r = 0.732$, $P < 0.05$) but time to exhaustion at Va max (6.11 ± 2 min01sec) was not related to V21 ($km.h^{-1}$) ($r = 0.27$). However, Tlim at Va max was related to V21 expressed in % Va max ($r = 0.775$). Tlim at Va max was also related to $\dot{W}$CL expressed in % $\dot{V}O_2$max ($r = 0.604$) and to $\dot{W}$CL expressed in % Va max ($r = 0.629$). Tlim at Va max and $\dot{W}$CL (expressed in % $\dot{V}O_2$max or in Va max) were both endurance indices but at maximal and submaximal intensities, $\dot{W}$CL being more specific to half marathon intensity.

Key Words : long-distance running; maximal O_2 uptake; maximal blood lactate steady state.

Abbreviations

Va max : running velocity at maximal oxygen uptake
AnT : anaerobic threshold
$\dot{V}O_2$: oxygen uptake
$\dot{V}O_2$max : maximal oxygen uptake
Tlim : time to exhaustion at Va max
$\dot{W}$CL : lactate steady state velocity
V21 : average velocities in half-marathon races (21.1 km)
CV : coefficient of variation
HR : heart rate
MAS : maximal aerobic speed ie, minimal speed which elicits $\dot{V}O_2$max
Lact 5 : lactatemia measured at the fith minute
Lact 20 : lactatemia measured at the twentieth minute
$\Delta L/\Delta t$: differential value of lactic acid blood concentrations versus time
RE : running economy expressed as the oxygen cost of running (in $ml.kg^{-1}.km^{-1}$)

Introduction

Running velocity at maximal oxygen uptake (Va max) seems to be the best predictor of performance in middle-distance running (LACOUR *et al.*, 1991; PADILLA *et al.*, 1992). WASSERMAN *et al.* (1973), KINDERMAN *et al.* (1979), DAVIS *et al.* (1983) and CAIOZZO *et al.* (1982) have suggested that the anaerobic threshold (AnT) reflected endurance capacity. Moreover, the onset of blood lactate accumulation and the lactate threshold are defined as the $\dot{V}O_2$ corresponding to a marked acceleration in the lactate curve around 3.5 $mmol.l^{-1}$ (SJÖDIN & JACOBS, 1981; AUNOLA & RUSKO, 1984). They are also additional parameters which correlate with long-distance training (COSTILL, 1976; FARREL *et al.*, 1979; SJÖDIN & SVEDENHAG, 1985). All these procedures consider the kinetics of ventilatory or blood parameters as blood acid lactic concentrations and their exponential augmentations with increasing intensity. However, the duration and the increments of the stages influence the AnT value (YOSHIDA, 1984), and the maximal lactate steady state work load is often overestimated (STEGMANN & KINDERMANN, 1982). LONDEREE & AMES (1975), LAFONTAINE *et al.* (1981) supported the lactate steady-state concept using rectangular stages in order to measure it as well as the corresponding maximal work loads. Moreover, NAGLE *et al.* (1970) using three independent stages of 60, 40 and 30 minutes of duration at 70, 80 and 90% $\dot{V}O_2$max respectively, found a lactate steady state equal to 77% $\dot{V}O_2$max.

Direct measurements of time to exhaustion at Va max (Tlim) (GLESER & VOGEL, 1973; MACLELLAN & SKINNER, 1985; LAVOIE & MERCIER, 1987; CAMUS *et al.*, 1988; HOUSH *et al.*, 1989; MCLELLAN & CHEUNG, 1992; PADILLA *et al.*, 1992; PEPPER *et al.*, 1992; PÉRONNET *et al.*, 1987; RAMSBOTTOM *et al.*, 1992; BILLAT *et al.*, 1994) indicate that the average time to exhaustion at Va max ranges from 2 min 30 s to 10 min 30 s. The reproducibility of Tlim at Va max and its relationship with lactate threshold have recently been assessed in sub-elite long distance runners (BILLAT *et al.*, 1993).

The aim of the present study was to estimate the importance of lactate steady state velocity ($\dot{W}$CL) and Va max and its time to exhaustion on the performance of a half-marathon defined by the velocity sustained over 21.1 km by these runners.

Methods

The population consisting of ten sub-elite male long distance runners (32 ± 4 years old) was homogeneous with regard to their average velocities in half-marathon (V21) races (17.5 ± 0.88 $km.h^{-1}$, CV = 5%).

The subjects performed three experimental protocols at interval of one week.

The subjects gave their written informed consent to participate in the study according to the *French National Commitee for Clinical Research.*

Experimental protocol

Determination of $\dot{V}O_2$ max and Va max

$\dot{V}O_2$ max and Va max were measured in a preliminary test session using a progressive exercise protocol on a treadmill (*Gymrol* 1800). The initial speed was set at 12 $km.h^{-1}$ (0% slope) and was increased by 2 $km.h^{-1}$ every 3 min up to 80% of the runner's best performance in 3000 m, and by 1 $km.h^{-1}$ thereafter. In the last 30 s of each work load, a finger tip blood sample was obtained and analyzed for lactate concentration (*YSI* 27). The critera used for $\dot{V}O_2$ max included : a plateau in $\dot{V}O_2$ despite an increase in running speed; respiratory exchange ratio above 1.1; HR over 90% of the predicted maximal HR (ASTRAND & RYHMING, 1954; TAYLOR *et al.*, 1955). The Va max was the lowest running speed which elicited a $\dot{V}O_2$ value equal to $\dot{V}O_2$ max.

Determination of time to exhaustion at Va max (Tlim)

Following a 20-min warm-up period at 60% Va max, the speed was quickly increased (less than 20 s) up to Va max and the subject was verbally encouraged to run to exhaustion. Finally, average speeds sustained over 21.1 km were expressed in $km.h^{-1}$ and as percentage of Va max.

Third exercise protocol : determination of lactate steady state velocity

Latate steady state velocity ($\dot{W}$CL) was determined with a protocol involving two twenty-minute exercises performed at 70-75 and 85-90% of $\dot{V}O_2$max. The lactic acid blood concentrations were collected and measured every 5 minutes during each exercise, the two sessions being separated by a forty minute rest period. The velocity corresponding to lactate steady state and called "maximal lactate steady state velocity" ($\dot{W}$CL) was measured according to a protocol proposed by CHASSAIN (1986) : the subjects ran twenty minutes at a constant velocity representing 70-75 and 85-90% $\dot{V}O_2$max. Lactatemia was measured at the fifth (Lact 5) and the twentieth minute (Lact 20) of the two exercises. $\dot{W}$CL was calculated and was defined as the velocity when the differential value of lactic acid blood concentrations versus time ($\Delta L/\Delta t$) is equal to zero (Fig. 1). Running economy (RE) was expressed as the oxygen cost of running (in $ml.kg^{-1}.km^{-1}$) at 75% $\dot{V}O_2$max during the first 20 min session (DI PRAMPERO *et al.*, 1986). The fractional utilization of $\dot{V}O_2$max over 21 km was calculated from the individual running economy values (oxygen consumed per kilo of body mass and kilometer).

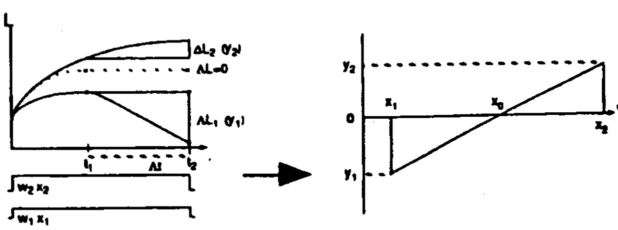

FIG. 1. *WCL determination from two exercises :*
$x_0 = \dot{W}CL$; $x_1 = W_1$; $x_2 = W_2$
$y_0 = \Delta L/\Delta t = 0$; $y_1 = \Delta L_1(-)$; $y_2 = \Delta L_2(+)$
it can be written : $\frac{y_2 - y_0}{y_0 - y_1} = \frac{x_2 - x_0}{x_0 - x_1}$; $\dot{W}CL = \frac{x_1 y_1 - x_2 y_2}{y_2 - y_1}$
x can also be : heart rate, $\dot{V}O_2$, $F\dot{V}O_{2max}$

For all experiments, $\dot{V}O_2$ and $\dot{V}CO_2$ were computed every 15 s (*Jaegger Eosprint*). Heart rate (HR) was also monitored (Siemens Electrocardioscope) and recorded (*Sportester* PE 3000) throughout each test.

Statistics

Data were reported as means ± SD. Means were compared using Student's *t* test for paired data at 5% level of confidence.

Results

Table I shows speed sustained over the half-marathon (during 1 h 12 min ± 2 min 27 s) $\dot{V}O_2$max, Va max, time to exhaustion at Vamax (Tlim) and $\dot{W}$CL expressed in km.h^{-1} and in % $\dot{V}O_2$ max measured in the ten subjects. $\dot{V}O_2$ achieved at the end of the progressive maximal test and at the end of time to exhaustion at Va max are not significantly different (Student paired *t* test) (68.1 ± 4.2 *versus* 67.4 ± 4.8 ml.kg^{-1}.min^{-1}). The correlation coefficients computed between the running velocity sustained over half-marathon races (V 21 in km.h^{-1}), Tlim and the bioenergetic characteristics of the ten runners are shown in Table II.

The main results show that in the small and homogeneous sample of runners, $\dot{W}$CL (km.h^{-1}) was nearly related to V21 (km.h^{-1}) ($r=0.55$, $P<0.07$); Va max (km.h^{-1}) was related to V21 ($r=0.732$; $P<0.05$) (Fig. 2); time to exhaustion at Va max (km.h^{-1} was not related to V21 (km.h^{-1}) ($r=0.27$). However, Tlim at Va max was related to V21 expressed as a percentage of Va max ($r=0.775$) (Fig. 4). Tlim at Va max was also related to $\dot{W}$CL expressed as a percentage of $\dot{V}O_2$ max ($r=0.604$) (Fig. 3) and to $\dot{W}$CL expressed as a percentage of Va max ($r=0.629$) (Fig. 5).

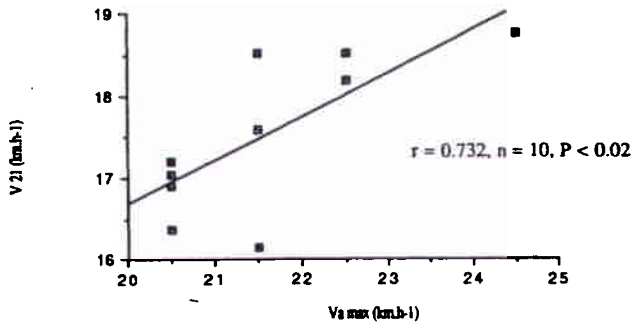

FIG. 2. *Relationship between velocity over 21km (V21 in km.h^{-1}) and velocity at $\dot{V}O_{2max}$ (Va max in km.h^{-1}).*

TABLE I. — *Individual values, means* ± SD, coefficient of variation (CV) and range of the data from the three experiments (see text)

Indices Subjects	$\dot{V}O_2$max ml.min^{-1}.kg^{-1}	Va max km.h^{-1}	V21 km.h^{-1}	V21 % $\dot{V}O_2$max	$\dot{W}$CL km.h^{-1}	$\dot{W}$CL % $\dot{V}O_2$max	Tlim min, s	RE ml.km^{-1}.kg^{-1}
CH	67.2	21.5	16.15	76	16.90	80.4	4.15	191
PX	68.2	21.5	18.51	92	18.10	89.7	11.00	203
RA	66.4	20.5	17.04	79	16.02	74.6	5.27	185
GA	76.1	24.5	18.75	74	18.17	72.0	3.47	181
LO	72.1	22.5	18.51	86	18.00	80.0	7.30	200
TE	62.7	20.5	16.36	84	17.12	90.9	6.15	193
PL	63.9	20.5	17.20	85	17.03	85.6	7.54	190
MD	70.3	22.5	18.18	85	16.62	74.8	4.40	198
AR	63.1	20.5	16.90	87	17.64	90.8	5.38	195
GR	71	21.5	17.60	85	17.23	77	5.16	206
Mean	68.1	21.6	17.50	83	17.21	81.7	6.11	194
SD	4.1	1.2	0.88	5	0.64	7.16	2.01	74
CV (%)	6	5.5	5.02	6	0.7	8.7	34	38
Minimum	62.7	20.5	16.15	74	16.02	72.0	3.47	181
Maximum	76.1	24.5	18.51	92	18.17	90.9	11.00	206

$\dot{V}O_2$max, maximal oxygen uptake (ml.min^{-1}.kg^{-1}); Va max = velocity at $\dot{V}O_2$max (km.h^{-1}); Tlim = time to exhaustion at Va max; $\dot{W}$CL = lactate steady state velocity; V21 velocity over 21km races (km.h^{-1}); RE = running economy; O_2 cost per km run and kg of body mass (ml.km^{-1}.kg^{-1}).

TABLE II. — *Coefficients of correlation (n = 10) between velocity over 21 km races (V21 km.h^{-1}) and times to exhaustion at Va max (Tlim in s) with bioenergetic characteristics.*

	$\dot{V}O_2$max (ml.min^{-1}.kg^{-1})	Va max (km.h^{-1})	$\dot{W}$CL (km.h^{-1})	$\dot{W}$CL (% Va max)	$\dot{W}$CL (% $\dot{V}O_2$max)	V21 (% Va max)	Tlim (s)
V21 (km.h^{-1})	0.007	0.732**	0.555*	-0.375	-0.38	0.263	0.27
Tlim (s)	0.016	-0.314	0.343	0.629**	0.604**	0.775***	

* $P<0.07$; ** $P<0.05$; $\dot{V}O_2$max, maximal oxygen uptake (ml.min^{-1}.kg^{-1}); Va max = velocity at $\dot{V}O_2$max $\dot{W}$CL = lactate steady-state velocity in km.h^{-1} and % $\dot{V}O_2$max.

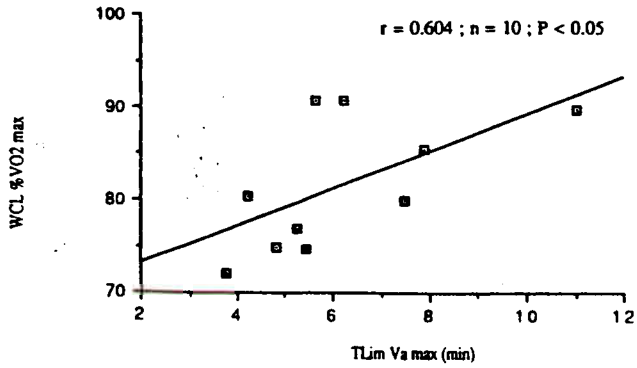

FIG. 3. *Relationship between lactate steady state velocity ($\dot{W}CL$ in % $\dot{V}O_2$max)* and time to exhaustion at velocity at $\dot{V}O_2$max (Tlim in minutes).

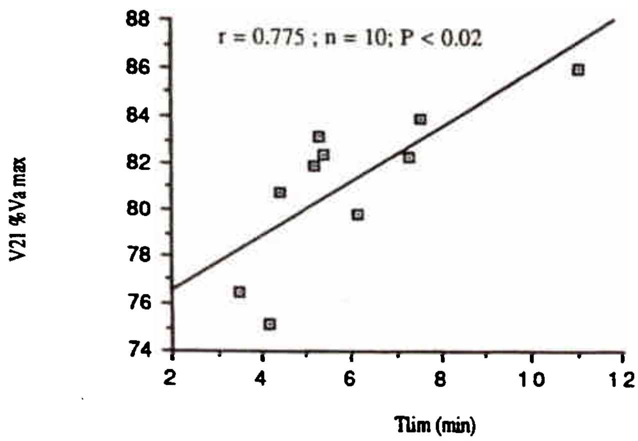

FIG. 4. *Relationship between velocity over 21km (V21 in % Va max) and time to exhaustion at velocity at $\dot{V}O_2$*max (Tlim in minutes).

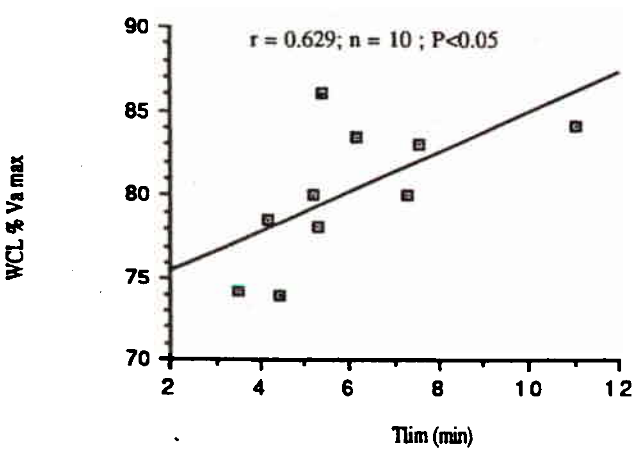

FIG. 5. *Relationship between lactate steady state velocity ($\dot{W}CL$ in % Va max) and time to exhaustion at velocity at $\dot{V}O_2$*max (Tlim in minutes).

Discussion

In a homogeneous group of subjects in regard to their velocities over 21 km (V21), there is no relationship between V21 and $\dot{V}O_2$max but between V21 expressed as a percentage of Va max and the time to exhaustion at Va max. A high level of Va max (ratio between $\dot{V}O_2$max and running economy) is essential to performance in long distance running in accordance with DI PRAMPERO *et al.* (1986) and LACOUR *et al.* (1991). Endurance at 100% $\dot{V}O_2$max (Va max), defined as the ability to sustain Va max as long as possible (time to exhaustion at Va max) was not related to velocity over 21 km. In the present experiment, the average value measured for Tlim at Va max is in accordance with previously reported data (GLESER & VOGEL, 1973; MAC LELLAN & SKINNER, 1985). In a homogeneous group with a coefficient of variation only equal to 6% for Va max, $\dot{V}O_2$max and V21, a wide scatter of the data around the average value was also observed : from 3 min 47 sec to 11 min and a coefficient of variation equal to 34% in accordance with literature (LAVOIE & MERCIER, 1987; BILLAT, 1992). However, Tlim is related to lactate steady state velocity ($\dot{W}CL$ in % $\dot{V}O_2$max).

$\dot{W}CL$ expressed in km.h^{-1} is related to V21 as previously shown in a recent study (BILLAT *et al.*, 1993). Over 21 km, the velocity is sustained for 74 min and produced a fraction of $\dot{V}O_2$max equal to 0.85. In a previous study (BILLAT, 1992) it has been assessed that maximal lactate steady-state power output could be sustained for one hour on a bicycle. If : $\Delta L/\Delta t = 0$, the body is more or less in aerobic conditions (DI PRAMPERO, 1986). DI PRAMPERO (1986) called this condition "evenly aerobic". Thus, he made a difference between "aerobic standard" when lactate production is nil (rate of apparition = 0) and real anaerobic conditions when lactacidemia increases continuously. This situation brings about an accelerated depletion of muscle glycogen stores in the muscle fibers producing lactate (FARREL *et al.*, 1979). That is the reason why the determination of a maximal steady state work-load is essential to high achievements in endurance sports such as long-distance running, swimming, cycling and triathlon. SID ALI *et al.* (1991) have found that $\dot{W}CL$ was very well correlated ($r > 0.97$) and almost equal to the critical speed determined by the slope of the linear relationship between distance and exhaustion time in eight subjects. In the same study, $\dot{W}CL$ was also well correlated with the maximal aerobic speed which elicits $\dot{V}O_2$max as determined by the track test proposed by LEGER and BOUCHER (1980).

In conclusion, the best predictor of the performance over 21km in sub-elite male long distance runners is velocity at $\dot{V}O_2$max and lactate steady state velocity ($\dot{W}CL$) when expressed in km.h^{-1}. $\dot{W}CL$ when expressed in fraction of $\dot{V}O_2$max is related to time to exhaustion at Va max another criterion of endurance but at 100% Va max. Time to exhaustion at Va max could be best related to performance in middle distance running.

Résumé

L'objectif de la présente étude est d'apprécier l'influence de la vitesse maximale de course compatible avec un état stable de la lactatémie ($\dot{W}CL$) et du temps de maintien de la vitesse de course à la consommation maximale d'oxygène (vitesse aérobie maximale : Va max) sur la vitesse d'un semi-marathon (V21). V21 est soutenue pendant 1 h 12 min ± 2 min 27 s par les 10 coureurs (âge moyen 32 ± 4 ans) participant à cette étude. Cette population était homogène concernant V21 (17.5 ± 0.88 km.h^{-1}, CV = 5%), Va max (21.6 ± 1.2 km.h^{-1}, CV 6%) et $\dot{V}O_2$max (68.1 ± 4.1 ml.kg^{-1}.min^{-1}, CV = 6%). V21 sollicitait 83 ± 5% de $\dot{V}O_2$max et 81 ± 3.3% de Va max. La fraction d'utilistion de $\dot{V}O_2$max sur 21 km était calculée d'après l'économie de course de chaque sujet (oxygène consommé par kilo de poids corporel et par kilomètre parcouru : 194 ± 74 ml.kg^{-1}.km^{-1}). La vitesse correspondant à un état stable de la lactatémie en fonction du temps ($\dot{W}$CL) était mesurée à partir de deux courses de 20 minutes à 70-75 et 85-90% de $\dot{V}O_2$max au cours desquelles étaient mesurée la lactatémie à la 5ème et 20ème minute. $\dot{W}$CL correspond alors à la vitesse (sur l'axe des x) que coupe la pente de la relation ΔLactate (20 min-5min)/Δvitesse (85-70% $\dot{V}O_2$max), ΔLactate étant égal à zéro. Les principaux résultats montrent que pour un petit échantillon homogène de sportifs, selon le critère de performance sur semi-marathon, $\dot{W}$CL (km.h^{-1}) est corrélée à V21 (km.h^{-1}) ($r = 0.55$, $P < 0.07$); Va max (km.h^{-1}) est corrélé à V21 ($r = 0.732$, $P < 0.05$). Le temps de maintien à Va max (6,11 ± 2 min 01 s) n'est pas corrélé à V21 lorsqu'il est exprimé en km.h^{-1} ($r = 0.27$) mais lui est corrélé lorsque V21 est exprimé en valeur relative de la vitesse à $\dot{V}O_2$ (Va max) ($r = 0,775$). De même, Tlim à Va max était corrélé à $\dot{W}$CL exprimé en % $\dot{V}O_2$max ($r = 0.604$) et en % de Va max ($r = 0,629$). Tlim à Va max et $\dot{W}$CL exprimé en % $\dot{V}O_2$max sont tous deux des indices d'endurance, mais respectivement à une intensité maximale et sous-maximale, $\dot{W}$CL étant plus spécifique de l'intensité de course sur semi-marathon.

Mots Clefs : course de longue distance; consommation maximale d'oxygène; état stable de la lactatémie.

Acknowledgements. — This study was supported by grants from *Caisse Centrale des Activités Sociales d'Electricite et Gaz de France.*

References

Astrand, P.O. & Ryhming, I. (1954) A nomogram for calculation of aerobic capacity (physical fitness) from pulse rate during submaximal work. *J. Appl. Physiol.* 7, 218-222.

Aunola, S. & Rusko, H. (1984) Reproducibility of aerobic and anaerobic thresholds in 20-25 year old men. *Eur. J. Appl. Physiol.* 53, 260-266.

Billat, V. (1992) Détermination d'une puissance critique aérobie par l'évolution de la lactatémie en régime continu d'exercice musculaire. *Science et motricité* 16, 3-11.

Billat, V., Renoux, J.C., Pinoteau, J., Petit, B. & Koralsztein, J.P. (1994) Reproducibility of running time to exhaustion at $\dot{V}O_2$max in sub-elite runners. *Med. Sci. Sports and Exerc.* 2, 254-257.

Caiozzo, V.J., Davis, J.A., Ellis, J.L., Pretto, C.A. & Mac Master, W.C. (1982) A comparison of gas exchange indices used to detect the anaerobic threshold. *J. Appl. Physiol. Respirat Exercise Physiol.* 53, 1184-1189.

Camus, G., Juchmes, J., Thys, H. & Fossion, A. (1988) Relation entre le temps limite et la consommation maximale d'oxygène dans la course supramaximale. *J. Physiol. (Paris)* 83, 26-39.

Chassain, A.P. (1986) Méthodes d'appréciation objective de la tolérance de l'organisme à l'effort : application à la mesure des puissances critiques de la fréquence cardiaque et de la lactatémie. *Science et sport* 1, 41-48.

Costill, D.L. (1976) The relation between selected physiological variables and distance running performance. *J. Sports Med. Phys. Fitness* 7, 61-66.

Davis, H.A., Bassett, J., Hughes, P. & Gass, G.L. (1983) Anaerobic threshold and lactate turn point. *Eur. J. appl. Physiol.* 50, 383-392.

Di Prampero, P: (1986) The anaerobic threshold concept : a critical evaluation. *Adv. cardiol.* 35, 24-34.

Di Prampero, P.E., Atchou, G., Bruckner, J.C. & Moia, C. (1986) The energetics of endurance running. *Eur. J. Appl. Physiol.* 55, 259-266.

Farrel, P.A., Wilmore, J.H., Coyle, E.F., Billing, J.E. & Costill, D.L. (1979) Plasma lactate accumulation and distance running performance. *Med. in Sports* 11, 338-344.

Gleser, M.A. & Vogel, J.A. (1973) Endurance capacity for prolonged exercise on the bicycle ergometer. *J. Appl. Physiol.* 34, 438-442.

Housh, D.J., Housh, T.J. & Bauge, S.M. (1989) The accuracy of critical power test for predicting time to exhaustion during cycle ergometry. *Ergonomics* 32, 997-1004.

Kindermann, W., Simono, G. & Keul, J. (1979) The significance of aerobic-anaerobic transition for the determination of workload intensities during endurance training. *Eur. J. Appl. physiol.* 42, 25-34.

Lacour, J.R., Padilla-Magunacelaya, S., Chatard, J.C., Arsac, L. & Barthelemy, J.C. (1991) Assessment of running velocity at maximal oxygen uptake. *Eur. J. Appl. Physiol.* 62, 77-82.

Lafontaine, T.P., Londeree, B.R. & Spath, W.K. (1981) The maximal steady state versus selected running events. *Med. Sci. Sports Exerc.* 13, 190-192.

Lavoie, N.F. & Mercier, T.H. (1987) Incremental and constant load determinations of $\dot{V}O_2$max and maximal constant load performance time. *Can. J. Appl. Sports Sci.* 12, 229-232.

Leger, L. & Boucher, M. (1980) An indirect continuous running multistage field test, the University of Montreal track test. *Can. J. Appl. Sports Sci.* 5, 77-84.

Londeree, B.R. & Ames, S.A. (1975) Maximal lactate steady state versus states of conditioning. *Eur. J. Appl. Physiol.* 34, 1-10.

McLellan, T.M. & Skinner, J.S. (1985) Submaximal endurance performance related to the ventilatory thresholds. *Can. J. Appl. Sports Sci.* 10, 81-87.

McLellan, T.M. & Cheung, S.Y. (1992) A comparative evaluation of the individual anaerobic threshold and the critical power. *Med. Sci. Sports Exerc.* 24, 543-550.

Nagle, F., Robinhold, D., Howley, E., Daniels, J., Baptista, G. & Stoedefalke, K. (1970) Lactic acid accumulation during running at submaximal aerobic demands. *Med. Sci. Sports* 2, 182-186.

Padilla, S., Bourdin, M., Barthelemy, J.C. & Lacour, J.R. (1992) Physiological correlates of middle-distance running performance. *Eur. J. Appl. Physiol.* 65, 561-566.

Pepper, M.L., Housh, T.J. & Johnson, G.O. (1992) The accuracy of the critical velocity test for predicting time to exhaustion during treadmill running. *Int. J. Sports. Med.* 2, 121-124.

Peronnet, F., Thibault, G., Rhodes, E.C. & McKenzie, D.C. (1987) Correlation between ventilatory threshold and endurance capability in marathon runners. *Med. Sci. Sports Exerc.* 6, 610-615.

Ramsbottom, R., Williams, C., Kerwin, D.G. & Nute, M.L.G. (1992) Physiological and metabolic responses of men and women to 5-km treadmill time trial. *Journal of Sports Sciences* 10, 119-129.

Sid-Ali, B., Vandewalle, H., Chair, K., Moreaux, A. & Monod, H. (1991) Lactate steady state velocity and distance-exhaustion time relationship in running. *Archiv. int. Physiol. Biochem. Biophys.* 99, 297-301.

Sjödin, B. & Jacobs, I. (1981) Onset of blood lactate accumulation and marathon running performance. *Int. J. Sports Med.* 2, 23-26.

Sjödin, B. & Svendenhag, J. (1985) Applied physiology of marathon running. *Sports Medicine* 2, 83-89.

Stegmann, H. & Kindermann, W. (1982) Comparison of prolonged exercise tests at individual anaerobic threshold and the fixed anaerobic threshold of 4 mmol.l^{-1} lactate. *Int. J. Sports Med.* 3, 105-110.

Taylor, H.L., Buskirk, E. & Henschel, A. (1955) Maximal oxygen intake as an objective measure of cardiorespiratory performance. *J. Appl. Physiol.* 8, 73-80.

Wasserman, K., Whipp, B.J., Koyal, S.N. & Beaver, V.L. (1973) Anaerobic threshold and respiratory gas exchanges during exercise. *J. Appl. Physiol.* 35, 236-343.

Yoshida, T. (1984) Effect of exercise duration during incremental exercise on the determination of anaerobic threshold and the onset of blood lactate accumulation. *Eur. J. Appl. Physiol.* 53, 196-199.

V. Billat PhD, Assistant Professor
Laboratoire des Sciences du Sport, UFR CIS,
Université Paris 12, 61 Av Général de Gaulle
F-94010 Créteil, France