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CARDIO-RESPIRATORY SYSTEM EFFICIENCY IN TRAINED ENDURANCE CYCLISTS

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Abstract

Introduction: Performance of the human cardio-respiratory system can be quantified during exercise using ventilatory efficiency and the oxygen uptake efficiency slope (OUES). However, only limited data exist on the association between these measures and oxygen uptake in trained subjects.

Materials and methods: In 12 endurance trained males (age range 26-50 years), ventilatory efficiency (mean $\pm$ SD: 27.52 $\pm$ 6.22) and OUES (mean $\pm$ SD: 5.75 $\pm$ 0.83) were determined during incremental exercise on a stationary cycle ergometer, terminated at maximal oxygen uptake ($\dot{V}O_2$max, mean $\pm$ SD: 65.88 $\pm$ 9.12 ml·kg^{-1}·min^{-1}).

Results: There was no correlation between neither $\dot{V}O_2$max and ventilatory efficiency (r=0.42, *P*>0.05), nor $\dot{V}O_2$max and OUES (r=-0.27, *P*>0.05). Oxygen uptake at the estimated anaerobic threshold neither correlated with ventilatory efficiency, nor with OUES. Ventilatory efficiency negatively correlated with OUES (r=-0. 57, *P*<0.05).

Conclusions. Although both ventilatory efficiency and OUES have wide acceptance as measures of cardio-respiratory performance in clinical populations, the utility of these measures for quantifying the systems' physiological function in endurance trained subjects remains to be determined.

Key words: *Ventilatory efficiency, oxygen uptake efficiency slope, $\dot{V}O_2$max*

Introduction

The efficiency of pulmonary ventilation can be quantified by the slope of the linear relation between carbon dioxide production ($\dot{V}CO_2$) and minute ventilation ($\dot{V}E$). This is conventionally modelled by: $\dot{V}E = a\ \dot{V}CO_2 + b$, where 'a' represents ventilatory efficiency [1]. Typical values range from 19 – 30 [2, 3] and a steeper slope (e.g. $\geq$ 34) indicates reduced ventilatory efficiency consistent with ill health [4-6]. Alternatively, oxygen uptake ($\dot{V}O_2$) may also be expressed as a function of $\dot{V}E$, and this non-linear relation has been modelled by: $\dot{V}O_2 = a\ \mathrm{Log}_{10}\ \dot{V}E + b$, where 'a' represents the oxygen uptake efficiency slope (OUES) [7, 8]. Typical values range from 3 – 5 [9] where a higher value (e.g. $\geq$ 5) indicates an increased oxygen uptake efficiency typical of a trained athlete. Both of these slopes represent measures of the efficiency of the physiological systems which support the body's ability to perform exercise. Also, both of these slopes may be used to quantify the tolerance to physical exertion in patients with reduced aerobic exercise capacity [10] and the response of these patients to training [11-14].

In both healthy controls and heart failure patients, high positive correlation coefficients between peak oxygen uptake ($\dot{V}O_2$ PEAK) and OUES have been reported (>0.94) despite a low correlation coefficient (-0.15) between ventilatory efficiency and $\dot{V}O_2$ PEAK [7]. Similarly, correlation coefficients of 0.68 and 0.78 were reported for the linear relation between OUES and $\dot{V}O_2$PEAK in cohorts of heart failure patients [15], whereas ventilatory efficiency showed a weaker, negative association with $\dot{V}O_2$ PEAK (-0.46). Others [16] also reported a weak negative correlation between ventilatory efficiency and $\dot{V}O_2$ PEAK (-0.53).

Trained endurance athletes typically have a high $\dot{V}O_2$max, due in part to efficient lungs, and the optimised delivery and use of oxygen by muscle. Therefore, measures of the efficiency of systems which support the body's ability to perform aerobic exercise are likely to show close association with $\dot{V}O_2$max. However, despite this expected close association, there is currently only limited data pertaining to endurance athletes. For example, in trained ($\dot{V}O_2$PEAK 65 ml·kg^{-1}·min^{-1}) and untrained ($\dot{V}O_2$PEAK 44 ml·kg^{-1}·min^{-1}) subjects, OUES and $\dot{V}O_2$PEAK were positively correlated (>0.8 for both cohorts) although ventilatory efficiency was not measured by these authors [9]. Previous reports consistently lack description of a possible association between ventilatory efficiency and the efficiency of oxygen uptake.

The aim of this study was to quantify, in a group of well trained endurance athletes, the relationships between:

1. $\dot{V}O_2$max and ventilatory efficiency;
2. $\dot{V}O_2$max and the oxygen uptake efficiency slope;
3. Ventilatory efficiency and oxygen uptake efficiency.

It was hypothesised that a negative correlation existed between these two measures of system efficiency.

Materials and Methods

With ethical approval, trained endurance athletes, (n=12) performed an incremental cardiopulmonary exercise test to volitional exhaustion on a stationary cycle ergometer (Lode Excalibur, Lode BV, Groningen, Netherlands). Subjects were all experienced competitive cyclists (National grade A (sub-elite level)), age range 26 – 50 years, all of whom had >5 years history of endurance training. Subjects performed an initial 10 minute warm up, and were asked to ride at their normal cadence. The initial 5 min of the warm up was at 60 W for all subjects, with the second 5 min period at 80 W. A power output of 80W corresponded to the lowest minimal power output used for subsequent incremental testing.

Subjects performed a continuous incremental test with 7-9 stages, where each stage was 5 minutes duration, during which a capillary blood sample was collected from a finger tip after 4 min and used for measurement of blood lactate concentration $[La^-]$ (Lactate Pro, Arkray, Kyoto, Japan). Heart rate was continuously monitored (S610, Polar Electro, Finland), and throughout the last minute of each stage, exhaled air was collected and analysed for oxygen and carbon dioxide content (Servomex O_2 + CO_2 model 1440), and total volume (Dry Gas Meter, Harvard Apparatus). Power output was increased by 20W at the start of each stage, with initial power based on the ability of the subject (in the region of 80 – 120 Watts for all subjects). When a lactate value greater than 4.5 mmol L^{-1} was achieved, exercise intensity was reduced and each subject was given a 10 minute active recovery at a power output approximately 50% below their estimated power at 4 $mmol{\cdot}L^{-1}$ $[La^-]$. Each subject then performed exercise to volitional exhaustion, starting at a power output equivalent to that achieved at a $[La^-]$ of approximately 4.5 $mmol{\cdot}L^{-1}$, during which power output was increased by 20W min^{-1}. Throughout each minute, exhaled air was collected and analysed for oxygen and carbon dioxide content, and total volume. The test was terminated when the subject could no longer continue, and had reached a plateau in their heart rate response to the exercise. The maximum heart rate of all subjects was within 10% of their age predicted maximum (220 – age), and analysis of the exhaled gases indicated that all subjects achieved a respiratory exchange ratio of >1.1 at test termination. Previous unpublished work using this $\dot{V}O_2$max protocol indicated that intra-subject reproducibility was $\leq$5 %.

Statistical analysis

Following convention, data for $\dot{V}E$ are reported under BTPS conditions (Body temperature, atmospheric pressure, saturated), whereas data for $\dot{V}O_2$ and $\dot{V}CO_2$ are reported under STPD conditions (Standard temperature, standard pressure, dry). For all subjects, minute $\dot{V}E$ was plotted as a function of $\dot{V}CO_2$ and modelled with linear regression, where $\dot{V}E = a\ \dot{V}CO_2 + b$. The slope (a) of this regression line was used as the measure of ventilatory efficiency. For all subjects, $\dot{V}O_2$ was plotted as a function of $\dot{V}E$ and modelled by a logarithmic function, where $\dot{V}O_2 = a\ Log_{10}\ \dot{V}E + b$. The slope (a) of this regression line was used as the measure of oxygen uptake efficiency (OUES). The association between $\dot{V}O_2$max and both ventilatory efficiency and OUES was determined using correlation, also the association between ventilatory efficiency and OUES was determined using correlation. Peak and minimum values for the ventilatory equivalents for O_2 and CO_2 were recorded – these were also correlated with measures of system efficiency.

Results

All subjects completed the exercise test and individual results with summary statistics are shown in table 1.

Mean $\pm$ SD $\dot{V}O_2$max was 65.88 $\pm$ 9.12 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$, mean $\dot{V}E$ *vs*. $\dot{V}CO_2$ slope was 28.10 $\pm$ 5.60, and mean OUES was 5.75 $\pm$ 0.83. For all subjects, the linear relation between $\dot{V}E$ and $\dot{V}CO_2$ recorded a high coefficient of determination (range: 0.81-> 0.99), and for all subjects, the non-linear relation between $\dot{V}E$ and $\dot{V}O_2$ recorded a high coefficient of determination (range: 0.85 ->0.99). A representative example of these measures is shown in figure 1, where the ventilatory efficiency [upper panel] is 18.45, and the oxygen uptake efficiency [lower panel] is 7.54.

There were no significant correlations between measures of oxygen uptake (neither maximal, submaximal, nor relative) and measures of cardio-respiratory system efficiency, as shown in table 2.

The association between ventilatory efficiency and OUES is shown in figure 2 [lower panel], where a weak but significant negative correlation coefficient of -0.57 was recorded (P<0.05). The association between ventilatory efficiency and $\dot{V}O_2$max, and the association between OUES and $\dot{V}O_2$max, is shown in figure 2 [upper panel], where correlation coefficients of 0.42 and -0.27 were recorded respectively (both P>0.05).

Discussion

The main findings of this study are firstly, $\dot{V}O_2$max does not correlate with measures of cardio-respiratory efficiency; and secondly, relative $\dot{V}O_2$ at the anaerobic threshold does not correlate with measures of cardio-respiratory efficiency. The study also uniquely reports a significant, negative association between ventilatory efficiency and OUES in trained endurance athletes, albeit fairly weak.

This study reports no association between $\dot{V}O_2$max and measures of system efficiency in endurance trained athletes, suggesting that maximal

Table 1. *Individual and summary statistics [mean (SD)] for maximum oxygen uptake ($\dot{V}O_2max$), ventilatory efficiency ($\dot{V}E$ vs. $\dot{V}CO_2$ slope), oxygen uptake efficiency slope (OUES), relative peak oxygen consumption at the onset of blood lactate accumulation (OBLA), and peak and minimum ventilatory equivalents for both O_2 and CO_2, in 12 trained endurance athletes*

$\dot{V}O_2max$ (ml·kg^{-1} ·min^{-1})	$\dot{V}E$ vs. $\dot{V}CO_2$ Slope	OUES	% $\dot{V}O_2max$ at OBLA	Ventilatory equivalent for O_2 ($\dot{V}E$: $\dot{V}O_2$)		Ventilatory equivalent for CO_2 ($\dot{V}E$: $\dot{V}CO_2$)	
				Peak	Minimum	Peak	Minimum
82.89	18.50	7.54	85.1	25.34	19.80	25.85	23.18
60.81	25.73	5.92	76.0	25.46	19.02	28.00	21.58
54.62	18.50	6.03	93.4	20.05	16.72	21.08	18.90
58.30	33.91	4.77	94.3	33.57	20.89	33.57	24.71
69.33	23.40	5.09	77.9	27.67	16.43	24.03	20.11
52.51	31.56	5.40	80.0	26.91	22.10	31.28	24.06
66.30	27.10	6.45	78.4	28.06	18.48	27.58	22.14
78.69	28.96	5.62	83.9	28.81	17.78	26.59	21.11
70.90	33.87	5.85	81.8	28.64	18.95	31.24	24.40
70.21	22.26	5.19	76.9	31.30	18.04	29.77	19.94
62.45	38.25	4.64	85.7	31.70	19.41	32.87	21.93
63.50	28.27	6.55	85.0	33.10	21.20	34.38	22.06
65.88	**27.52**	**5.75**	**83.20**	**28.38**	**19.07**	**28.85**	**22.01**
(9.12)	(6.22)	(0.83)	(6.00)	(3.80)	(1.74)	(4.06)	(1.84)

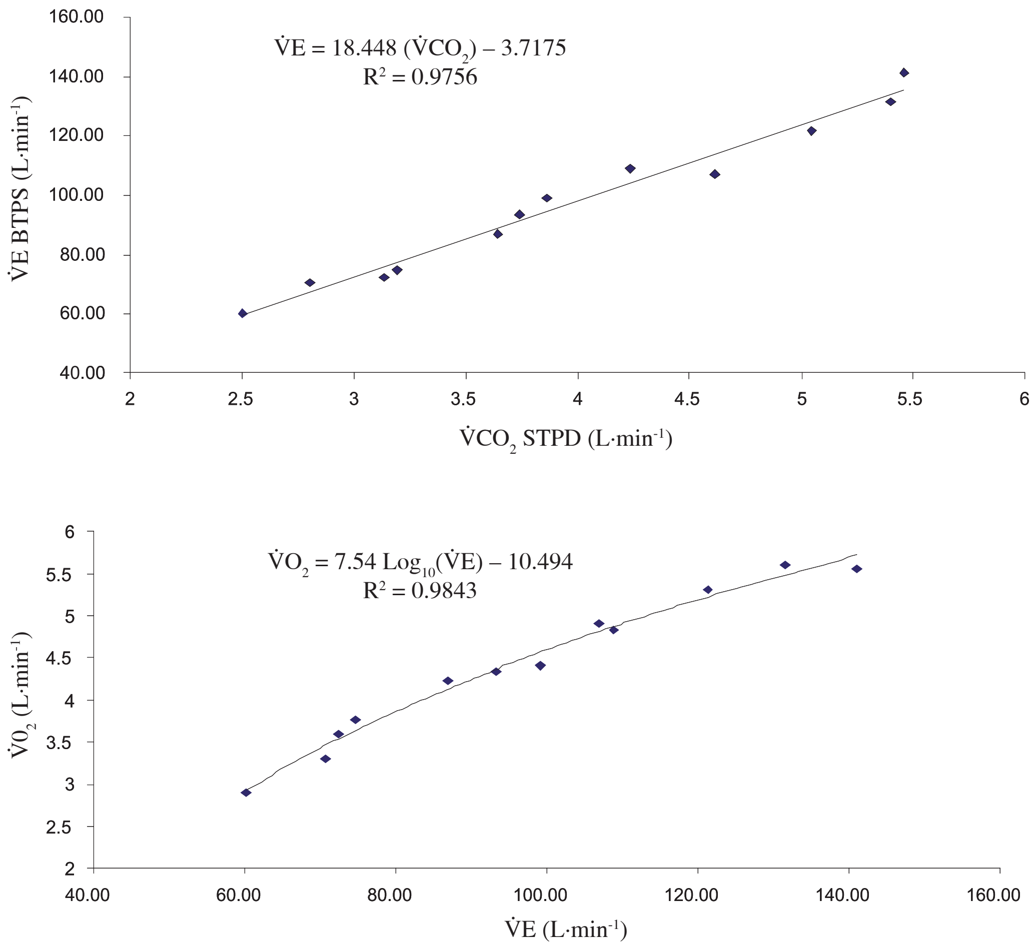

Fig. 1. *Representative example of the relation between minute ventilation ($\dot{V}E$) and carbon dioxide output ($\dot{V}CO_2$) [upper panel], and the relation between oxygen uptake ($\dot{V}O_2$) and minute ventilation ($\dot{V}E$) [lower panel], in an endurance trained athlete ($\dot{V}O_2max$ = 82.89 ml·kg^{-1}·min^{-1})*

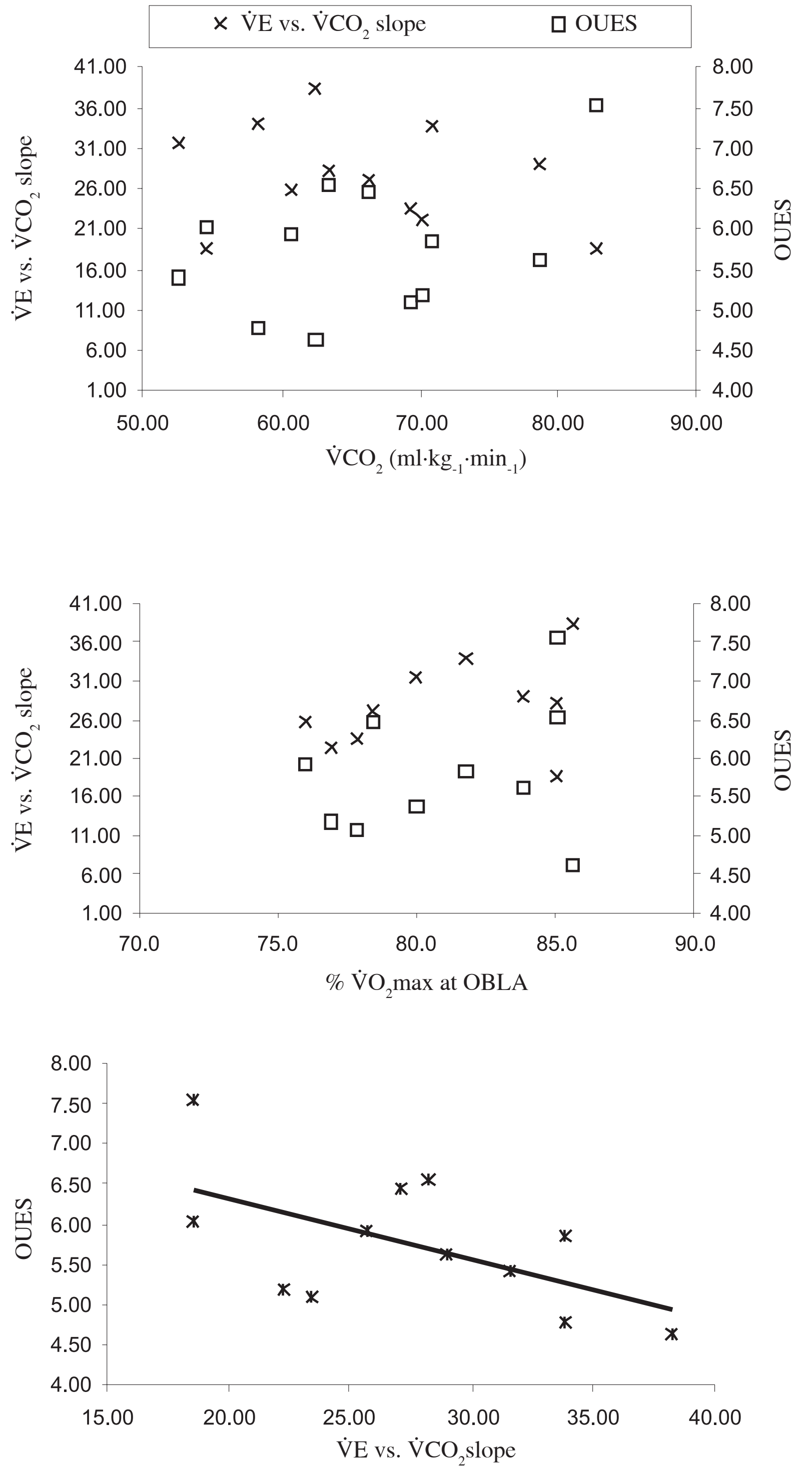

Fig. 2. *Measures of system efficiency plotted as a function of maximum oxygen uptake [upper panel], relative maximum oxygen uptake [middle panel}, and the relation between measures of system efficiency [lower panel], in 12 trained endurance athletes*

Table 2. *Correlations between measures of oxygen uptake and ventilatory efficiency (V̇E vs. V̇CO_2 slope), oxygen uptake efficiency slope (OUES), and peak and minimum ventilatory equivalents for both O_2 and CO_2, in 12 trained endurance athletes*

	V̇E vs. V̇CO_2 Slope	OUES	Ventilatory equivalent for O_2 (V̇E : V̇O_2)		Ventilatory equivalent for CO_2 (V̇E : V̇CO_2)	
			Peak	Minimum	Peak	Minimum
V̇O_2max (ml·kg^{-1}·min^{-1})	0.42	-0.27	0.08	-0.30	-0.21	-0.03
V̇O_2AT (ml·kg^{-1}·min^{-1})	-0.21	0.41	0.08	-0.20	-0.18	0.06
% V̇O_2max at OBLA	0.01	-0.05	-0.01	0.14	0.03	0.13

oxygen uptake is independent of both ventilatory efficiency and oxygen uptake efficiency. Endurance athletes usually have a high $\dot{V}O_2$max and typically have the ability to exercise at a high proportion of their maximum – hence it was reasonable to assume that measures of the efficiency of systems which support exercise should correlate with $\dot{V}O_2$max. However, system efficiency may have little or no relevance at $\dot{V}O_2$max as the duration an athlete can perform exercise at $\dot{V}O_2$max is very short. Therefore, in the current study, the associations between $\dot{V}O_2$ at the estimated anaerobic threshold (coincident with a 4 $mmol{\cdot}L^{-1}$ capillary blood lactate in this study) and both OUES and ventilatory efficiency were also quantified. However, these were also not significant. This may suggest that although measures of system efficiency are adequate in quantifying the cardio-respiratory response to exercise in clinical populations [1, 10, 17, 18] and healthy untrained subjects [19], they may have little efficacy in quantifying the performance of physiological systems in endurance trained athletes [20].

In the present study, a weak but significant correlation existed between the two measures of system efficiency. While both measures relate a metabolic/respiratory component (either $\dot{V}O_2$ or $\dot{V}CO_2$) to a system response – in this case, pulmonary ventilation, this is the first study to report an association between these two measures in endurance athletes. Ventilatory efficiency and the OUES have different origins. The $\dot{V}E$ *vs.* $\dot{V}CO_2$ slope is an indicator of the efficiency of removal of CO_2 by the lung, whereas the OUES is an indicator of delivery, extraction, and O_2 use by the active tissue. Increased pulmonary vascular resistance [21], a decline in pulmonary perfusion [22], and a mismatching of pulmonary ventilation to perfusion [23], all contribute to a steeper $\dot{V}E$ *vs.* $\dot{V}CO_2$ slope. In contrast, it has been suggested that the OUES incorporates, in a single index, cardiovascular and peripheral factors that determine oxygen uptake, as well as pulmonary factors that influence the ventilatory response to exercise [15]. The small population in the present study were all endurance trained, albeit non-elite, and although speculative, perhaps a stronger correlation between measures of efficiency would be present in elite endurance trained individuals.

In the current study, ventilatory efficiency and OUES were calculated from 100% of the data obtained during incremental exercise up to $\dot{V}O_2$max.The OUES may become more reliable when calculated from data obtained from higher levels of exercise intensity [24], however, the OUES differs little when calculated only from data up to 75% [7, 25]. Calculation of the $\dot{V}E$ vs. $\dot{V}CO_2$ slope using all data up to $\dot{V}O_2$max (as in the current study) has been recommended [5, 26], although this slope may steepen above the anaerobic threshold due in part to an increased sensitivity to arterial PCO_2. For example, marginally higher $\dot{V}E$ vs. $\dot{V}CO_2$ slope values were reported when all data up to $\dot{V}O_2$max were included in the calculation, compared to a lower slope calculated using only data from sub-maximal exercise intensities [3]. In the present study, we are confident that using 100% of the data collected up to $\dot{V}O_2$max to calculate both ventilatory efficiency and OUES is robust and reliable.

Using multiple data points to calculate ventilatory efficiency and OUES has proven efficacy when used with clinical populations [5, 6, 10], and this has been the approach taken in the current study. More recently [27], the importance of the lowest ventilatory equivalent for CO_2 ($\dot{V}E : \dot{V}CO_2$ min) has been demonstrated. Indeed, it has been shown that $\dot{V}E : \dot{V}CO_2$ min is the best single predictor of both mortality and morbidity in patients (n=508) with heart failure during a 6 month period following diagnosis and treatment [27]. In the present study of trained athletes, both peak and minimum ventilatory equivalents for both O_2 and CO_2 are reported, although there was no correlation between these measures and measures of oxygen uptake (either at $\dot{V}O_2$max or OBLA). Differences in a clinical cohort [27] and athletes are profound, as evidenced by comparing the different oxygen uptakes of heart failure patients (peak $\dot{V}O_2$ of 12.1 ± 4 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$) to that of trained athletes ($\dot{V}O_2$max was 65.88 $\pm$ 9.12 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$), thus the importance of minimum and peak ventilatory equivalents for O_2 and CO_2 in trained athletes remains undetermined.

In summary, this study reports a significant association between OUES and ventilatory efficiency in endurance trained athletes. This study also reports that maximal oxygen uptake appears to be independent of cardio-respiratory system efficiency. Also, the relative oxygen uptake at the anaerobic threshold, which is perhaps more important for an endurance athlete, appears to be independent of measures of cardio-respiratory system efficiency.

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