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ORIGINAL ARTICLE

A new incremental test for VO_{2max} accurate measurement by increasing VO_{2max} plateau duration, allowing the investigation of its limiting factors

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Abstract The purpose of this study was to (1) validate a new exercise protocol for accurate measurement of VO_{2max} by obtention of a VO_{2max} plateau for all subjects fit and unfit (2) test the hypothesis that VO_{2max} plateau duration is not correlated with VO_{2max} and (3) verify that limiting factors of VO_{2max} plateau duration are different from those of VO_{2max} amplitude. Therefore, 14 subjects performed two incremental cycling tests: (1) a classical incremental test (CIT) to determine VO_{2max}, the power at VO_{2max} (PVO_{2max}) and at the lactate threshold (PLT) (2) a new incremental test (NIT) in which the power was decreased just after the subject reached VO_{2max}. During both protocols, heart rate, stroke volume, cardiac output, the arterio-venous difference and the oxygen blood saturation were recorded. The results showed that, with the NIT, subject could maintain a long VO_{2max} plateau (6 ± 3 min), even those who could not reach VO_{2max} plateau at the end of CIT ($n = 5$). The VO_{2max} plateau duration was not correlated with VO_{2max} amplitude which was correlated with the power at SV_{max} ($r = 0.888$, $p < 0.001$). The VO_{2max} plateau duration was correlated with the power decrease (W/s) during the VO_{2max} plateau ($r = -0.72$, $p = 0.003$) but not with cardiac-related factors nor with PVO_{2max}. In conclusion, these experiments showed that it was possible to get a long VO_{2max} plateau at the end of NIT whatever the individual VO_{2max} amplitude was. The limiting factor of VO_{2max} duration was the power output.

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Introduction

The concept of a plateau in oxygen uptake with increasing intensity of exercise until a maximum was central to Hill and Lupton's (1923) description of maximal oxygen uptake (VO_{2max}), and is considered as the gold standard parameter of the cardio respiratory system's ability to maximize delivery and to utilize oxygen (Hawkins et al. 2007; Howley 2007).

To determine this VO_{2max} value, many protocols were tested during the last century. Initially, constantly loaded exercise protocols (Hill and Lupton 1923; Taylor et al. 1955), typically distributed over several days, were used to measure the VO_{2max}. Then, the steady state protocols were replaced by the incremental tests on 1 day, which remains nowadays the recommended test in the practitioner plans and allowing the experts to determine the VO_{2max} and the ventilatory thresholds (American college of sports medicine 2006; Wasserman et al. 1999). However, the matter of VO_{2max} assessment at the end of the incremental test remains unclear because the VO_{2max} plateau occurs only for 50% of the subjects in average (Doherty et al. 2003). Therefore, the determination of VO_{2max} at the end of incremental test is not obvious for subjects not able to maintain a plateau. The absence of VO_{2max} plateau has been interpreted as an impossibility, for these subjects with a low VO_{2max} and a low fitness level, to sustain pain and fatigue at the end of this kind of incremental test (Astorino et al. 2005; Howley et al. 1995; Shephard 2009). Another explanation was the incompatibility of maintaining the

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stroke volume (SV), heart rate (HR) and the arterio-venous difference (Da-vO_2) at their maximal values according to Fick equation at the end of incremental test (Bergh et al. 2000; Ekblom 2009). Finally, the power output at the end of incremental test, independently of VO_{2max} values, could be the major limiting factor to get VO_{2max} plateau. Stoudemire et al. 1996 systematically reduced treadmill speed but maintained VO_2 at VO_{2max}. In this study, the independent variable was a rating perceived exertion in Borg scale which is a subject dependent parameter. In the present study, we propose a VO_{2max} controlled protocol after reaching VO_{2max} by modulation of the power. Here, the independent factor is not subject dependant but estimated by the operator.

For this reason, we propose here to validate a new incremental test (NIT) which assesses the accurate VO_{2max} value by maintaining a long VO_{2max} plateau duration in one incremental protocol. The NIT modifies the CIT test by decreasing the power output when VO_{2max} is reached instead of increased power in CIT. Moreover, the NIT determines the PVO_{2max}, the power associated with the Lactic threshold (PLT), and all the cardiac variables.

This study showed that it was possible to get a VO_{2max} plateau at the end of an incremental test irrespective of every individual VO_{2max} amplitude, and to identify the plateau duration limiting factors. For this purpose, we tested the hypothesis that (1) the decrease of power just after reaching VO_{2max}, measured in the previous CIT, allowed to get a VO_{2max} plateau in all subjects (2) the VO_{2max} plateau duration was not correlated with VO_{2max} (3) the limiting factors of VO_{2max} amplitude and VO_{2max} duration at the end of incremental tests were different.

Methods

Subjects

Seventeen healthy, active men and women (5 women and 12 men), voluntarily took part in the study. Before their participation, all subjects were informed of the risks and stresses associated with the protocol and gave their written consent voluntarily. The present study was conformed to the standards set by the Declaration of Helsinki, and all the procedures were approved by the Local Research Ethics Committee. All subjects were free of known cardiovascular, respiratory, and circulatory dysfunction. None of them were under any prescribed medication. All tests were at least 2-h postprandial and subjects were asked to refrain from caffeine intake prior to testing on the test days. Subjects performed each exercise test on a separate day.

Experimental design and exercise protocols

After familiarisation with the laboratory and procedures, each subject performed two exercise protocols on their bicycle placed on a Cyclus II ergometer (RBM, Leipzig, Deutschland). All the tests were performed until exhaustion and were separated by at least 72 h. The subjects were verbally encouraged to reach their maximum.

The first test was the classical incremental test (CIT) during which the power output was increased every 3 min from 0.5 Watt per kg of body weight, as previously described (Wasserman et al. 1999). The incremental protocol with a 3 min stage was chosen for the demonstration of a steady state in physiological variable (lactate threshold, stroke volume, heart rate…) and this protocol demonstrated a high incidence of VO_{2max} plateau at this end of the test.

It permitted to determine VO_{2max}, the lowest power which elicited VO_{2max} (PVO_{2max}), and the lactate threshold (T_{lac}) as determined from the relationship between blood lactate concentration and VO_2 and the power associated with the lactate threshold (PLT). The lactate inflection point (T_{lac}) was identified as an abrupt and non linear increase in blood lactate occured as work intensity (VO_2) increased (Gaesser and Poole 1986). This method identified the point when the lactate is accumulated above the steady state value which there is a net contribution of non-aerobic metabolism to the energetic.

The second test was a NIT. This test was exactly identical to the CIT before the subject reached VO_{2max} (as measured with the CIT). At this time, power was decreased from PVO_{2max} to PLT with different individual patterns while maintaining a VO_{2max} plateau during the longest time possible. During the first second of the VO_{2max} plateau, the first power decreased by 29 W/10 s on average. Then, the power continuously adjusted by stage of 5 or 10 W so that the power was at its lowest point possible. In the same way, in this case VO_2 declined lower than 95% VO_{2max}, the power was increased by the same procedure by stage of 5 or 10 W. The test stopped when the subject did not support the VO_{2max}, any longer, at its maximum or when the subject stopped the test by himself.

Data collection procedure

During both tests, electrocardiogram collected with an electrocardiograph function of the gas analyzer (Quark b^2, Cosmed, Rome, Italy), stroke volume (SV) and heart rate (HR) were recorded beat-by-beat by a non-invasive cardiac output measurement using analysis of thoracic electrical bioimpedance signals (Lab1, Physioflow, Manatec Type PF05L1, Strasbourg, France). Cardiac output (CO) was calculated from HR and SV values. The VO_2 and CO

values were synchronized over 5 s intervals to obtain the arterio-venous difference (Da-vO_2). The oxygen blood saturation (SaO_2) was recorded every 2 min and the end of VO_{2max} during both tests with a non-invasive pulse oximeter placed at the fingertip (Oxypleth, Novametrix Medical System, Wallingford, USA). Before each test, the oxygen analyzer was calibrated according to the manufacturer's instructions and using a 3L syringe (Quinton instruments, USA) for the turbine flow-meter calibration. Oxygen uptake was measured breath-by-breath throughout each test using a gas analyzer (Quark b^2, Cosmed, Rome, Italy). The expired gas concentrations were averaged every 5 s.

The lactate blood concentration was measured with lactate pro® (lactate pro, ARKRAY inc, Kyoto, Japan) placed at the fingertip for each power stage, every 2 min during the VO_{2max} plateau, at the end point of the plateau and at 2 and 4 min during the recovery. The subjects were given strong verbal encouragement to exercise until volitional fatigue, but were not given progress feedback. The rating of perceived exertion (RPE) was recorded at the end of each power stage, every 2 min during VO_{2max} plateau, and at the end of the test with RPE Borg scale (Borg 1982).

Data analysis

The VO_{2max} attainment was confirmed by at least one of the following criteria: (1) VO_2 variations (ΔVO_2) lower than 50 mL min^{-1} during at least 1 min (plateau), (2) the following four parameters should be fulfilled—a respiratory exchange ratio (RER) >1.10, HR >90% of the theoretical maximal HR (Hill and Lupton 1923), subjective RPE >16, blood lactate concentration above 8 mmol L^{-1} (Astrand and Rodahl 1986). The duration of the VO_{2max} plateau sustained between VO_{2max}, as it is determined above, is 95% of $VO_{2max.}$ This range took into account the experimental and biological VO_2 variability in the repeated testing of each subject (Katch et al. 1982). The minimal duration for considering a VO_{2max} plateau was 1 min (criteria 1). Therefore, three subjects were also tested and excluded from the present report as they did not present a VO_2 plateau at this end of the CIT and did not reach all the secondary criteria.

Statistical analysis

When normality and equality of the variances were verified (Sigma Stat software, Jandel Scientific, Chicago, IL, USA), a one-way analysis of variance (ANOVA) (Staview 5.5, Statsoft, Berkeley, CA, USA) test was performed to test for any protocol effect. A post-hoc test (PLSD of Fischer) was then applied to test the difference between the exercise protocols CIT and NIT. Correlations between variables of Fick equation and respiratory factors: SV, CO, HR, Da-vO_2, VE and the duration at VO_{2max} plateau were determined using Pearson's product moment correlation coefficient (Staview 5.5, Statsoft, Berkeley, CA, USA). Moreover, in both tests, the duration of VO_{2max} plateau was split in quarters, 25, 50, 75, and 100% of VO_{2max} plateau. Then, an ANOVA for repeated measures (Staview 5.5, Statsoft, Berkeley, CA, USA) was applied for analyzing the steady state of variables of Fick equation, VE, RPE and blood lactate variables during the plateau of VO_{2max}. We also compared the physiological variables during CIT and NIT at the absolutely same time of VO_{2max} plateau (SAT) corresponded to the time limit at VO_{2max} in CIT and corresponded to 37 ± 27% of VO_{2max} plateau duration during NIT.

Results

Descriptive characteristics of the subjects

Table 1 indicates the individual physical and physiological values. The group included three women and 11 men. The average age, height and weight were respectively 30 ± 7 years, 173 ± 9 cm and 69 ± 10 kg. During the CIT, the VO_{2max}, the PVO_{2max} and the PLT were measured and the means were respectively 55 ± 9 mL kg^{-1} min^{-1}, 314 ± 69 and 271 ± 69 W.

VO_{2max} plateau measured with the NIT

In the NIT, once the subjects had reached VO_{2max}, as measured in the previous CIT (Table 1), the VO_{2max} plateau was maintained by the adjustment of power (Fig. 1). With this protocol, all the subjects, including those who did not attain a VO_{2max} plateau in CIT ($n = 5$), were able to maintain their VO_{2max} during 6 ± 3 min (Table 2). This average value of plateau duration was significantly different from the plateau duration obtained with the CIT (1 min 40 s ± 1 min, $p < 0.0001$). Among the 14 subjects, 13 of them sustained their VO_{2max} plateau for more than 3 min, eight of them for more than 5 min, and for one only less than 2 min (Table 2). In contrast, in CIT, only seven of the subjects (50%) sustained VO_{2max} plateau for more than 1 min, two of them for more than 3 min and two of them had a VO_{2max} plateau equal to 1 min (Table 2). Therefore, using the CIT, the average VO_{2max} measured for subjects exhibits a plateau that was not significantly different from the average VO_{2max} measured for subjects not maintaining a plateau.

Independence between VO_{2max} plateau duration and VO_{2max} amplitude

During the NIT, all subjects exhibited a VO_{2max} plateau. Moreover, the duration of the VO_{2max} plateau was not

Table 1 Subject characteristics

Subjects	Gender	Age (years)	Height (cm)	Weight (kg)	VO_{2max} (mL kg^{-1} min^{-1})	PLT (W)	PVO_{2max} (W)
1	M	28	180	74	60	280	360
2	M	18	179	59	61	300	330
3	M	33	164	57	57	240	270
4	M	30	183	72	59	320	360
5	M	37	183	88	55	350	400
6	M	32	181	67	64	320	360
7	M	31	173	63	61	270	330
8	F	42	156	67	40	150	210
9	F	26	171	73	34	150	210
10	M	39	185	86	48	315	360
11	F	24	159	52	52	175	200
12	M	36	172	70	56	280	320
13	M	35	174	65	59	280	280
14	M	19	174	66	66	360	400
Mean ± SD	–	30 ± 7	173 ± 9	68 ± 10	55 ± 9	271 ± 69	314 ± 69

linearly correlated with VO_{2max} ($r^2 = -0.028$) (Fig. 2). During the CIT, only 50% of the subjects could maintain a VO_{2max} plateau and this VO_{2max} plateau duration was not correlated with VO_{2max} amplitude ($p = 0.8$).

Limiting factors of VO_{2max} amplitude and VO_{2max} plateau duration

In the CIT, the VO_{2max} amplitude was correlated with the power at SV_{max} ($r = 0.888$, $p < 0.001$). For 43% of subjects ($n = 6$) SV_{max} was reached before reaching VO_{2max}. During a NIT, such a correlation could not be found ($p > 0.05$) between the VO_{2max} plateau duration and neither PSV_{max}, Da-vO_2, SV_{max}, HR_{max}, PVO_{2max} nor PLT in % PVO_{2max}, separately.

The average power during the VO_{2max} plateau, reported to PVO_{2max}, was significantly lower in the NIT than in the CIT (91 ± 5% PVO_{2max} for NIT vs. 102 ± 3% PVO_{2max} for CIT, $p < 0.0001$; Table 3). At 25, 50, 75 and 100% of VO_{2max} plateau duration, the power during the VO_{2max} plateau was significantly lower in the NIT than in the CIT (Table 4). Moreover, the VO_{2max} plateau duration was correlated with the rate of power decreased (W/s) imposed to maintain the plateau ($r = -0.72$, $p = 0.003$; Fig. 3).

As shown in Table 1, the PLT values were lower or equal to the PVO_{2max} values leading to average the lower power value for PLT (average 271 ± 69 W) than for PVO_{2max} (mean 314 ± 69 W). During the NIT, the VO_{2max} plateau was maintained by continously modulating power between the PVO_{2max} and PLT. Nevertheless, the average value of power output during a VO_{2max} plateau in NIT (mean 279 ± 62 W) was closer to PLT values (average 271 ± 69 W) than to the PVO_{2max} values (average 314 ± 69 W) (Tables 1, 3; Fig. 1). In addition, during NIT, at the absolutely same time of VO_{2max} plateau (SAT) corresponded to the time limit at VO_{2max} in CIT and corresponded to 37 ± 27% of VO_{2max} plateau duration during NIT, lactate blood concentration was significantly lower during NIT than during CIT (7.6 ± 2.4 mmol L^{-1} for NIT vs. 13.0 ± 2.2 mmol L^{-1} for CIT). Nevertheless, blood lactate concentration was not significantly different at the beginning and at this end of the VO_{2max} plateau during both the tests (Table 3), whereas the VO_{2max} plateau duration was significantly longer during the NIT than the CIT. The rate of increase of blood lactate concentration was lower during the NIT compared with the CIT.

At the end of both tests, all the subjects scored 20 on the RPE Borg Scale (Borg 1982). Nevertheless, the mean of RPE score was different between two tests at SAT (20 ± 0 for CIT vs. 17 ± 2 for NIT). During the NIT, the three subjects, with the VO_{2max}< at 50 mL kg^{-1} min^{-1}, had a score on RPE scale at the beginning of the VO_{2max} plateau significantly lower than the other subjects (respectively 13 ± 2 vs. 17 ± 2, $p = 0.01$).

Discussion

A new exercise protocol allowing to get VO_{2max} plateau in fit and unfit subjects at the end of incremental protocol

The so-called "classical test" (CIT) typically corresponds to an incremental test used to measure VO_{2max} in previous studies (Astorino et al. 2005; Doherty et al. 2003; Howley et al. 1995; Shephard 2009). During the CIT, the power is

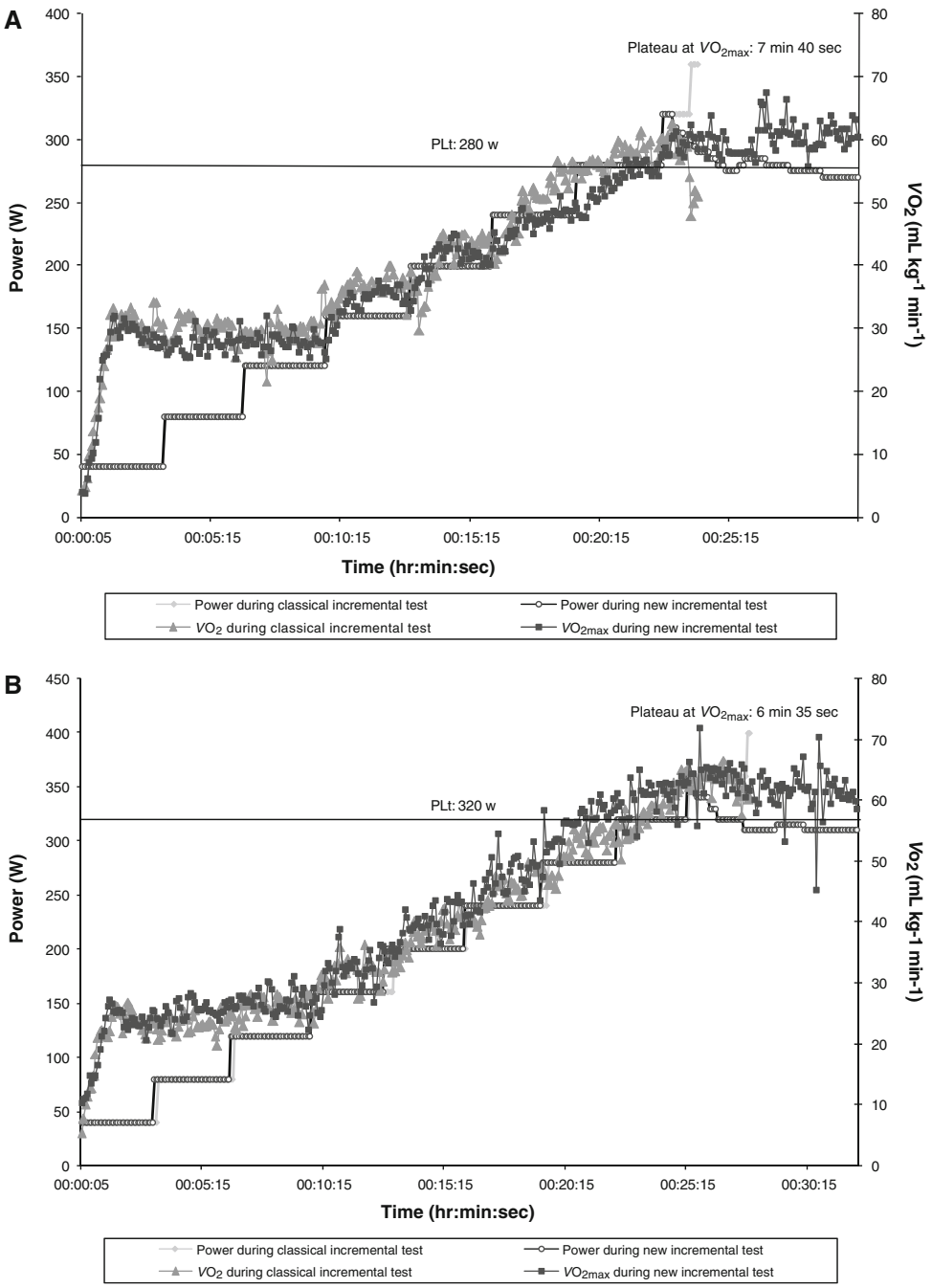

Fig. 1 **a**, **b** Oxygen uptake (mL kg^{-1} min^{-1}) and power output (W) during CIT (*grey line*) and NIT (*black line*) of two representative subjects. PLT is the power associated with the lactic threshold. VO_{2max} plateau duration during NIT is significantly different than during CIT

increasing by steps until the end of the test. At the end of CIT, if the VO_2 does not increase, achieving a plateau whereas the power continues to increase, the steady state of VO_{2max} attests the accuracy of the subject's VO_{2max} measurement (Niemelä et al. 1980). For this reason, the mean power of the VO_{2max} plateau in the CIT test was higher than PVO_{2max} (102 ± 3% of PVO_{2max}; Table 3). Nevertheless, in 50% of cases on average, the test is stopped before the VO_2 reached a steady state value; therefore, it is difficult to conclude that the VO_2 attained is the VO_{2max} (Day et al. 2003; Doherty et al. 2003; Gibson et al. 1999; Lucía et al. 2006). Furthermore, the physiological mechanisms responsible for the absence of the VO_{2max} plateau at the end of the CIT test are not yet completely elucidated (Astorino and White 2010; Doherty et al. 2003; Howley et al. 1995; Shephard 2009).

However, for the first time, this study proposes a single exercise protocol in which all subjects were able to maintain a VO_{2max} plateau for more than 1 min at the end of the incremental test, independently of their VO_{2max} value by decreasing the power. With this NIT, the plateau was accurately determined. Therefore, the factors limiting the

Table 2 Time at VO_{2max} (s) and VO_{2max} during each protocol: classical incremental test (CIT) and new incremental test (NIT)

Subjects	Time at VO_{2max} (s)		VO_{2max} (mL kg^{-1} min^{-1})	
	CIT	NIT	CIT	NIT
1	55	295	60	59
2	210	265	61	60
3	195	320	57	57
4	115	250	59	57
5	35	495	55	56
6	85	395	64	62
7	60	190	61	59
8	40	715	40	42
9	60	475	34	35
10	45	680	48	50
11	130	335	52	50
12	55	65	56	56
13	170	460	59	60
14	145	225	66	66
Mean ± SD	100 ± 60	369 ± 182*	55 ± 9	55 ± 8

* $p < 0.0001$

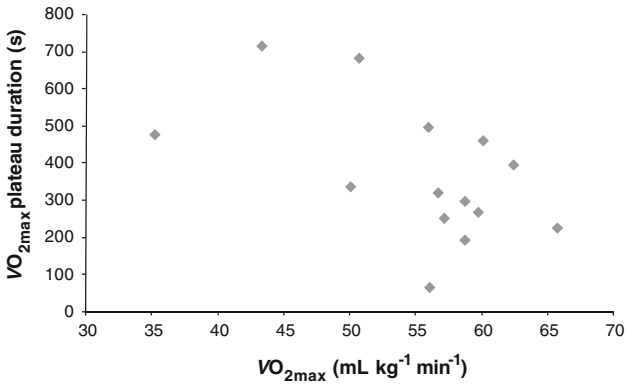

Fig. 2 Relationship between VO_{2max} plateau duration (s) and VO_{2max} (mL kg^{-1} min^{-1}) in new incremental test (*NIT*)

VO_{2max} plateau could be investigated, as the duration of the plateau was over 1 min in all subjects. Indeed, during the NIT, all subjects, including those who did not attain a VO_{2max} plateau at the end of CIT ($n = 5$), maintained their VO_{2max} plateau. For subjects that maintained a plateau in both tests, the plateau was longer in the NIT test than in the CIT (Table 2). The proportion of subjects reaching a plateau in a CIT test in this experiment is in agreement with the previous studies using classical protocols where power is increased at the end of the test (CIT) (Day et al. 2003; Doherty et al. 2003; Gibson et al. 1999; Lucía et al. 2006).

In previous studies, the lack of a VO_{2max} plateau at this end of the incremental test is often explained by an inadequate motivational effort in poorly trained subjects or by the low VO_2 of the subjects (Doherty et al. 2003; Wagner 1999). With the NIT, the decrease of power at the end of the test to maintain VO_{2max} value seems to overcome these inconvenient factors, enabling all subjects, with the VO_{2max} range between 34 and 66 mL kg^{-1} min^{-1}, to maintain their efforts at VO_{2max}. Among the 14 subjects, three subjects (one man and two women) who had the lowest VO_{2max} (< at 50 mL kg^{-1} min^{-1}) during the CIT could maintain these low levels for more than 7 min 55 s in NIT. In addition, these three subjects presented an RPE score significantly lower than the other subjects at the beginning of the VO_{2max} plateau, but not at the end of the VO_{2max} plateau. The behavior of these three subjects during the NIT seems to suggest that the VO_{2max} plateau does not depend on the subjects physical fitness, as reported by Astorino et al. (2005) but rather on the adequacy of the test to the subject fitness during the incremental phase as shown in previous studies (Day et al. 2003; Midgley et al. 2008; Yoon et al. 2007). Thus, when adjusting the power at the end of the incremental test, the VO_{2max} plateau could be maintained for all subjects.

The VO_{2max} plateau duration was not correlated with VO_{2max} amplitude

In our study, during the NIT, the VO_{2max} plateau duration was not correlated with the VO_{2max} value. Our results are obtained with subjects exhibiting a wide range of VO_{2max} (34–66 mL kg^{-1} min^{-1}). It is the first time that the independence between the VO_{2max} amplitude and the VO_{2max} plateau duration were shown. Nevertheless, this result could be supposed if we analyzed the studies including subjects with high VO_{2max} values (Lucía et al. 2006; Lacour et al. 2007). Indeed, all the subjects do not necessary maintain a VO_{2max} plateau at the end of CIT. Lucía et al. (2006) showed that only 47% of the subjects demonstrated a VO_{2max} plateau, out of a 38 male professional road cyclist group, with a VO_{2max} amplitude at 74 ± 6 mL kg^{-1} min^{-1} on average. In 2007, Lacour et al. showed that only 40% of the subjects maintained a VO_{2max} in a 94 elite rower group with a VO_{2max} amplitude of 64 ± 5 mL kg^{-1} min^{-1} on average. In these studies, in spite of high VO_{2max} values, the percentage of subject who maintained a VO_{2max} plateau corresponded to the other studies (Day et al. 2003; Doherty et al. 2003; Gibson et al. 1999; Lucía et al. 2006) including subjects with lower VO_{2max} values. Then, the relation between VO_{2max} amplitude and VO_{2max} plateau could be questioned.

Limiting factors of VO_{2max} amplitude and VO_{2max} duration are different

As in this NIT, in which the accurate VO_{2max} could be measured for all subjects, it was possible to determine the

Table 3 Maximal values and VO_{2max} plateau values during CIT and NIT

Maximal values	Protocols		*p*
	CIT	NIT	
VO_{2max} (mL kg^{-1} min^{-1})	55 ± 9	55 ± 8	0.95
CO_{max} (L min^{-1})	24 ± 4	23 ± 4	0.68
SV_{max} (mL)	137 ± 29	128 ± 21	0.37
HR_{max} (beat min^{-1})	190 ± 11	187 ± 11	0.46
ΔSaO_2 (%)	3 ± 3	2 ± 3	0.26
VO_{2max} plateau's values			
Time at VO_{2max} (s)	100 ± 60	369 ± 182	<0.0001
Power (W)	320 ± 68	278 ± 62	0.1
Power (%PVO_{2max})	102 ± 3	91 ± 5	<0.0001
Power (%PLT)	120 ± 11	104 ± 9	0.0003
CO (%max)	82 ± 11	85 ± 10	0.92
SV (%max)	82 ± 19	85 ± 10	0.55
HR (%max)	98 ± 2	98 ± 2	0.77
Da-vO_2 (mL O_2 100 mL^{-1})	19 ± 4	20 ± 4	0.66
Lac t_{beg} (mmol L^{-1})	6.9 ± 0.8	7.3 ± 1.8	0.61
Lac (mmol L^{-1})	11.0 ± 1.5	11.0 ± 2.0	0.76
Lac t_{end} (mmol L^{-1})	12.0 ± 1.9	11.8 ± 2.2	0.82

Values are mean ± SD

VO_{2max} Maximal oxygen uptake, CO_{max} maximal cardiac output, SV_{max} maximal stroke volume, HR_{max} maximal heart rate, *Time at* VO_{2max} time at VO_{2max} during both tests, *Power* mean of power during the VO_{2max} plateau, *Power* (% PVO_{2max}) mean of power during the VO_{2max} plateau reported to PVO_{2max}, *Power* (% PLT) mean of power during the VO_{2max} plateau reported to PLT, *CO* (% max) during the VO_{2max} plateau reported to CO_{max}, *SV* (% max) during the VO_{2max} plateau reported to SV_{max}, *HR* (% max) during the VO_{2max} plateau reported to HR_{max}, *Da-*vO_2 arterio-venous difference, *Lac* t_{beg} blood lactate concentration at the beginning of the VO_{2max} plateau, *Lac* mean of blood lactate concentration during the VO_{2max} plateau, *Lac* t_{end} blood lactate concentration at the end of the VO_{2max} plateau

Table 4 Power, reported to PVO_{2max}, during the VO_{2max} plateau duration for both tests

% VO_{2max} plateau duration	Protocols		*p*
	CIT	NIT	
25	100 ± 0	94 ± 5	0.0005
50	100 ± 0	89 ± 6	0.0001
75	103 ± 6	88 ± 6	0.0001
100	105 ± 6	87 ± 6	0.0001

Values are mean ± SD

main factors limiting the duration of the VO_{2max} plateau and the amplitude of VO_{2max}. In previous studies, the factors limiting VO_{2max} amplitude were widely investigated. The Da-vO_2 by the arterial oxygen concentration (CaO_2) (Knight et al. 1993), the O_2 delivery (DO_2) (Wagner 1999) and the SV_{max} (di Prampero 1989, 2003; Levine 2008) were reported as the main parameters involved in VO_{2max} amplitude. More precisely, the incapacity of the subject to increase the SV until the end of the incremental test was currently recognized to be a limit of VO_{2max} amplitude. Indeed, the VO_{2max} was higher if the PSV_{max} was corresponding to the PVO_{2max} (Gledhill et al. 1994). In untrained subjects, the SV_{max} values correspond to 40% PVO_{2max} values (Zhou et al. 2001) whereas in endurance trained subjects, SV continues to increase until the PVO_{2max} value is reached (Gledhill et al. 1994). The results measured here with our study confirmed this limitation of the VO_{2max} amplitude by the correlation between the VO_{2max} amplitude and the PSV_{max}. Nevertheless, in our study, the duration of the VO_{2max} plateau was not correlated with the PSV_{max}.

In the NIT, when the VO_{2max} is attained, the power is monitored to maintain the VO_2 at its maximum with the lowest amount of power as possible. With this method, the power varied between PVO_{2max} and PLT with different individual patterns (Fig 2). Consequently, the average power during the VO_{2max} plateau was significantly lower than in the CIT and the VO_{2max} plateau duration was correlated with the power decrease (%VO_{2max} plateau duration). Indeed, the faster the power decrease, the longer the VO_{2max} plateau. The fast decrease between two powers values, during the VO_{2max} plateau, will allow the subject to exploit the delay and to adapt this VO_2 kinetics. The slower adaptation of VO_2 allows the VO_{2max} to last longer with lower power output, thus avoiding premature effort stop. When the power was decreased rapidly, the number of

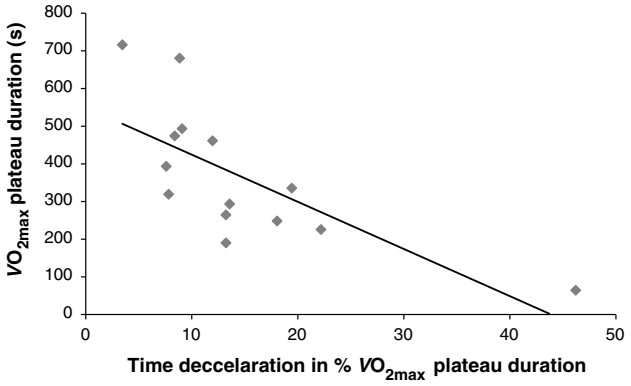

Fig. 3 Relationship between VO_{2max} plateau duration (s) and the time during the power decrease, reported to VO_{2max} plateau duration in new incremental test (*NIT*) ($r = -0.72$, $p = 0.003$)

requested fibers II was decreased and the VO_2 of these fibers was not immediately decreased. This possible explanation of "de-recruited" fibers with the maintenance of VO_2 slow component was recently demonstrated by Vanhatalo et al. (2011). They concluded that the recruitment of the fibers II was not required for the development of the VO_2 slow component during voluntary exercise in humans. Then, the fiber type recruitment profiles (and changes thereof) may explain the slowing of VO_2 kinetics at higher work rates (Poole et al. 2008). The delay and the VO_2 slow component may be responsible for the maintenance of VO_{2max} when the power output is not its maximum (Astrand and Saltin 1961; Billat et al. 1999; di Prampero 1999; Hagberg et al. 1978; Hawkins et al. 2007; Howley et al. 1995; Taylor et al. 1955). However, when the VO_2 decreased below VO_{2max}, the power was incremented to elevate VO_2 to the VO_{2max} (Fig. 1).

In addition, the significant power decrease reduced the blood lactate concentration increase during the VO_{2max} plateau. Indeed, blood lactate concentration was significantly lower during NIT than during CIT at SAT. This result was in accordance with the decrease of the fibers II requested when the power output was decreased during the VO_{2max} plateau, with a maintenance of VO_2 at its maximal value and with a VO_2 slow component (Vanhatalo et al. 2011). However, blood lactate concentration was not significantly different at the beginning and at this end of the VO_{2max} plateau for the either test (Table 3). The power decrease imposed immediately after reaching VO_{2max} results in a lower rate of blood lactate concentration kinetic during the VO_{2max} plateau, consequently, this helped to sustain longer VO_{2max} as it demonstrated with the intermittent protocol (Billat et al. 2000; Christensen et al. 1960). Indeed, Billat et al. (1994) demonstrated, using the equation of Monod and Scherrer (1965), that the subjects who have the highest values of PLT, expressed in % PVO_{2max} had the longest time limit at PVO_{2max}.

Moreover, this possible explanation of the length of the VO_{2max} plateau with the implication of an anaerobic source was explained by the critical power (CP) concept in recent studies. CP corresponds to the power output threshold above which VO_{2max} can be achieved during a constant load exercise (Poole et al. 1988, 1990). CP defined the lower boundary of severe exercise: it corresponds to 79% power maximum attainable during an incremental test (Hill et al. 2002). If the intensity of exercise was above CP, the highest rate of energy transduction by the oxidative ATP production was attainable and the anaerobic metabolism permits to longer support the exercise (Jones et al. 2010). Nevertheless the exercise stopped when the anaerobic source was depleted (Jones et al. 2010). During NIT, the variation of power above the CP allowed to longer protect the anaerobic source and, of course, maintain the VO_{2max} plateau longer. During NIT, the mean of power during the VO_{2max} plateau was 91% of PVO_{2max}, corresponding to 82% Ppeak thus higher than PC as the limit value to involve anaerobic capacity is 79% Ppeak as demonstrated by Hill et al. 2002 for 11 subjects with mean VO_{2max} value at 39.5 ± 7.0 mL kg^{-1} min^{-1}. Nevertheless, during the VO_{2max} plateau, if the power dropped for short time (few seconds) it would be too short to change significatively the aerobic contribution during the plateau. The link between the anaerobic reserve and aerobic capacity for the endurance at VO_{2max} was confirmed by Gordon et al. (2011), who demonstrated the correlation between the incidence of VO_{2max} plateau at the end of an incremental test and the anaerobic capacity. Nevertheless, further investigations are necessary to explicit the differential contribution of anaerobic and aerobic metabolism and expressed the mean of power during the VO_{2max} in % PC instead of % PVO_{2max}. This would determine accurately the energetic expenditure profile of the power variation during the VO_{2max} plateau.

Finally, the power variation resulted in the reduction of the subject's sensations in RPE Borg Scale during the VO_{2max} plateau. The power lowering immediately after reaching VO_{2max} enables the subject to be relieve from discomfort and pain very early during the plateau, and consequently RPE was significantly different between both tests at SAT.

Conclusion

The study demonstrate that it was possible to get a VO_{2max} plateau in all subjects, independently of their VO_{2max} values, if the power is adjusted at this end of the incremental test. When reaching VO_{2max}, the NIT sets the VO_{2max} plateau as the controlled variable instead of the power in

the CIT. For the first time, the VO_{2max} plateau duration measured corresponded to the endurance time at VO_{2max} and not to the endurance time at the power output at this end of the incremental protocol. This NIT allowed sustaining the VO_{2max} longer with power variations. In addition, it provides an overview of physiological parameters of the subjects. In the future, the NIT protocol may possibly be used as a unique test. Therefore, the power should be modulated when the VO_{2max} plateau is reached during several minute, or when the RPM is obviously decreased or if the VO_2 falls to a level corresponding to the end of the test in CIT protocol. Then, this NIT may accurately determines the VO_{2max} values. Then, the matter was to determine the limiting factors of the VO_{2max} plateau duration rather than when this plateau was reached. The VO_{2max} plateau duration was correlated to the decrease of power during the plateau but not to the VO_{2max} value. In NIT, the power variation during the VO_{2max} plateau was in the severe intensity domain above the CP and confirmed the implication of the anaerobic metabolism. This result confirmed the relationship, previously demonstrated, between the aerobic capacity and the anaerobic capacity during exercise with high workload. Further studies will be necessary to elucidate more precisely the implication of the power variation to improve the aerobic and anaerobic capacities during the VO_{2max} plateau used the PC in reference but not the PVO_{2max}.

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