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Methods

Incidence Of The Oxygen Plateau at VO_2max During Exercise Testing To Volitional Fatigue

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TODD A. ASTORINO, ROBERT A. ROBERGS, FARZANEH GHIASVAND, DEREK MARKS, AND STEVE BURNS. **Incidence Of The Oxygen Plateau at VO_2max During Exercise Testing To Volitional Fatigue. JEP**online, 3(4):1-12, 2000. The purpose of this study was to better clarify the VO_2 response to exercise to VO_2max by comparing data derived from different time averaging intervals and exercise protocols. Sixteen active subjects (12 men and 4 women, mean age, height, weight, and VO_2max = 31.6±8.9 yr, 172.0±6.6 cm, 70.8±12.7 kg, 3,212±652 mL/min) completed three different VO_2max tests on a cycle ergometer (a 25 Watt/min ramp protocol (R), a 75 Watt/3 min step protocol (S), and a 25 Watt/min ramp protocol (H) under hypoxic conditions (F_IO_2 = 15 %, P_B = 635 mm Hg) on separate days. During each test, subjects breathed humidified air from a Tissot tank, and breath-by-breath gas exchange was obtained by a Medical Graphics metabolic cart. All breath-by-breath data were smoothed using an 11-breath moving average. These data were then time-averaged into 15, 30, and 60 s sampling intervals. Criteria for attainment of VO_2max included two of the following: RER $\geq$ 1.1, maximal heart rate (HR) within 10 b/min of the calculated value, or an O_2 plateau ($\Delta VO_2 \leq$ 50 mL/min) with an increase in power output. Average VO_2max was significantly lower (F (2, 30) = 84.37, p < .001) for the H (2,532±562 mL/min) compared to the S (3,112±660 mL/min) and R (3,212±651 mL/min) protocols. Average maximal RER was significantly different (F (2, 30) = 3.77, p < .05) across protocols, however no differences were exhibited between means. Average HR at VO_2max was significantly lower (F (2, 30) = 12.26, p < .001) during the H trial (169±13 b/min) compared to the R (176±9 b/min) and S (178±9 b/min) protocols. The incidence at which subjects demonstrated a plateau in VO_2 for all protocols combined were 100, 100, 57 and 8 % for the 11 breath, 15 s, 30 s and 1 min averaging, respectively. Data of the change in VO_2 between VO_2max and the closest neighboring data point revealed that variability was greatest for the longer time averaged data. This response was similar for each protocol. These findings show that shorter sampling intervals (breath-by-breath and 15 s) are most suitable for the detection of the VO_2 plateau during progressive exercise to VO_2max. In addition, ramp and step protocols produce similar results, and acute normobaric hypoxia does not decrease the incidence of a VO_2 plateau at VO_2max using 11 breath or 15 s time averaging procedures.

Key Words: hypoxia, sampling interval, cycle ergometer, breath-by-breath

INTRODUCTION

Maximal oxygen uptake (VO_2max) is the fundamental measure of exercise physiology, and in combination with the concept of a VO_2 plateau, has been described as "*the single most influential concept in modern exercise physiology*" (1). VO_2max is widely recognized as both a representation of the functional limitations of the cardiovascular system as well as a measure of aerobic fitness. This measure originates from pioneering research by A. V. Hill and colleagues (2) that not only introduced the concept but also attempted to explain its physiological mechanisms. Hill commented… "*In running…the oxygen intake may attain its maximum and remain constant merely because it cannot go any higher owing to the limitations of the circulatory and respiratory system*." Hill also attempted to explain the onset of fatigue: … "*At the higher speeds the requirement of the body for oxygen…cannot be satisfied…lactic acid accumulates, a continuously increasing oxygen debt being incurred, fatigue and exhaustion setting in*." These conclusions were accepted by exercise physiologists for the next 70 years, and until recently the concept of VO_2max was not critically evaluated by research.

Also introduced by Hill and colleagues in the 1920s was the concept of the oxygen plateau, or a maintenance in oxygen uptake with an increasing oxygen demand. This theory was supported by research from Taylor et al. (3) that revealed a maintenance of oxygen consumption ($\Delta VO_2 \leq 150$ mL/min) with an increase in treadmill grade in 108 of 115 subjects who completed a discontinuous VO_2max protocol. Nevertheless, findings by Myers et al. (4) demonstrated that only two of six subjects revealed a plateau in VO_2 at termination of ramp treadmill testing. These findings refuting the O_2 plateau phenomenon were corroborated by data in a follow-up study by these investigators (5), who then recommended the use of a longer sampling interval (30 - 60 s) to enhance the precision of gas exchange data.

Recently, heated debate concerning the concept of VO_2max and the O_2 plateau has led to a re-examination of the assumptions and findings of classic research by Hill and Lupton. Initially, Howley, Bassett, and Walsh (6) reviewed the history and validity of current criteria for the attainment of VO_2max. They concluded that none of the established criteria was suitable for confirming the appearance of VO_2max. More recently, these researchers (7) responded to assertions by Noakes (8) stating that the "cardiovascular/anaerobic model" of VO_2max proposed by Hill was incorrect, and that the O_2 plateau demonstrated by Hill was obtained from flawed methodology. After review of all evidence, Howley and Bassett suggested that the classical VO_2max paradigm of Hill was valid, and that Noakes' beliefs lacked strong scientific evidence and generated several paradoxes. Not to be outdone, Noakes (1) introduced an alternative model describing additional possible limitations to maximal exercise, namely that skeletal muscle contraction is mediated by a hierarchy of regulators specifically designed to prevent organ damage consequent with myocardial ischemia.

This debate as of yet has not identified the exact limitations to VO_2max, but it has challenged current exercise physiologists to reinvestigate the fundamental measure of our field and its related controls. Therefore, the primary aim of the present study was to use more precise sampling techniques (breath-by-breath sampling of VO_2) to better clarify the VO_2 response to exercise to VO_2max using a variety of sampling intervals and VO_2max protocols. It was hypothesized that shorter sampling intervals would yield greater incidence of a plateau in VO_2 at VO_2max in healthy, active individuals, and that this incidence would be similar for different protocols and during acute normobaric hypoxia.

METHODS

Subjects

Healthy, active subjects (12 males and 4 females) were recruited from the faculty, undergraduate, and graduate student populations at the university, as well as the surrounding community. The mean age, height, weight, and VO_2max of the subjects were 31.6±9 yr, 172.0± 6.6 cm, 70.85±12.67 kg, and 3,212±652 mL/min, respectively. All subjects signed a written informed consent before volunteering for the study, and all procedures were approved by the university Human Subjects Institutional Review Board. All subjects resided and were acclimatized to altitudes between 1,525 and 2,225 m above sea level and all testing was completed at 1,525 m above sea level (P_B = 626 - 638 mm Hg).

Experimental Procedures

Each subject completed three different VO_2max protocols, a 75 Watt/3 min step protocol (S), a 25 Watt/min ramp protocol with workload set at 50 Watt for the first two minutes (R), and the identical ramp protocol under hypoxic (F_IO_2 =15 % O_2, P_B = 635 mm Hg) conditions (H). The order of these tests was randomized according to a Latin Squares design (9) and assigned to subjects based on subject number. Subjects and all researchers with the exception of those operating the gas exchange system were blinded as to the specific VO_2max test to be administered that day. All tests were separated by at least two days.

Initially, subjects were familiarized with the experimental apparatus, which consisted of exercise on a cycle ergometer (Corval Lode bv, Goningen, The Netherlands) during which gas exchange was continuously monitored by a breath-by-breath system (MedGraphics CPX-D, St. Paul, MN). Humidified inspired air was directed from the high-pressure tank through a sample of distilled water, and then collected in a 100 L Tissot spirometric tank. Subjects inspired air from the tank and expired through a plastic mouthpiece and 3-way valve (Hans Rudolph Inc., Kansas City, MO). This metabolic cart measures expired airflow by means of a pneumotach connected to the mouthpiece. A sample line is connected to the pneumotach from which air is continuously pumped to O_2 and CO_2 gas analyzers. Prior to testing, the pneumotach was calibrated with ten samples from a 3 L calibration syringe. The gas analyzers were also calibrated before each test to room air and medically-certified calibration gases (12.29 % O_2 and 5.12% CO_2, respectively). Heart rate (HR) was continuously recorded during exercise by electrocardiography (Quinton Instruments, Seattle, WA).

Prior to exercise, the subject's height and weight were recorded. Seat and bar height of the cycle ergometer were set according to the subject's specifications, and resting gas exchange data were obtained. Exercise was then started, with subjects completing the predetermined VO_2max protocol of between 8 and 12 minutes duration. Subjects were instructed to maintain a pedal cadence between 80 and 100 rpm during exercise and to exercise to volitional fatigue. Termination of the test occurred when the subject was unable to maintain a pedaling cadence of 40 rpm.

Maximal oxygen consumption was assessed by the attainment of the following criteria: (1) a plateau ($\Delta VO_2 \leq$ 50 mL/min at VO_2peak and the closest neighboring data point) in VO_2 with increases in external work, (2) maximal respiratory exchange ratio (RER) $\geq$ 1.1, and (3) maximal HR within 10 b/min of the age-predicted maximum (220 – age). All subjects met the first two criteria.

Breath-by-breath gas exchange data from all tests were transferred to a spreadsheet program (Microsoft Excel 8.0) for further analysis. All VO_2 data were smoothed using an 11-breath moving average. In addition, data from the VO_2max tests were time-averaged using 15, 30, and 60 s intervals to examine the incidence of an oxygen plateau at different sampling intervals.

Statistics

All data were analyzed using SPSS (Version 8.0). One-way analysis of variance (ANOVA) with repeated measures was used to examine differences in VO_2max, RERmax, and HRmax between the VO_2max tests. If a significant $\underline{F}$ ratio was obtained, Tukey's HSD was used to locate differences between the means. Statistical significance was set at 0.05. With a sample size equal to sixteen and standard deviation equal to 600 mL/min, we could detect a difference in VO_2 of 540 mL/min using an unpaired, one-tailed t-test with significance set at 0.05.

RESULTS

Gas exchange and heart rate data

VO_2max was significantly different across protocols, $\underline{F}$ (2, 30)=84.37, $\underline{p} < 0.001$, MS_e=25,617.65. Average VO_2max for the H (2,532±562 mL/min) was significantly lower (HSD=14.52, $\underline{p}$<0.001, and HSD=17.01, $\underline{p}$<0.001) compared to the S (3,112±660 mL/min) and R (3,212±652 mL/min) protocols (Figure 1a). A significant main effect for maximal RER was exhibited between protocols, $\underline{F}$ (2, 30)=3.77, $\underline{p}$ <0.05, MS_e=2.60 X 10^{-3}. However, Tukey's post hoc test revealed no differences between mean values of maximal RER for the R (1.3±0.1) compared to the H (1.4±0.1) or S (1.3±0.1) protocol (Figure 1b). Maximal HR was significantly different between the protocols, $\underline{F}$ (2, 30)=12.26, $\underline{p}$ < .05, MS_e=28.03. Maximal HR during H (169±13 b/min) was significantly lower (HSD=6.71, $\underline{p}$<0.01) than that in the S (178±9 b/min) protocol (Figure 1c).

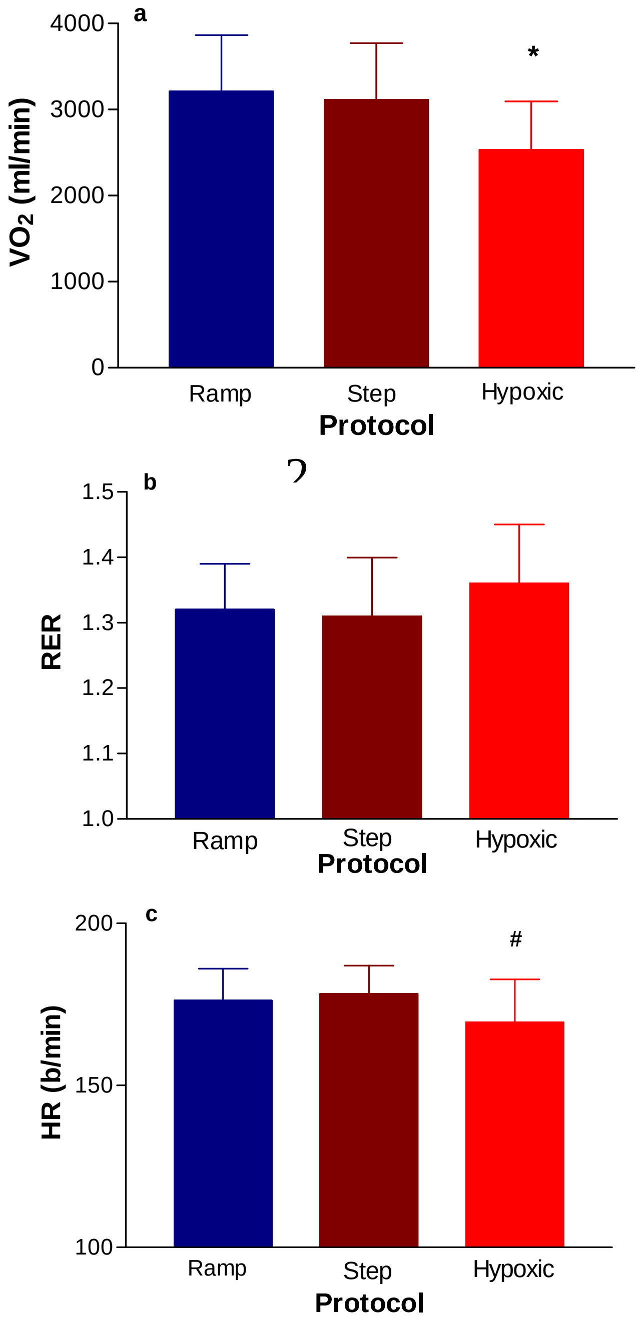

Figure 1: Mean±SD data from the different protocols for a) VO_2max , b) RERmax and c) HRmax.
* = significantly lower in H compared to S and R protocols; # = significantly lower in H compared to S protocol.

Incidence of a plateau in VO_2

All subjects for all tests demonstrated a plateau in VO_2 when VO_2 was sampled either breath-by-breath or every 15 s (Figures 2a and 2b). Subjects expressed a plateau 57 % of the time (27 of 48 tests) when data were sampled every 30 s (Figure 2c). For the 30 s sampling interval, the R protocol displayed a plateau in VO_2 during 8 of 16 VO_2max tests, while the S and H protocols revealed appearance of the plateau in 6 and 13 out of 16 tests, respectively. In contrast, only 8 % of subjects (4 of 48 tests) displayed a plateau in VO_2 when data were sampled every minute (Figure 2d). Table 1 presents data of ΔVO_2 between VO_2max and the closest neighboring data point for all subjects across all protocols. It is evident that the ΔVO_2 at VO_2max is smaller with shorter sampling intervals, and when gas exchange data are obtained breath-by-breath or every 15 s, all subjects display a ΔVO_2 at VO_2max less than 50 mL/min, indicating a plateau in VO_2. Data of the mean change in VO_2 between VO_2max and the closest neighboring data point based on 60 s, 30 s, 15 s, and breath-by-breath data revealed that variability was greatest for the longer time averaged data (Figure 3). This response was similar for each protocol. Means of this data for the 60 s, 30 s, 15 s, and breath-by-breath averaging were 149.3±70.8, 55.1±40.7, 22.3±15.5, and 11.2±11.5 mL/min, respectively. With the exception of the H protocol, the mean ΔVO_2 at VO_2max was greater than 50 mL/min when longer (30 s and 60 s) sampling intervals were used.

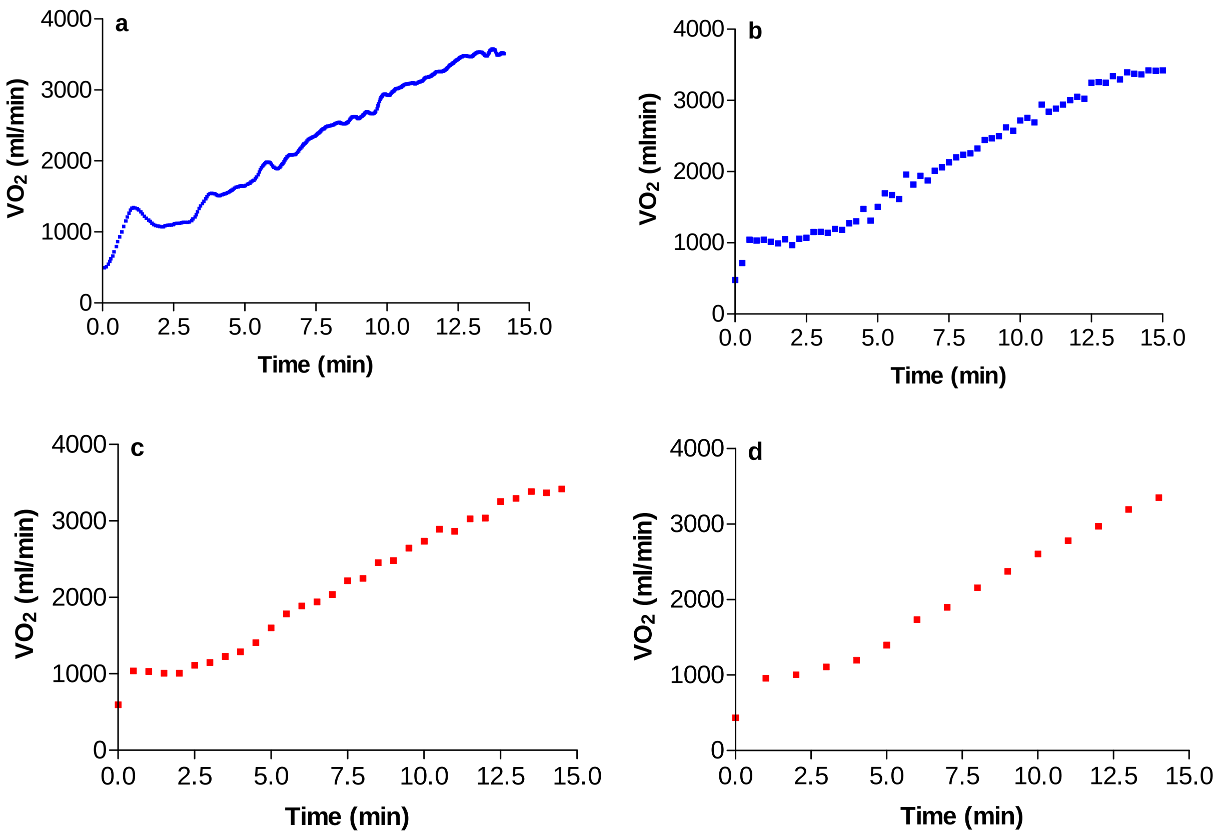

Figure 2: Appearance of the VO_2 Plateau for a) 11 breath average, b) 15 s time-averaging c) 30 s time-averaging, and d) 60 s time-averaging for a representative subject.

Table 1: ΔVO_2 at $VO_2max^{a}_{x}$ for all Subjects across all Protocols and Data Sampling Intervals

	Ramp				*Step*				*Hypoxia*			
Subject	b-b[a]	15 s	30 s	60 s	b-b	15 s	30 s	60 s	b-b	15 s	30 s	60 s
1	7.2[b]	32.0	70.5	266.0	21.1	18.0	130.5	225.8	6.6	18.0	90.0	175.0
2	6.1	18.0	120.5	216.8	9.9	29.0	69.0	82.5	1.9	11.0	48.5	209.5
3	14.0	26.0	45.5	139.8	1.6	20.0	60.0	139.3	1.0	1.0	6.0	89.0
4	3.5	17.0	36.0	110.5	7.3	38.0	120.0	95.8	5.1	7.0	25.5	83.5
5	7.3	9.0	97.0	120.8	3.3	12.0	13.0	176.0	0.64	8.0	23.6	17.1
6	20.3	26.0	30.0	161.0	32.7	34.0	33.0	184.5	16.5	7.0	17.5	124.0
7	4.0	22.0	20.5	211.3	1.5	41.0	158.5	167.3	10.6	31.0	26.0	160.5
8	12.1	9.0	54.5	214.5	27.0	17.0	83.5	144.0	12.0	29.0	17.5	284.0
9	37.3	45.3	40.0	210.5	44.6	11.0	39.5	154.3	6.8	20.0	66.0	144.8
10	11.5	33.0	96.0	154.5	8.4	35.0	62.5	110.3	25.3	45.0	8.0	75.3
11	3.0	16.0	17.0	88.3	17.3	13.0	46.0	54.8	3.8	22.0	7.5	29.8
12	7.2	1.0	170.5	93.7	0.63	46.0	47.0	15.8	2.7	39.0	17.0	30.0
13	5.0	6.0	34.0	191.8	2.8	29.0	73.0	195.3	3.5	17.0	37.0	97.8
14	49.3	10.5	56.5	227.3	16.3	8.0	53.0	240.5	22.3	4.0	56.0	311.3
15	18.8	42.0	112.0	215.3	0.6	17.0	118.0	212.0	9.7	21.0	4.5	127.5
16	3.5	0.0	26.0	54.8	4.0	21.7	38.0	95.8	2.6	16.0	25.0	207.0

[a] = ΔVO_2 in mL/min; [b] = Breath-by-breath sampling interval

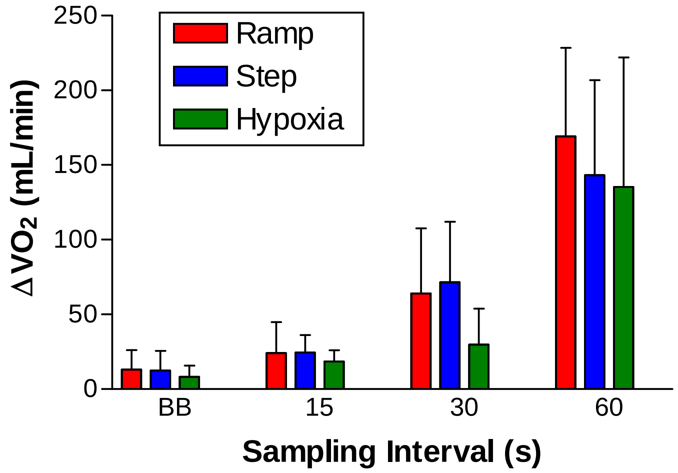

Figure 3: The change in VO_2 between VO_2max and the closest neighboring VO_2 data point for each trial and data averaging method. Compiled means for all protocols at each averaging interval were all significantly ($p<0.05$) different from each other.

Attainment of RER and heart rate criteria

Table 2 demonstrates that all subjects expressed an RER greater than 1.15 during the R protocol. In contrast, only 38 % of subjects met the HR criteria during the R protocol (their observed HRmax at VO_2max was within 10 b/min of the age-predicted theoretical value (220 – age)).

Table 2: Incidence of the Attainment of HR and RER criteria at VO_2max for each subject.

Subject	[a]*TH HR_{max} (b/min)*	[b]*OBS HR_{max} (b/min)*	*Incidence*	[c]*RER_{max}*	*Incidence*
1	191	183	Yes	1.40	Yes
2	193	177	No	1.38	Yes
3	182	180	Yes	1.33	Yes
4	190	179	No	1.17	Yes
5	199	180	No	1.24	Yes
6	183	177	Yes	1.37	Yes
7	199	189	Yes	1.38	Yes
8	196	182	No	1.27	Yes
9	182	160	No	1.39	Yes
10	193	173	No	1.36	Yes
11	165	151	No	1.21	Yes
12	192	182	Yes	1.26	Yes
13	176	167	Yes	1.31	Yes
14	194	183	No	1.31	Yes
15	190	179	No	1.24	Yes
16	190	171	No	1.21	Yes
X $\pm$ SD	188.4 $\pm$ 8.9	176.2 $\pm$ 9.8	37.5%	1.32 $\pm$ .07	100%

[a] = Theoretical HRmax = (220 – age); [b] = Observed HRmax; [c] = RERmax criteria $\geq$ 1.1

DISCUSSION

The primary aim of the present investigation was to better clarify the VO_2 response to exercise to VO_2max using more accurate sampling techniques as well as a variety of VO_2max protocols and sampling intervals. The most significant finding was that a plateau in VO_2 occurs universally in young, healthy, active subjects exercising to volitional fatigue when shorter sampling intervals (breath-by-breath and 15 s) are used. Second, the incidence of the O_2 plateau is independent of the specific VO_2max protocol prescribed. These conclusions may influence current exercise physiologists to realize that the O_2 plateau is a real phenomenon, and that its incidence is influenced by the specific sampling interval used by gas exchange acquisition systems.

The O_2 plateau concept was introduced by Hill and Lupton (2) in response to an observed maintenance of VO_2 with greater speeds of running in men. Data obtained three decades later by Taylor et al. (3) supported the plateau phenomenon, as it demonstrated a plateau in VO_2 in 108 out of 115 subjects completing a discontinuous VO_2max protocol on a treadmill. Furthermore, results from Mitchell et al. (10) revealed a plateau in VO_2 at VO_2max, representing an increase in VO_2<54 mL/min at the highest workload, in 72 % of subjects completing consecutive but intermittent exercise bouts of 2.5 min duration. Nevertheless, subsequent research (11, 12) in children required to complete treadmill exercise to exhaustion suggested that a plateau in VO_2 ($\leq$ 2.1 mL/kg/min) is elusive in this population. Similar findings were reported by Rowland (13) in nine children (mean age=11.4±1.2 yr) and by Armstrong et al. (14) in 35 children (mean age=9.9±0.4 yr). More recent data pertaining to the incidence of a plateau in VO_2 at VO_2max is also equivocal in adults. Stamford (15) denoted a plateau in VO_2 (< 150 mL/min) between successive treadmill grades in ten men completing four different VO_2max protocols on a treadmill. Furthermore, Eldridge et al. (16) observed a plateau in VO_2 ($\leq$3 mL/kg/min during the final 90 s of exercise) in 77 % of normal subjects and patients with coronary artery disease completing maximal exercise. In addition, other researchers (17) reported a plateau in VO_2 (change in VO_2<150 mL/min, or 2.1 mL/kg/min, between successive treadmill elevations) in 50 % and 60 % of active males completing continuous and discontinuous VO_2max tests on a treadmill. Similar findings regarding the prevalence of a plateau in VO_2 in adults have also been demonstrated by other investigators (18, 10). However, Froelicher et al. (19) observed an O_2 plateau or a decline in VO_2 at volitional fatigue in 33 % of subjects completing the Taylor protocol, 17 % of subjects completing the Balke protocol, and 7 % of subjects performing the Bruce protocol. Similarly, data by Myers et al. (4) revealed a plateau in VO_2, defined as the slope of the VO_2-time relationship not differing significantly from zero, occurred in only two of six subjects in response to ramp treadmill testing. A subsequent investigation (5) observed marked variability in the slopes of the VO_2 response to both submaximal exercise and incremental exercise to fatigue, regardless of the sampling interval used, leading these authors to conclude that the O_2 plateau is not a valid physiological marker for maximal exertion.

An initial explanation for the universal incidence of the O_2 plateau in the present investigation compared to previous findings is the sampling technique used. Breath-by-breath gas exchange offers great temporal resolution by calculating values for VO_2 and VCO_2 more frequently than previously established sampling techniques. The 11-breath moving average employed herein attenuated the majority of inherent noise in breath-by-breath data, as each breath represented the average value of the five breaths following and preceding it. Thus, a very precise representation of the VO_2-O_2 demand relationship was obtained throughout exercise, leading to the ability to detect a VO_2 plateau at VO_2max if indeed it did occur. Furthermore, the longer sampling intervals proposed by previous research (5, 6) would require subjects to sustain workloads at or above VO_2max for up to 2 - 3 min to demonstrate a plateau, which is not feasible in most individuals. Also, observations in our laboratory reveal that longer sampling intervals tend to significantly underestimate VO_2max. In the present study, the O_2 plateau was not always realized when gas exchange data were sampled every 30 s (57 % incidence) and 60 s (8 % incidence). Using 1 min data averaging techniques, Duncan et al. (17) observed non-incidence of the plateau in 45 % of subjects. This is not surprising, since such long sampling intervals could easily miss the appearance of a plateau in VO_2. Similarly, Myers et al. (5) denoted a lack of a plateau in VO_2 in 66 % of subjects when gas exchange was obtained every 30 s. Therefore, it is apparent that the duration of the specific sampling interval used has a dramatic effect on prevalence of the VO_2 plateau.

The rather stringent plateau criterion ($\Delta VO_2 \leq 50$ mL/min with an increase in power output) used in the present study lends further credence to our findings. In fact, it has been suggested that cut-off values of 50 - 60 mL/min constitute a true plateau as they approach the limitations of one’s ability to measure changes in VO_2max (6). The criterion used by Taylor et al. (3), a change in $VO_2 \leq 150$ mL/min or 2.1 mL/kg/min with a 2.5 % increase in grade, has been extensively used to confirm incidence of VO_2max. Astrand (20) employed a mere leveling off of oxygen uptake as a suitable criterion, yet in earlier work (18) he denoted a change in VO_2 less than 80 mL/min to confirm that VO_2max had been attained. Also, Issekutz et al. (21) defined the O_2 plateau as less than 100 mL/min, since this VO_2 was about 1/3 of the oxygen uptake required for a stage change. Lastly, Cumming and Friesen (22) used a <50 mL/min criterion, since it was roughly equal to 1/3 of the anticipated increase in VO_2 for a given increase in power output. Thus, the scientific literature lacks an exact definition of a plateau in VO_2 at VO_2max, although the criterion established in the present study seems suitable for future application in exercise testing.

Our finding of the incidence of the O_2 plateau across different VO_2max tests is supported by previous research. Sheehan et al. (23) required a group of 10 - 12 year-old boys to complete a series of treadmill protocols to VO_2max. Results indicated that a plateau in VO_2 was common across the different protocols. Moreover, Stamford (15) observed a plateau in VO_2 for each of four step and constant load VO_2max tests performed by ten young men. Previous investigations failing to observe a plateau in VO_2 across different protocols (19, 17) are characterized by 1 min sampling intervals which we show are unable to precisely identify a plateau in VO_2. Again, it is apparent that the specific sampling intervals used greatly influence the prevalence of the O_2 plateau across different VO_2max protocols.

Despite the fact that the concept of VO_2max has existed for over 75 years, currently no suitable criteria exist to confirm its incidence. A thorough review (6) of the efficacy of a plateau in VO_2, elevated RER and blood lactate concentrations, and maximal heart rate highlighted the limitations of previous dogma, namely that many of these criteria were developed from intermittent protocols with dramatic increases in power output per day. In contrast, at the present time continuous tests with smaller work rate increments per stage are widely used. Findings from the present investigation offer two suitable criteria to confirm the incidence of VO_2max: (1) a plateau in $VO_2 \leq 50$ mL/min with an increase in power output, and (2) RER at $VO_2max \geq 1.15$. The maximal HR criterion within 10 b/min of the age-predicted value was achieved in only 38 % of our subjects, implying that HR at VO_2max is highly variable among individuals. Almost 30 yr ago, Cumming and Borysyk (24) stated that the range of maximal heart rate was too variable to use as a criterion to confirm VO_2max. Furthermore, the American College of Sports Medicine (25) mandates that estimated maximal heart rates should not be used to identify an endpoint during exercise testing. Therefore, this criterion should not be used to confirm the attainment of VO_2max.

However, the ideal statistical assessment of the suitability of criteria to confirm VO_2max is not to compare mean values. Valid criteria would be characterized by not only being related to a VO_2 plateau but also to discriminate between individuals who do and do not attain a plateau. To date, no research design and appropriate statistical assessment has been conducted on this topic.

In the past, the term VO_2peak has been used rather interchangeably with VO_2max to reflect the highest value attained for maximal oxygen uptake. Rowell (26) commented that VO_2peak represents the highest VO_2 attained under specific conditions, including arm or cycle ergometry, whereas VO_2max describes the highest VO_2 value achieved during treadmill exercise involving at least 50 % of the muscle mass. In addition, VO_2max is commonly used when criteria are not satisfied, although little agreement exists as to what they really are. Also, it has been suggested that VO_2peak should represent symptom-limited VO_2 during exercise, and is not related to VO_2max (27). All in all, our establishment of what appear to be two suitable criteria support the notion that VO_2peak should not be applied to healthy subjects exercising to volitional fatigue if these criteria are met. We recommend that the term VO_2peak should be used if the VO_2 plateau and RER criteria are not met.

All subjects expressed a plateau in VO_2 during the severe H trial when gas exchange data were obtained breath-by-breath or every 15 s. This corroborates previous work (28) denoting a plateau in one-leg VO_2 at VO_2max in sedentary subjects during acute hypoxia (12 and 15 $\%O_2$). Furthermore, when gas exchange data were obtained every 30 s, 13 out of 16 subjects expressed a plateau in VO_2 in response to the H trial, in comparison to prevalence of the O_2 plateau in only 8 and 6 subjects during the R and S protocols, respectively. Data in rowers (29) exercising to VO_2max during hypoxia (15.8 $\%O_2$) also revealed a plateau in VO_2 at VO_2max. The prescribed hypoxia in the present study was equivalent to 3,900 m, a rather moderate to high altitude. In response to the H trial, mean VO_2max was 21 % lower compared to the R trial, which is similar to the approximate 9.2 % decrease in VO_2max observed with every additional 1,000 m increase in altitude above 700 m (30). However, individual VO_2max decrements in response to hypoxia are highly variable. In regards to the RER criterion, Knight et al. (31) reported a mean RER equal to 1.36±0.03 in male cyclists exercising to VO_2max in hypoxia (12 $\%O_2$). This is identical to the maximal RER (1.36±0.09) recorded in the present study. Taken together, these data imply that VO_2max is a valid concept during hypoxic conditions, as argued by Wagner (32).

CONCLUSIONS

The primary finding of the present investigation was that sampling intervals dramatically influence the incidence of the VO_2 plateau at VO_2max. When shorter sampling intervals (11 breath and 15 s averages) were used, there was 100 % incidence of a plateau ($\Delta VO_2 \leq 50$ mL/min) in VO_2 at VO_2max with an increase in O_2 demand. However, the VO_2 plateau was manifested only 57 % and 8 % of the time when gas exchange was obtained every 30 s and 60 s, respectively. In addition, incidence of the VO_2 plateau was similar for ramp and 3 min step increment protocols, as well as during hypoxia equivalent to 3,900 m altitude. Two suitable criteria to confirm appearance of VO_2max include a plateau in $VO_2 \leq 50$ mL/min and RER $\geq$ 1.15 at VO_2max. Because of the establishment of these criteria, VO_2peak should only be used to describe symptom-limited VO_2max in the absence of a VO_2 plateau or the RER criteria. In addition, it is recommended that relatively short sampling intervals ($\leq$ 15 s) be used to assess the VO_2 response to incremental exercise to VO_2max. The present findings may lead scientists and clinicians to alter the methodology used in exercise testing to obtain a better assessment of VO_2max.

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