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Methodology: VO_2max

A STANDARD METHOD FOR THE DETERMINATION OF MAXIMAL AEROBIC POWER FROM BREATH-BY-BREATH VO_2 DATA OBTAINED DURING A CONTINUOUS RAMP TEST ON A BICYCLE ERGOMETER.

DANIEL B. DWYER.

School of Human Life Sciences, University of Tasmania, Australia

ABSTRACT

A STANDARD METHOD FOR THE DETERMINATION OF MAXIMAL AEROBIC POWER FROM BREATH-BY-BREATH VO_2 DATA OBTAINED DURING A CONTINUOUS RAMP TEST ON A BICYCLE ERGOMETER. **Dwyer, DB. JEP**online. 2004;7(5):1-9. There is no standard method for identifying a plateau in VO_2 or determining VO_2 peak where no plateau occurs. The purpose of the present investigation was to determine the optimal sample interval duration for VO_2 data collected during incremental exercise tests on a bicycle ergometer and to define a plateau criterion that is applicable to a range of ramp rates. A statistical analysis was performed on VO_2 data collected from 20 subjects who performed an incremental ramp test. Breath by breath data were analysed to determine the variance of VO_2 which was used to calculate the minimum sample interval duration and a confidence interval which is used to identify a plateau in VO_2 data. Results indicate that the accurate determination of VO_2 to within a 5% error requires a minimum sample interval duration of 20 s. Further analysis indicates that a plateau may be defined as an increase in VO_2 of less than 8.0 mL/min/Watt on the two highest successive 20 s sample intervals. The present plateau criterion is applicable to a range of test protocols for bicycle ergometry and is more selective than previous criteria. It is suggested that where no plateau occurs, the highest value in any (20 s) sample interval is chosen as labelled as VO_2 peak.

Key words: Aerobic power, VO_2 max, VO_2 peak, Sample size, Plateau criteria.

INTRODUCTION

There is no widely adopted method for the analysis of VO_2 data and definition for a plateau in VO_2 during incremental exercise testing (1,2,3). A survey of the literature indicates a wide variety of sample interval durations (30-60 s) are in use (4) and often duration is not described at all (5). Previous work has shown that sample interval duration affects the variability of VO_2 data (6), the likelihood of identifying a plateau in VO_2 (3) and the actual value recorded as VO_2 max (6). Most of these reports conclude that a standard sample interval duration should be adopted, but none have made recommendations with the exception of Astorino et al. (1) who recommended using intervals of less than or equal to 15 s. The only report that recommended a sample interval duration (1) did not use a mathematical rationale and did not address the concerns raised by a previous review regarding short (≤30 s) sample intervals (2).

Wasserman et al. (7) and others (8,9) maintain that a plateau in VO_2 with increased work rate is required for the determination of VO_2max. Despite this, a standard definition for a plateau in VO_2 is also absent from the literature (2). Previous reports include a variety of definitions including a plateau in VO_2 over 15s (5), 20 s (10), 40 s (11) an increase of < 50 mL (1) or <100 mL (12) in one minute and some authors omit a definition completely (13). The most commonly used criteria for a plateau in VO_2 is probably that published by Taylor et al. (14), which is also prescribed by the American College of Sports Medicine (15). Taylor et al. (14) defined a plateau in VO_2 by using a statistical technique to determine a maximum limit of increase in VO_2 (0.150 L/min) between the last two work rates of their test protocol. This absolute limit of increase was intended to be used only for their test protocol and would be inappropriate to use for test protocols that were very different. The "plateau issue" has become even more problematic recently with challenges to the meaning of a plateau itself (16, 17,18) and discussion about why some subjects achieve a plateau and others do not (1).

Given the importance of the determination of aerobic power, the effect of the sample interval duration and the definition of a plateau in VO_2 are important considerations (3). Therefore, the purpose of the present investigation was to establish a standard sample interval duration for incremental cycle ergometry. In addition, a modified version of the plateau criterion previously described by Taylor et al. (14) is presented, which is applicable to a variety of continuous exercise test protocols used in cycle ergometry. A statistical rationale for both methods is provided.

METHODS

Subjects

Fourteen men and six women volunteered to participate in this study. All subjects were apparently healthy and were recreationally active. The age and body mass of the male and female subjects were 23.9 ± 3.5 yr and 75.2 ± 6.8 kg and 27.5 ± 7.0 yr and 66.6 ± 6.3 kg respectively. Written informed consent was obtained from each subject and all subjects were familiarized with the testing equipment and experimental procedures. Subjects were instructed not to engage in vigorous physical activity for 48 hr or to eat for 4 hr prior to the testing session. The University Human Ethics committee approved this study and all testing procedures conformed to the guidelines described in the Declaration of Helsinki (1989).

Determination of VO_2max

The maximal rate of oxygen consumption (VO_2max) was determined using a continuous, incremental exercise protocol conducted on an electronically braked cycle ergometer (Lode, Excalibur Sport V2.0, Groningen, Netherlands). Pedal rate was maintained at 70 rev/min throughout the test. After 3min of unloaded cycling, the work rate was increased using a continuous ramp protocol by 25 or 30 Watts/min until volitional exhaustion. The rate of increase in work rate was varied according to the body weight and estimated aerobic power of each subject. Heart rate was monitored continuously using an electrocardiograph (Lohmeier, Munchen, Germany) with a CM5 electrode configuration and VO_2 was measured breath-by-breath (MedGraphics® CPX, Cardiorespiratory Diagnostic Systems, St. Paul, MN, USA). All subjects were familiarised with the test protocol prior to completing the actual test.

Determination Of The Standard Deviation Of VO_2 Data

The standard deviation of breath-by-breath VO_2 data was required to calculate sample interval duration. This was accomplished by deleting the first two minutes and last minute of VO_2 data, leaving a relatively linear data segment (Figure 1). The first two minutes and last minute of VO_2 data were excluded from this analysis because this data is generally "noisy" due to hyperventilation. Using the least-squares method, a line of best fit was determined and its goodness of fit was tested using Pearson's Correlation coefficient. The line of best fit was mathematically subtracted from the measured VO_2 values, which generated a constant mean and residuals (Figure 1). The population SD of the VO_2 data could then be calculated using the standard equation; $SD = (\Sigma(X-u)^2/N)^{1/2}$.

Calculation Of Sample Interval Duration

The distribution of breath-by-breath VO_2 data were examined for normality using the Kolmogrov-Smirnov test. The number of samples (breaths) required to achieve a certain sample error (5%) was calculated by applying the following sample size equation; $N = ((z_{\alpha/2} \cdot s)/E)^2$ (19), where N represents the required sample size, $z_{\alpha/2}$ is the z-score for a two tailed t-test with an alpha level of 0.05 ($z_{\alpha/2} = 1.96$), s is the population SD and E is the sample error. In the present study, the optimal sample interval duration was selected as the sample interval that corresponded to a 5% error in the mean VO_2 peak reported here (5% of 3.0 L/min). The choice of a 5% error was arbitrary and reflects the broadly accepted error rate for statistical tests. Sample interval size corresponding to a 1,2,3 and 4% error were also calculated (see Table 1).

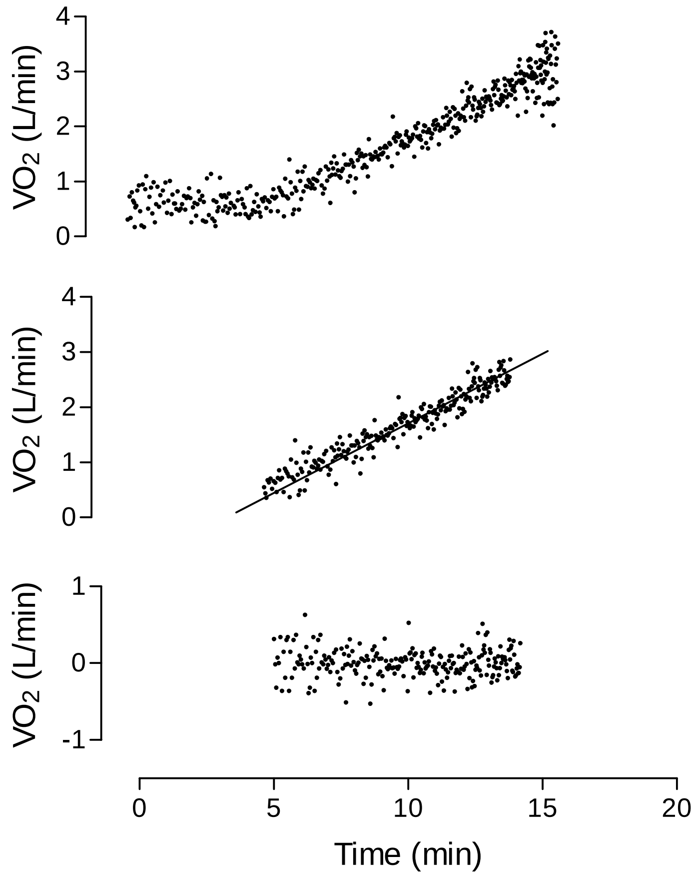

Figure 1. Determination of the Standard Deviation of VO_2 Data. The top graph shows an example of raw breath-by-breath VO_2 data from an incremental exercise test. The middle graph illustrates the middle "linear" portion of the data and a line of best fit. The bottom graph illustrates the result of subtracting the line of best fit from the raw data (the residuals), which allows the calculation of standard deviation.

The sample size equation used in the present study determines the number of samples (breaths) required for the determination of a population mean (VO_2). However, during incremental exercise testing, mean VO_2 is typically calculated for a pre-determined sample interval measured in seconds (eg. 20 s or 60 s), not a number of breaths. Thus, the mean duration of each breath, measured over the middle portion of the VO_2 data, were recorded for each subject and a mean breath period was calculated for the whole group.

Determination Of A Plateau In VO_2 During Incremental Cycling To Exhaustion

Breath-by breath VO_2 data collected during testing was transferred to a personal computer and analyzed using a custom made program (LabVIEW 5.0, National Instruments). VO_2 data were averaged over time using the predetermined sample interval (20 s see Results) beginning at the point of exhaustion and working backward. This procedure eliminated the potential problem of obtaining an incomplete sample interval (near VO_2 peak) that may cause an erroneous VO_2 max or VO_2 peak value (eg. if the total time to exhaustion was 10 min 7 s, the final sample interval would only include 7 s of data).

The method used to identify a plateau in VO_2 during continuous incremental cycling was determined by modifying the methods previously described by Taylor et al. (14). The mean ± SD oxygen cost (mL/Watt) of cycling was calculated from the slope of the line of best fit, which was then used to linearise the VO_2 data. Thus, the expected increase in VO_2 for any given sample interval and ramp rate could be calculated. A one-tailed confidence interval with an alpha level of 0.05 was determined (± 1.645 SD) because we are only concerned with determining whether the actual increase in VO_2 was significantly less than the expected increase in VO_2. A plateau in VO_2 was established if the increase in VO_2 between two consecutive 20 s sample intervals was less than the expected increase in VO_2 minus 1.645 standard deviations (see Figure 3). The highest VO_2 value averaged in any single sample interval was expressed as VO_2max, where a plateau in VO_2 occurred. Where no plateau in VO_2 could be identified, the highest VO_2 value averaged in any single sample interval was expressed as VO_2 peak. Subjects who demonstrated a plateau in VO_2 during the incremental test were eliminated from further analysis of the effect of sample interval on VO_2 peak.

The Effect Of Sample Interval Duration On VO_2 Peak

VO_2 peak during the incremental cycling test was calculated over a range of sample intervals (10, 20, 30 and 60 s) to examine the effect of the duration of the sample interval.

Statistical Analyses

VO_2 values are presented as mean ± SD. The Kolmogorov-Smirnov test was used to determine whether the linearised VO_2 data were distributed normally and a repeated measures ANOVA was used to determine differences in VO_2 peak across a range of sample interval durations (Statistical Package for the Social Sciences, version 9.0). Bonferroni multiple comparison post hoc analysis was used to identify where the differences occurred and statistical significance was accepted at $p<0.05$.

RESULTS

Incremental Exercise Test

Twenty (20) subjects completed the incremental exercise test, 14 at 25 Watts/min and 6 at 30 Watts/min. All subjects achieved a peak heart rate within 7 beats/min of their age predicted maximum heart rate and an RER ≥ 1.15. The average Pearson's Correlation Coefficient ($r = 0.938$) from all subjects suggested a strong, linear relationship ($p < 0.001$) between raw VO_2 data and the lines of best fit. TheVO_2 data from the middle linear portion of the test were found to be normally distributed and hence suitable for the calculation of standard deviation. The SD of the VO_2 data was calculated to be 0.19±0.06 L/min and the mean breath period was determined to be 2.61 ± 0.42 s.

The Optimal Sample Interval For Determining VO_2 Peak

During incremental cycling, the optimal duration of the sample interval for determining VO_2 was calculated on the basis of a 5% error of the mean VO_2 peak for all subjects. In the present study, this 5% error equates to an absolute error of 0.150 L/min. Using the sample size equation, it was calculated that 16 s of VO_2 data is the minimum sample interval duration required for incremental cycling. Due to the nature of many automated gas analysis systems and for the sake of convenience it was decided to round this figure upward to the nearest 5 s without increasing the sample error. Therefore a sample interval of 20 s was considered a more convenient duration and the sample error was reduced from 5% to 4.4%.

Table 1. The minimum sample interval size of VO_2 data, for a given sample error.

Sample Error (%)	*Required Sample Interval Size (s)*
1	405
2	101
3	45
4	25
5	16

Mean Oxygen Cost Of Incremental Cycling

The mean oxygen cost calculated during incremental cycling in the present study was 9.1 ± 0.7 mL/min/Watt. Thus, the mean oxygen cost was used to calculate the expected increase in VO_2 for any pre-determined sample interval and ramp rate. In addition, the expected increase in VO_2 minus 1.645 standard deviations was calculated to be 8.0 mL/min/Watt. This “plateau index” (8.0 mL/min/Watt) was used to determine the largest permissible increase in VO_2, measured over two consecutive (20 s) sample intervals, to establish a plateau. Table 2 shows the expected increase in VO_2 calculated during a 20 s sample interval for 25 and 30 Watt/min ramp rates.

Table 2. Expected Increase and Maximum Increase of VO_2 for Various Ramp Rates.

Ramp Rate (Watts/min)	*Expected increase in VO_2 ±SD (mL/min) over 20 s*	*Maximum increase of VO_2 (mL/min) over 20 s to qualify for a plateau*
20	60 ±5	52
25	76 ±6	66
30	91 ±7	80

The expected increase in VO_2 is the product of the ramp rate indicated and an oxygen cost of 9.1 ± 0.7 mL/min/Watt. The maximum increase indicates the maximum allowable difference between the two highest consecutive VO_2 values to qualify as a plateau.

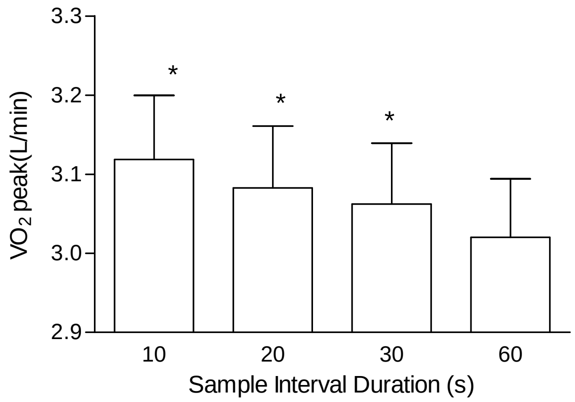

Figure 2. The Effect of Sample Interval Duration on VO_2peak. * indicates a significant difference to VO_2peak calculated over 60 s.

Nine subjects demonstrated a plateau in VO_2 during continuous incremental cycling using the present criterion and were eliminated from further analysis. Mean VO_2 max was 2.88 ± 0.3 L/min and the mean VO_2 peak for the 11 remaining subjects who failed to demonstrate a plateau in VO_2 was 3.25 ± 0.31 L/min, calculated from the highest VO_2 value measured in any single 20 s sample interval (peak RER=1.3 ± 0.08; peak HR=187 ± 9 b/min). Additionally, VO_2 peak was calculated over various sample intervals to demonstrate the effect of varying sample interval on VO_2 peak. There were significant differences ($p<0.05$) between all mean VO_2 peak values calculated for each sample interval (Figure 2).

DISCUSSION

The findings of the present investigation indicate that for incremental cycle ergometry, VO_2 data should be analyzed in 20 s sample intervals and that a plateau be defined as a difference in VO_2 between the two highest successive sample intervals, which is less than 8.0 mL/min/Watt. This" plateau index" allows the calculation of the maximum allowable increase in VO_2 to qualify as a plateau, for ramp rates used typically in cycle ergometry (25-30 Watts/min). It is suggested that where this plateau criterion is met, the highest VO_2 in any 20 s sample interval may be reported as VO_2max, otherwise the highest value may be reported as VO_2 peak.

In a review of the criteria for maximal oxygen uptake, Howley et al. (2) suggested that use of sample intervals less than 60 s would introduce unacceptably large errors. Their conclusion was based upon the assumption that all sample intervals contain extreme values, which are part of the normal variability in VO_2 data, and that smaller intervals are more susceptible to the effects of these extreme values. While this is true, when examining breath-by-breath data, extreme values appear both above and below the mean VO_2 for any sample interval of reasonable duration. In the present study, these extreme values were found to be distributed normally, when sampled over a duration of several minutes. In an attempt to determine what a “reasonable” duration is, and to actually specify a sample error, the present work used a statistical technique which takes into the account the degree of variability of VO_2 data.

The application of 20 s sample intervals to VO_2 data from incremental exercise, improves sensitivity to peaks while maintaining a 5% error, when compared with 60 s sample intervals (3). Although the results in Table 1 indicate that longer sample intervals incur smaller sample errors, when trying to identify the maximum value from incremental data, there is a “trade-off” between sample error and sample sensitivity. Longer sample intervals offer a lower sample error at the expense of sensitivity to peaks (3). Increasing the sample interval from 20 s to 60 s for incremental VO_2 data offers an improvement in sample error of only 2%, while sensitivity to peaks may fall by as much as 5% in some individuals (Figure 2). The strategy of the present work was to maximize sensitivity to peaks while minimizing sample error. This was achieved by selecting the shortest acceptable sample interval, which achieves greatest sensitivity while restricting sample error to within 5%.

An important limitation of the present method is that it makes the assumption that the mean (± SD) oxygen cost of cycling is constant throughout submaximal workloads and at VO_2peak. However, there are other reports that the oxygen cost of cycling increases non-linearly (20). Analyses of the VO_2 data from the present report indicate that SD increases at VO_2max. In addition the oxygen cost of exercise reported here is slightly less than at least one previous report (21) but within the range reported by another (22). These inconsistencies make it very difficult to determine highly accurate and reliable criteria for a plateau in VO_2. While further investigation is warranted in this area, the consistent application of any reasonable criteria is probably preferable to the inconsistent application of a variety of different criteria.

There was large variability in the calculated sample interval for individuals, due to the strong influence of standard deviation of VO_2 on sample size. The application of relatively small sample intervals to VO_2 data with a large standard deviation would generate a sample error greater than 5%. Therefore, it may be more useful to calculate sample interval duration for each individual where standard deviation of VO_2 is significantly larger than the mean standard deviation of VO_2 data reported here. In addition, the sample interval size recommended here is also based upon an absolute error in VO_2 (150 mL/min or 5% of group mean VO_2 peak in the present investigation) in addition to the assumption that the VO_2 response to incremental exercise is linear. Investigators should choose the size of the allowable sample error in either absolute (L/min) or relative (% of VO_2peak) terms. If a relative error is chosen (eg. 5% of VO_2peak), sample intervals shorter than 20 s can be applied to groups with higher aerobic power because the absolute error will increase (ie. 5% of 5.0 L/min is 0.25 L/min). Conversely, an absolute sample error (in L/min) does not change the sample interval, regardless of the expected VO_2peak.

The definition of a VO_2 plateau (14) has been interpreted in many ways (discussion by 2 & 6) and the underlying physiological concept remains contentious (18). Taylor et al. (14) identified a plateau in VO_2 by comparing the two final VO_2 values, averaged over sample intervals of 60 s, during a running test. This comparison was made between the actual and the expected increase in VO_2, which depended upon the oxygen cost of the exercise, the rate of increase of work rate and the sample interval duration. Taylor et al. (14) calculated the 90% confidence interval of the expected increase in VO_2 (299 ± 86 mL/min), which resulted in a limit of increase of 150 mL/min. A plateau was defined where the actual increase was less than the calculated limit of increase (Figure 3). It is important to note this absolute limit is only valid for the test protocol and mode of exercise used by Taylor et al. (14) and was probably not intended to be used for different testing protocols. In the present investigation, the method of Taylor et al. (14) was modified by using a more selective 95% confidence interval and adapting their methodology to account for differing ramp rate (Watts/min), oxygen cost (mL/min/Watt) and sample interval duration. This modification is intended to provide a method that is reliable and offers appropriate sensitivity to a plateau in VO_2 for a variety of incremental test protocols for cycle ergometry.

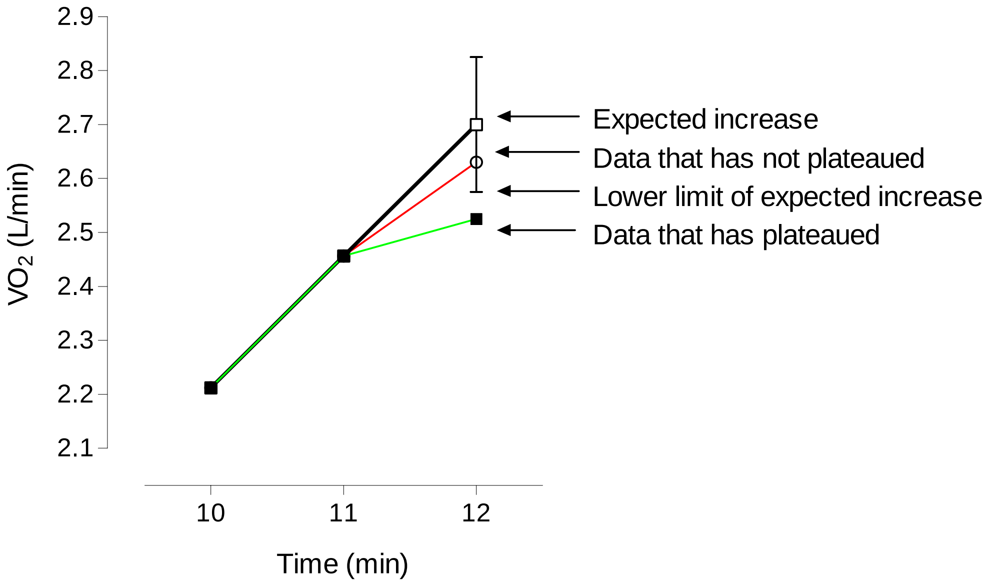

Figure 3. Taylor's Plateau Concept. A plateau is defined as an increase in VO_2 in the last two sample intervals of an incremental exercise test, which is less than the minimum expected increase. Error bars indicate the range of the expected increase in VO_2 calculated as the average increase ±1.645 SD.

This adaptation of Taylor's method has been described previously by at least two authors who recalculated the confidence interval and cut off value for their own VO_2 data (23,24). However the present work makes a further adaptation of Taylor's method by determining a "plateau index" which was calculated by determining the lower limit of a 95% confidence interval of the mean oxygen cost cycle ergometry for a range of ramp rates (25-30 Watts/min). The "plateau index" of 8.0 mL/min/Watt can be used to determine the maximum difference between the two highest consecutive VO_2 data points, required to identify a plateau. Where a ramp rate of 30 Watts/min is used and data are divided into 20 s intervals, the limit of increase to qualify for a plateau is 80 ml (ie. There is a 10 Watt increase for every 20 s interval, therefore, the limit is; 8 mL/min/Watt x 10 Watts = 80 mL/min, see Table 2). In the present report, this criterion identified nine subjects who attained a VO_2 plateaue in a group of 20 (45%), which is similar to rates reported previously (2,23,25).

The present method was devised using VO_2 data from a continuous incremental protocol because this is now a common design that has clear advantages over a discontinuous protocol (eg. it is easier to accurately identify the ventilatory thresholds). It is difficult to assess the validity of the present method for discontinuous protocols, although a previous report indicates that the incidence of a plateau in VO_2 is the same for continuous and discontinuous test protocols (23). Furthermore, this method may be applied to mixing chamber VO_2 data from a continuous incremental test, although it is difficult to determine whether the differences between averaging breath-by-breath data for 20 s and taking a 20 s average of VO_2 data from a mixing chamber data, are important.

CONCLUSIONS

The present report provides a rationale for a new method of analysis of VO_2 data and suggests a standard sample interval duration and plateau criterion. Analysis of sample size indicates that 20 s sample intervals offer a sample error of ~%5 when applied to VO_2 data collected during incremental cycle ergometry. Furthermore, a modified version of the plateau criterion reported by Taylor et al. (14) is presented, which sets the maximum increase in VO_2 between the two highest consecutive sample intervals at 8.0 mL/min/Watt, to qualify as a plateau. The application of this sample method and plateau criterion has limitations and requires further work to be validated for discontinuous test protocols and other modes of exercise.

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Address for correspondence: Dr. Daniel Dwyer, School of Human Life Sciences, University of Tasmania, Locked Bag 1320, Launceston, Tasmania 7250, Australia ; Phone: +61 3 6324 5485; Fax: +61 3 6324 3658; Email: d.dwyer@utas.edu.au

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