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Challenging a dogma of exercise physiology: Does an incremental exercise test for valid $\dot{V}O_{2max}$ determination really need to last between 8-12 minutes?

Running head: 8-12 minutes for $\dot{V}O_{2max}$ test?

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Figure legend

Figure 1. Distribution of $\dot{V}O_{2max}$ values from two studies that involved repeated determinations of $\dot{V}O_{2max}$ using incremental test protocols with 1 and 3 min stage durations. The horizontal lines positioned within the plots represent the mean $\dot{V}O_{2max}$ values. Differences in $\dot{V}O_{2max}$ between test protocols were statistically insignificant for both studies. The mean times to exhaustion were: reference[23], 1-min protocol = 9.1 (SD 0.8) min, 3-min protocol = 24.4 (SD 2.6) min; reference[25], 1-min protocol = 10.4 (SD 1.7) min, 3-min protocol = 25.9 (SD 4.0) min.

Abstract

A widely cited recommendation is that to elicit valid $\dot{V}O_{2max}$ values, incremental exercise tests should last between 8-12 min. However, this recommendation originated from the findings of a single experimental study conducted by Buchfuhrer et al. in 1983. Although this study is an important contribution to scientific knowledge, it should not be viewed as sufficient evidence to support the recommendation that incremental exercise tests should last between 8-12 min to elicit valid $\dot{V}O_{2max}$ values. At least eight studies have reported durations as short as 5 min and as long as 26 min elicit $\dot{V}O_{2max}$ values similar to $\dot{V}O_{2max}$ derived from tests of 8-12 min duration. Two studies reported that the shorter test protocols elicited significantly higher $\dot{V}O_{2max}$ values in untrained men and women. In three studies that reported significantly higher $\dot{V}O_{2max}$ determined during tests of 8-12 min than during more prolonged tests, the prolonged tests were associated with maximal treadmill grades of 20-25%, compared to 6-10% in the shorter tests. Intolerable treadmill grades may have therefore limited the ability to elicit $\dot{V}O_{2max}$, rather than the prolonged test duration. In view of the available evidence, test administrators, reviewers, and journal editors should not view 8-12 min duration for incremental exercise tests as obligatory for valid $\dot{V}O_{2max}$ determination. Current evidence suggests that to elicit valid $\dot{V}O_{2max}$ values, cycle ergometer tests should last between 7 and 26 min and treadmill tests between 5 and 26 min. This is dependent on the qualification that short tests are preceded by an adequate warm-up and that treadmill grades do not exceed 15%. Current research is too limited to indicate appropriate test duration ranges for discontinuous test protocols, or protocols incorporating high treadmill grades.

Key words: Cardiopulmonary exercise testing; maximal oxygen uptake; methodology; protocol.

Incremental exercise tests used to determine the maximal oxygen uptake ($\dot{V}O_{2max}$) often differ considerably in methodological characteristics, such as stage duration and increment size. Differences may be due to personal preference or customary practice. Alternatively, the test administrator may wish to simultaneously identify “secondary” measures such as the lactate and ventilatory thresholds, work efficiency, and peak work rate, which have been used to assess physical functional capacity, enable prescription of accurate exercise intensity, and monitor responses to physical training programmes.[1-4] Determination of particular secondary measures, however, may be better suited to either short duration, or more prolonged incremental exercise tests. For example, relatively short ramp, or pseudo-ramp, protocols have been regarded as suitable for determination of the anaerobic threshold by pulmonary gas exchange,[5] whereas accurate lactate threshold determination requires more prolonged test protocols.[5, 6] If $\dot{V}O_{2max}$ is the only variable of interest, then time-efficiency may be the primary consideration.[7, 8] Test durations that are too short, or too long, however, may result in subjects reaching their limit of exercise tolerance before $\dot{V}O_{2max}$ has been elicited.[9] The range of incremental exercise test durations that elicit valid $\dot{V}O_{2max}$ values, is therefore of interest to researchers and clinicians involved in $\dot{V}O_{2max}$ determination.

A widely cited recommendation is that to elicit valid $\dot{V}O_{2max}$ values, incremental exercise tests should last between 8-12 min. Exercise testing guidelines published by the American College of Sports Medicine, American Thoracic Society/American College of Chest Physicians, Australian Institute of Sport, and the British Association of Sport and Exercise Sciences, have all included this recommendation.[10-13] Numerous studies have also cited the 8-12 min “criterion” as quality assurance that subjects probably attained $\dot{V}O_{2max}$ during the incremental exercise test (e.g.[14-19]). The 8-12 min criterion originated from the findings of a single experimental study conducted by Buchfuhrer et al. in 1983.[9] This study involved five apparently healthy males who each performed five treadmill and three cycle ergometer incremental exercise tests. The test duration means for the five treadmill tests were 7.0 (SD 0.5), 10.6 (SD 1.0), 11.4 (SD 1.0), 15.1 (SD 0.9), and 26.4 (SD 1.6) min, and for the cycle ergometer tests 5.8 (SD 1.1), 10.6 (SD 2.2), and 18.0 (SD 3.6) min. Based on their findings, the authors concluded that "to obtain the highest $\dot{V}O_{2max}$ during incremental exercise on a given ergometer, we suggest selecting a work rate increment to bring the subject to his limit of exercise tolerance in 10 ± 2 min" (p.1563).

Although the Buchfuhrer et al.[9] study is an important contribution to scientific knowledge, it should not be viewed as sufficient evidence to support the recommendation that incremental exercise tests should last between 8-12 min to elicit valid $\dot{V}O_{2max}$ values. Firstly, of the five treadmill tests, only differences in $\dot{V}O_{2max}$ between the tests with mean times to exhaustion of 7.0 and 11.4 min were statistically significant. Secondly, the subjects were moderately fit men, so it is not known whether the results can be validly extrapolated to sedentary or well-trained individuals, women, children, the elderly, or individuals with chronic diseases, where differences in exercise tolerance are likely to be apparent. Generalizing the results from such a small sample may also be associated with considerable error.[20] Thirdly, evaluation of the influence of test duration on $\dot{V}O_{2max}$ determination was confounded by differences in maximal treadmill grade between protocols. Finally, Buchfuhrer et al.[9] stated that prolonged $\dot{V}O_{2max}$ tests do not provide any additional information and used this point to substantiate their recommendation that incremental exercise tests should last between 8-12 min. We believe that identifying the validity of simultaneously determining such variables as the lactate threshold and work efficiency, in addition to $\dot{V}O_{2max}$, during a more prolonged incremental exercise test, would have great practical value. Moreover, such an approach to testing is already being used by researchers.[21, 22]

Many other experimental studies have involved repeat determinations of $\dot{V}O_{2max}$ using incremental exercise tests of varying duration (Tables 1 and 2). Whereas some studies[24, 30-32] have supported the findings of Buchfuhrer et al.,[9] the same,[24, 31] and other studies,[8, 25-29] have reported small, insignificant differences in $\dot{V}O_{2max}$ between test protocols of 8-12 min duration and protocols shorter or longer than this range. The practical insignificance of these small differences can be appreciated when considering that the repeated measures coefficient of variation for $\dot{V}O_{2max}$ has been reported to be between around 4%;[33, 34] or 2 $mL \cdot kg^{-1} \cdot min^{-1}$ for an individual with a $\dot{V}O_{2max}$ of 50 $mL \cdot kg^{-1} \cdot min^{-1}$.

Two studies reported that valid $\dot{V}O_{2max}$ values can be elicited with incremental exercise tests as prolonged as 25-26 min in both trained and untrained individuals[23, 25] (highlighted in Figure 1). Short rest periods between stages may be particularly effective for eliciting $\dot{V}O_{2max}$ during prolonged incremental exercise tests,[27] since rest periods would attenuate the cumulative fatigue associated with each stage. However, a slightly longer test with a mean time to exhaustion of 28 min resulted in significantly lower $\dot{V}O_{2max}$ than a test protocol with a mean time to exhaustion of 11 min.[24] Three studies have reported significantly lower $\dot{V}O_{2max}$ values for tests with mean times to exhaustion of 20-27 min, compared to tests of between 8-12 min.[30-32] However, the prolonged tests in these studies were associated with maximal treadmill grades of 20-25%, compared to 6-10% in the shorter tests. High maximal treadmill grades may be poorly tolerated[8, 35, 36] and provides an alternative explanation for the significantly lower $\dot{V}O_{2\,max}$ in the prolonged tests.

Two studies[26, 31] reported that test protocols with mean times to exhaustion of 6.6 and 7.4 min, respectively, elicited significantly higher $\dot{V}O_{2\,max}$ values than protocols with mean times to exhaustion between 8-12 min, in untrained men and women. Further support for the efficacy of shorter test protocols in eliciting $\dot{V}O_{2\,max}$ is provided by Kang et al.,[8] who reported that an incremental exercise test of around 5-min duration elicited $\dot{V}O_{2\,max}$ values similar to incremental exercise tests of 8-12 min duration. Short incremental tests may be particularly suitable for trained individuals, due to their faster oxygen uptake kinetics.[37] We could find no studies except that of Buchfuhrer et al.[9] that has reported significantly higher $\dot{V}O_{2\,max}$ in incremental exercise tests between 8-12 min and protocols shorter than this range, in apparently healthy subjects. It is also noteworthy that single square wave runs that average between 2-6 min, performed to the limit of exercise tolerance, have been shown to elicit $\dot{V}O_{2\,max}$.[38, 39] However, short incremental test protocols may not be suitable for patients with impaired cardiorespiratory function. Agostoni et al.[40] reported that heart failure patients elicited significantly higher $\dot{V}O_{2peak}$ values in an incremental test protocol with a mean duration of 9.7 (SD 0.8) min compared to a protocol with a mean duration of 5.3 (SD 0.5) min. Additionally, although the direct determination of $\dot{V}O_{2\,max}$ has been found to be robust to relatively large deviations in test duration in apparently healthy individuals, it should be noted that this does not appear true for estimates of $\dot{V}O_{2max}$ derived from external workload; where short incremental test protocols tend to overestimate $\dot{V}O_{2max}$ in comparison to longer protocols.[26, 41]

The preceding warm-up period is important when considering the effect of incremental exercise test duration on $\dot{V}O_{2max}$ determination. An appropriate warm-up is often considered necessary to facilitate subject comfort and safety,[35, 42] in particular, to prevent abnormal cardiac responses associated with the onset of sudden strenuous exercise.[43, 44] Although a warm-up would appear necessary for short test protocols incorporating large stage increments or high initial workloads, it could be argued that the initial stages of prolonged test protocols typically provide sufficiently slow progression from light to maximal exercise and that a separate warm-up period is not warranted. The assertion that short incremental exercise test protocols are time efficient, may not, therefore, be justified.

A potential limitation in evaluating past research for establishing the effect of incremental exercise test duration on $\dot{V}O_{2max}$ determination is that many test protocols were associated with a large degree of dispersion around the mean test duration. Based on the mean (SD) test durations for the studies in Tables 1 and 2, it is also clear that in some studies, the distributions of the test durations for particular test protocols overlap. Future research investigating the effect of test duration on $\dot{V}O_{2max}$ determination should attempt to minimise the variability of test duration around the target test time, so that more accurate inferences can be made from the research findings.

In conclusion, since its publication in 1983, the study by Buchfuhrer et al.[9] has been used to form a dogmatic view that incremental exercise tests should last between 8-12 min to elicit valid $\dot{V}O_{2max}$ values. The present paper challenges this premise and we urge test administrators, journal editors, and reviewers not to view 8-12 min duration for incremental exercise tests as obligatory for valid $\dot{V}O_{2max}$ determination. Current evidence suggests that to elicit the $\dot{V}O_{2max}$ of apparently healthy individuals, continuous cycle ergometer tests should generally last between 7 and 26 min and continuous treadmill tests between 5 and 26 min. This is dependent on the qualification that short tests are preceded by an appropriate warm-up and that treadmill grades do not exceed 15%. We also recommend that after the incremental test and a short rest period, subjects should perform a "supramaximal" bout of square wave exercise to their limit of exercise tolerance to help verify that $\dot{V}O_{2max}$ has been elicited.[45, 46] Current research is too limited to indicate appropriate test duration ranges for discontinuous test protocols, or protocols incorporating high treadmill grades.

Further research is required to support or challenge our guidelines, as well as establishing the effect of discontinuous test protocols and protocols with high treadmill grades on the range of test durations that elicit valid $\dot{V}O_{2max}$ values. Further research is also needed to establish whether population-specific guidelines are required.

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Table 1. Summary of studies that have used continuous, incremental cycle ergometry test protocols of different durations for the repeated determination of $\dot{V}O_{2max}$. The studies are organised in descending order of publication date. Time to exhaustion (t_{lim}) and $\dot{V}O_{2max}$ are reported as mean (SD). When the original study reported the standard error of the mean, the standard deviation was calculated using the formula: SEM √n, where SEM is the standard error of the mean and n is the sample size.

Study	Subjects	Test protocols	t_{lim} (min)	$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})
Bentley and McNaughton (2003)[23]	9 male triathletes	A. 150 + 30 W / 1 min	9.1 (0.8)	62.7 (2.6)
		B. 50% + 5% PPO / 3 min	24.4 (2.6)	61.2 (3.6)
Weston et al. (2002)[24]	12 male cyclists/ triathletes	A. 75 W + 50 W / 1 min	7.2 (0.8)	66.4 (7.8)^{a}
		B. 75 W + 30 W / 1 min	11.1 (1.4)	66.5 (7.6)^{b}
		C. 75 W + 10 W / 1 min	27.9 (3.8)	63.3 (7.2)^{a,b}
Bishop et al. (1998)[25]	8 moderately active women	A. 50 + 25 W / 1 min	10.4 (1.7)	42.2 (7.6)
		B. 50 + 25 W / 3 min	25.9 (4.0)	43.8 (6.1)
Myers et al. (1991)[26]	41 healthy & diseased men	A. 50 W / 2 min	7.1 (1.1)	18.1 (7.0)
		B. Ramp protocol individualized to elicit exhaustion in ~10 min	9.4 (0.8)	18.5 (7.0)
		C. 25 W / 2 min	10.3 (2.2)	17.7 (7.0)
Buchfuhrer et al. (1983)[9]	5 moderately active men	A. 0 + 60 W / 1 min	5.8 (1.1)	44.7 (11.3)^{b,c}
		B. 0 + 30 W / 1 min	10.6 (2.2)	50.3 (12.8)^{b}
		D. 0 + 15 W / 1 min	18.0 (3.6)	48.3 (11.9)^{c}

Like superscript letters within a study represent statistically significant differences. **PPO** = peak power output.

Table 2. Summary of studies that have used incremental treadmill test protocols of different durations for the repeated determination of $\dot{V}O_{2max}$. The studies are organised in descending order of publication date. Time to exhaustion (t_{lim}) and $\dot{V}O_{2max}$ are reported as mean (SD). When the original study reported the standard error of the mean, the standard deviation was calculated using the formula: SEM √n, where SEM is the standard error of the mean and n is the sample size.

Study	Subjects	Test protocols	Max grade (%)*	t_{lim} (min) ¥	$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})
Midgley et al. (2007)[27]	9 male distance runners	A. 1 km·h^{-1}/1 min for first 5 increments, then 0.5 km·h^{-1}/1 min	1.0	10.3 (1.7)	54.9 (7.2)
		B. 1 km·h^{-1}/2 min (30s rest intervals between stages)	1.0	17.9 (2.0)	55.0 (6.9)
		C. 1 km·h^{-1}/3 min (30s rest intervals between stages)	1.0	26.0 (2.4)	53.4 (6.0)
Kang et al. (2001)[8]	12 trained men	A. 0 + 2% / 2 min at constant 14.4 km·h^{-1}	10.0	10.4 (1.4)	68.0‡
		B. 0 + 2% / 2 min at constant 9.7 km·h^{-1}	14.0	14.5 (1.7)	66.0‡[a]
		C. 0.7 + 1.4/1.4/1.4/1.1 km·h^{-1} & 10 + 2% increments every 3 min	20.0	17.0 (1.7)	64.0‡[a]
	15 untrained men	A. 0 + 2% / 2 min at constant 14.4 km·h^{-1}	4.0	4.9 (1.2)	45.2‡
		B. 0 + 2% / 2 min at constant 9.7 km·h^{-1}	8.0	9.8 (1.9)	45.0‡
		C. 0.7 + 1.4/1.4/1.4/1.1 km·h^{-1} & 10 + 2% increments every 3 min	18.0	12.4 (1.5)	45.1‡
	10 untrained women	A. 0 + 2% / 2 min at constant 14.4 km·h^{-1}	4.0	5.3 (1.9)	42.5‡
		B. 0 + 2% / 2 min at constant 9.7 km·h^{-1}	8.0	9.0 (2.5)	42.5‡
		C. 0.7 + 1.4/1.4/1.4/1.1 km·h^{-1} & 10 + 2% increments every 3 min	16.0	11.0 (1.9)	41.2‡
Myers et al. (1991)[26]	41 healthy & diseased men	A. 1.3/1.4/1.3/1.3/0.8 km·h^{-1} & 10 + 2% increments every 3 min	14.0	6.6 (1.5)	22.3 (8.0)[a,b]
		B. Ramp protocol with ramp rate individualized to elicit exhaustion in ~10 min	?	9.1 (1.4)	21.0 (8.0)[a]
		C. 0 + 2.5%/2 min at 3.2 then constant 4.8 km·h^{-1}	10.0	10.4 (3.4)	21.1 (8.0)[b]
Nordrehaug et al. (1991)[28]	10 healthy men	A 2 + 2km·h^{-1}/3 min at constant 15% grade	15.0	11.9 (2.2)	51.1 (11.1)
		B. 2.4 + 0.6/ 1.4/1.3/1.3/0.8 km·h^{-1} & 10 + 2% increments every 3 min	18.0	13.5 (1.7)	51.8 (10.5)
		C. 2 + 2km·h^{-1}/3 min at constant 0% grade	0.0	21.8 (3.0)	49.2 (9.7)
McConnell and Clark (1988)[29]	10 male runners	A. 0 + 2.5%/1 min at a constant 12.9 km·h^{-1}	25.0	10.1 (0.6)	65.0 (5.6)
		C. 0 + 2.5%/2 min at a constant 14.0 km·h^{-1}	12.5	11.8 (1.1)	66.2 (3.9)
		B. 0 + 2.5%/2 min at a constant 12.9 km·h^{-1}	15.0	13.1 (1.2)	64.5 (5.3)
		D. 0 + 2.5%/2 min at a constant 12.7 km·h^{-1}	15.0	13.6 (2.5)	64.7 (5.8)

Table 2. Continued.

Study	Subjects	Test protocols	Max grade (%)∗	t_{lim} (min) ¥	$\dot{V}O_{2max}$ (mL·kg^{-1}·min^{-1})
Buchfuhrer et al. (1983)[9]	5 moderately active men	A. 4.2% / 1 min (constant 5.5 km·h^{-1})	25.2	7.0 (1.1)	49.1 (12.3)[a]
		B. 1.7% / 1 min (constant 7.2 km·h^{-1})	17.0	10.6 (2.2)	51.9 (13.1)
		C. 2.5% / 1 min (constant 5.5 km·h^{-1})	27.5	11.4 (2.2)	52.5 (12.8)[a]
		D. 1.7% / 1 min (constant 5.5 km·h^{-1})	25.5	15.1 (2.0)	51.7 (13.1)
		E. 0.8% / 1 min (constant 5.5 km·h^{-1})	20.8	26.4 (3.6)	50.3 (11.6)
Pollock et al. (1982)[30]	29 sedentary women	A. 2.7 + 1.3/1.4/1.3/1.3/0.8 km·h^{-1} & 2% increments every 3 min	6.0	9.5 (0.9)	36.9 (4.1)[a]
		B. 0% + 2.5% / 3 min at a constant 4.8 km·h^{-1}	17.5	21.7 (3.2)	35.0 (5.3)[a]
	20 active women	A. 2.7 + 1.3/1.4/1.3/1.3/0.8 km·h^{-1} & 2% increments every 3 min	6.0	11.4 (1.0)	46.1 (4.8)[b]
		B. 0% + 2.5% / 3 min at a constant 4.8 km·h^{-1}	25.0	27.5 (3.0)	43.2 (3.8)[b]
Pollock et al. (1976)[31]	29 sedentary men	A. 0 + 2.5% / 2 min at constant speed (dependent on individual's fitness)	7.5	7.4 (1.1)	37.7 (4.2)[a]
		B. 2.7 + 1.6 km·h^{-1}/ 2-3 min increments at 10% and then 15%	15.0	8.2 (1.1)	36.3 (4.4)
		C. 2.7 + 1.3/1.3/1.3/1.3/0.8/0.8 km·h^{-1} & 10 + 2% increments every 3 min	16.0	9.4 (1.1)	35.3 (3.9)[a]
		D. 0 + 2 + 1% / 1 min at a constant 5.3 km·h^{-1}	15.0	14.6 (2.7)	35.8 (4.1)
	22 active men	A. 0 + 2.5%/2 min at constant speed (dependent on individual's fitness)	10.0	8.3 (1.0)	47.3 (5.4)[b]
		B. 2.7 + 1.6 km·h^{-1}/ 2-3 min increments at 10% and then 15%	15.0	10.5 (1.4)	46.7 (5.5)
		C. 2.7 + 1.3/1.3/1.3/1.3/0.8/0.8 km·h^{-1} & 10 + 2% increments every 3 min	16.0	11.5 (1.0)	46.3 (5.7)
		D. 0 + 2 + 1% / 1 min at a constant 5.3 km·h^{-1}	20.0	19.8 (2.9)	44.1 (4.4)[b]
Froelicher et al. (1974)[32]	15 healthy men	A. 0 + 2.5% / 3 min at a constant 11.3 km·h^{-1} (5 min rest between stages)	7.5	†11.7	47.4†[a,b]
		B. 2.7 + 1.3/1.4/1.3/1.3/0.8 km·h^{-1} & 10 + 2% increments every 3 min	18.0	†13.0	44.3†[a]
		C. 0 + 2 + 1% / 1 min at a constant 5.3 km·h^{-1}	24.0	†23.7	42.8†[b]

Like superscript letters within a study represent statistically significant differences. ∗ Mean maximal treadmill grade estimated from the treadmill test protocol and the mean time to exhaustion, where not reported in the original study. **¥** Rest periods in discontinuous protocols not included. **#** Constant, self-selected treadmill speed. Appropriate grade increments to achieve target test times for each subject were estimated from previous habituation trials. **‡** $\dot{V}O_{2max}$ taken from the bar charts in Figure 2 of the original paper, as the actual values were not reported. **?** Mean maximal treadmill grade could not be estimated. **†** Mean value for three trials.

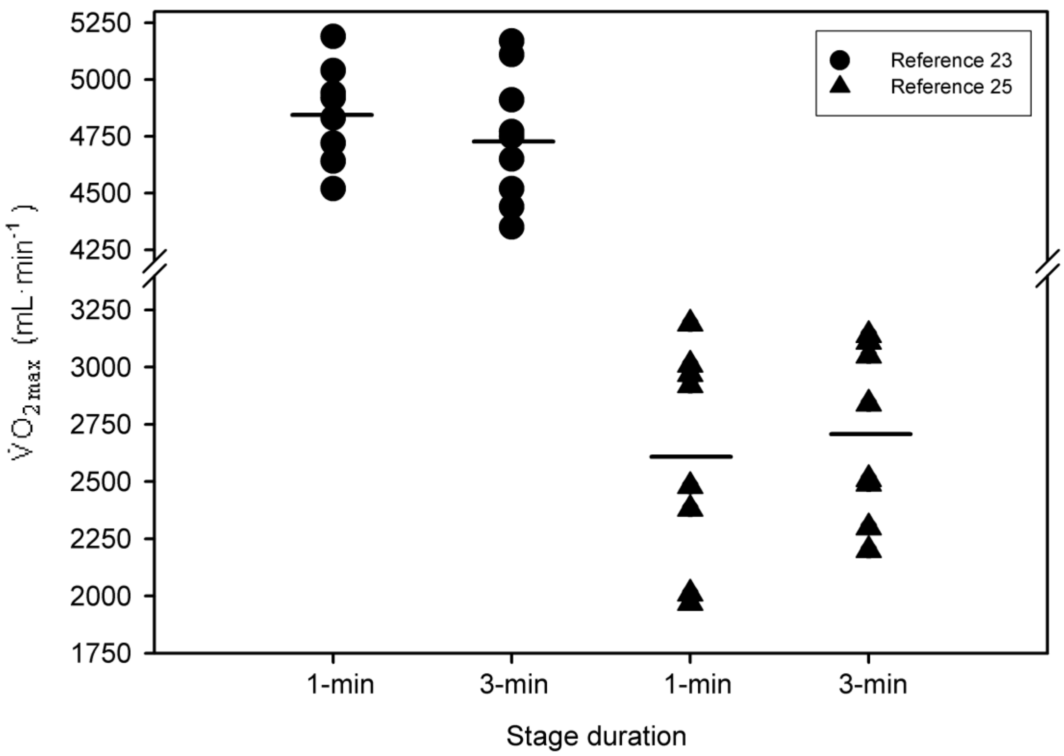
5250
5000
4750
4500
4250
3250
3000
2750
2500
2250
2000
1750
VO2max (mL·min-1)
Reference 23
Reference 25
1-min
3-min
1-min
3-min
Stage duration

Figure 1